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Hanford Immobilized LAW Product Acceptance: Initial Tanks Focus Area Testing Data Package

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February 2000

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Summary

A matrix of 55 glasses was developed and tested with the aim to identify the impact of glass composition on long-term corrosion behavior and to develop an acceptable composition region for Hanford LAW glasses. Of the 55 glasses, 45 were designed to systematically vary the glass composition and 10 were selected because large and growing databases on their corrosion characteristics had accumulated. The targeted compositions of these glasses are listed in Section 3.1. All glasses were fabricated according to standard procedures and heat treated to simulate the slow cooling that occurs to a portion of the glass to be fabricated in the future vitrification plant at Hanford. The homogeneity of test glasses, characterized with electron and optical microscopy and X-ray diffraction, are discussed in Section 3.1. The densities of these glasses were measured with gas pycnometry and are reported in Section 3.2. The performance of these 55 glasses in the product consistency test (PCT) and the vapor-hydration test (VHT) were characterized in Sections 3.5 and 3.6.

PCT series were performed at 90°C with glass surface area to solution-volume ratios (S/Vs) of 2000 m^{-1} for 7 days and S/V values of 20,000 m^{-1} for 10, 100, and 1000 h. The PCT corrosion extents, determined as functions of time from solution-composition analyses, are listed in Section 3.5. The normalized releases for the 1000-h tests range from 0.1 to 6.3 g/m^2 for boron and from 0.1 to 7.2 g/m^2 for sodium. Based on the boron releases, the estimated release rates for these glasses range up to 1.0 and 0.1 $g/m^2/d$ for periods of 1 and 1000 h, respectively. The glasses with the highest boron release rates were HLP-31, -02, -39, -41, and -27 at 10 h and HLP-51, -41, -33, and -39, and -31 at 1000 h. For the sodium data, the release rates range up to 0.7 and 0.2 $g/m^2/d$ for periods of 1 and 1000 h, respectively. The glasses with the highest sodium release rates were HLP-31, -02, -41, -39,and -27 at 1 h and HLP-52, -33, -41, -42, and -31 at 1000 h. Insufficient information concerning the alteration products formed during PCT was available to make a comparison to the VHT or other data.

VHTs were performed at temperatures between 150°C and 300°C for times up to 280 days. The preliminary alteration rates of most glasses have been determined at 200°C. These rates, listed in Section 3.6.2, are preliminary and are expected to change as further data are generated. Rates measured at higher and lower temperatures were also reported in Section 3.6.4 for selected glasses. The glasses with high resistance to VHT (e.g., alteration rates $\leq$ 14 $g/m^2/d$) take long times to corrode sufficiently for an accurate measurement of rate. For these glasses, the rates are likely to change when more data have been collected. The preliminary glass alteration rates ranged from 0.0 to 1219 $g/m^2/d$ at 200°C and cover at least three orders of magnitude. The rates of only four glasses exceeded 100 $g/m^2/d$—HLP-52, HLP-53, HLP-02, and HLP-46. The remaining test matrix glasses are highly resistant to the VHT, possibly indicating high durability. The alteration products formed during VHT of selected glasses were characterized with XRD. Section 3.6.3 summarizes the phases found to form during the alteration of selected test glasses. Most tested samples altered to form analcime and sodium aluminum silicate hydrate, which are frequently formed also in other alteration tests.

The precision and accuracy of test methods were in Section 1.0 with data found in literature on the behavior of selected test matrix glasses in the PCT and VHT and with a series of glasses with the same targeted composition (repeated glasses) added to the test matrix. A comparison of results from PCT and VHT is discussed briefly in Section 1.0.

Glossary

Accelerated tests	tests conducted to attain certain conditions faster than it would be possible under natural conditions or tests conducted under conditions that increase the reaction rate
AES	atomic emission spectroscopy
AGCR	acceptable glass composition region
Alteration products	thermodynamically more stable phases formed during glass corrosion. These phases may incorporate constituents from glass and other species from the solution, atmosphere, and barrier materials.
Amount of glass dissolved	mass of glass dissolved, calculated from the thickness of glass reacted, which is determined by subtracting the remaining glass layer thickness (determined by OM/IA) from initial glass thickness
ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
Behavior	the response of a material to its environment, specifically to the temperature and solution chemistry
Corrosion	the process of glass dissolution and conversion to alteration products
Corrosion layer	layer of corrosion products formed on the surface of bulk glass
Corrosion rate	the rate at which glass is dissolved or converted to alteration products
Dissolution	the process of dissolving solid material into the solution
DIW	deionized water
DOE	U.S. Department of Energy
E_a	apparent activation energy
EDS	energy dispersive spectroscopy
HLP	Hanford LAW product acceptance (glass nomenclature)
HLW	high-level waste
HVV	Hanford Vitrification Vendor
IA	image analysis
ICP	inductively coupled plasma
ILAW	immobilized low-activity waste
LAW	low-activity waste
LRM	low-activity waste reference material
m_d	mass of glass altered in g/m^2
OM	optical microscopy
PA	performance assessment
PCT	Product Consistency Test
PCT-A	method A of the PCT as defined in ASTM (1998)

PCT-B	method B of the PCT as defined in ASTM (1998)
PDF	powder diffraction file
Performance	the ability of the burial system, primarily waste form in this work, to meet regulatory limits on release of radioactive and hazardous components
PNNL	Pacific Northwest National Laboratory
r	alteration rate in $g/m^2/d$
repeated glasses	multiple glasses with the same target composition, fabricated and tested separately
S/V	glass surface area to solution volume ratio
SEM	scanning electron microscopy
SRTC	Savannah River Technology Center
SRTC-ML	SRTC mobile laboratory
t	time
TBD	to be determined
TFA	Tanks Focus Area
VHT	Vapor Hydration Test
XRD	X-ray diffraction

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1.0 Introduction

The Hanford Site's mission has been to produce nuclear materials for the U.S. Department of Energy (DOE) and its predecessors. A large inventory of radioactive and mixed waste, largely generated during plutonium production, exists in 177 underground single- and double-shell tanks. These wastes are to be retrieved and separated into low-activity waste (LAW) and high-level waste (HLW) fractions. The total volume of LAW requiring immobilization will include the LAW separated from the tank waste, as well as new wastes generated by the retrieval, pretreatment, and immobilization processes. Per the Tri-Party Agreement (1994), both the LAW and HLW will be vitrified. It has been estimated that vitrification of the LAW waste will result in over 500,000 metric tons or 200,000 m^3 of immobilized LAW (ILAW) glass.

DOE is proceeding with an approach to privatize the treatment and immobilization of Hanford's LAW and HLW. DOE will deliver these wastes to a private contractor for treatment and immobilization and will receive the products (immobilized waste) for storage and ultimate disposal. The ILAW glass is to be disposed of onsite in a near-surface burial facility. It must be demonstrated that the disposal system will adequately retain the radionuclides and prevent contamination of the surrounding environment. Waste-form performance is the first line of defense against releases of contaminants after disposal and an integral part of the multiple engineered barrier system. Mann et al. (1998) found that the release of radionuclides from the waste form via interaction/reaction with water is the prime threat to the environment surrounding the disposal site. The two major dose contributors in Hanford ILAW glass that must be retained are ^{99}Tc and ^{79}Se (Mann et al. 1998).

McGrail et al. (1998) describe the strategy for testing and modeling to determine/assess the radionuclide release rates from ILAW glass. This strategy requires extensive testing and modeling for each glass considered. The program includes, for example, *in situ* testing, tests with waste-package components, tests that simulate the hydrology and geochemistry of the burial site, and coupled flow-reaction modeling. The resources required to perform such a thorough study on a large number of glasses are not practical. The Tanks Focus Area (TFA) Immobilization Program, DOE-EM Office of Science and Technology, has outlined a task to help reduce DOE's risk of accepting an ILAW glass that will not meet performance expectations. The TFA task is highly integrated with the Performance Assessment (PA) task described by McGrail et al. (1998). The goal of the PA task is to determine the long-term performance of the Hanford vitrification vendor (HVV) glass to be buried in the Hanford Site near a surface-disposal facility. The goal of the TFA task is to relate the long-term performance to glass composition and to provide a means for screening glass compositions proposed by the HVV.

In this study (the TFA task), a team from Pacific Northwest National Laboratory (PNNL) and Savannah River Technology Center (SRTC) is measuring the impacts of systematic glass-composition variation on the responses from accelerated laboratory corrosion tests of representative LAW glasses. A committee of experts, assembled to identify the appropriate testing program, determined that no single short-term test or pair of short-term tests was capable of determining the long-term performance of a waste glass (Vienna et al. 1999). However, the committee did conclude that the combination of two tests, the product consistency test (PCT) and vapor-hydration test (VHT), could give valuable indications of the relative rate at which a glass could be expected to corrode in the burial scenario.[a] These data are being generated and will be used to

[a] To fully understand the long-term performance of a glass additional testing is required. McGrail et al. (1998 and 1999) discuss how this information is being gathered for a few selected glasses.

- quantify the effect of glass composition on response to PCT and VHT
- supply selected glass compositions to the PA Program for further testing (along with PCT and VHT results)
- help identify the appropriate glass-acceptance specifications for the HVV in concert with other DOE activities
- supply a database to support glass-acceptance specifications and support the PA by giving an indication of the range of test responses and possibly identify an irregularities in glass behavior.

This is planned to be a two-stage task; the first stage, described in this report, is nearing completion. The second stage will be planned based on the knowledge gained from the first stage and concurrent work on the Hanford PA study (described by McGrail et al. 1998) and the glass development program of the HVV. In the second stage, a second tier of glass compositions will be designed and tested to account for any additional components introduced by the HVV and to better cover the initial composition region. Additional tests may also be performed on existing glasses, if needed, to better understand glass behavior. This report provides the status for the first stage of testing and recommends possible approaches for the next stage.

2.0 Experimental Approach

Fourty-five glasses with systematically varying compositions were fabricated along with ten additional glasses, including glasses similar to those being considered by the HVV. The glasses were heat treated to simulate slow cooling that is expected to occur during plant operation. The homogeneity, density, and chemical composition of test glasses were measured. The responses of each glass to the VHT and the PCT were measured.

2.1 Test Matrix Design

A matrix of 55 glasses was developed and tested with the aim to identify the relationship between glass composition and response to the PCT and VHT (Vienna et al. 1999). The target compositions of these Hanford LAW product-acceptance (HLP) glasses are listed in Table 2-1. They are split into four groups of glasses:

1. The first 24 glasses contained variations in nine components—SiO_2, Al_2O_3, B_2O_3, Fe_2O_3, TiO_2, ZnO, ZrO_2, MgO, and waste (primarily Na_2O)—one-at-a-time (HLP-01 through -24) from a central composition (HLP-01). These glasses give a direct indication of the impact of each of these oxides on the behavior of glasses in the testing program. Glasses HLP-44 and -45 have the same target composition as HLP-01, but were melted and heat treated under reducing atmospheres to increase the ratio of two valent to total iron (Fe(II)/Fe).
2. Four glasses (HLP-01, -25, -26, and -43) have the same target composition and were fabricated and tested separately to assess the reproducibility of the glass fabrication and test procedures.
3. Sixteen glasses (HLP-27 through -42) varied four components at a time—SiO_2, Al_2O_3, B_2O_3, and waste (primarily Na_2O)—to assess the interactive effects of the components expected to have the largest effect on glass behavior in corrosion testing.
4. The final 10 glasses (HLP-46 through -56) (see below) were included because large and growing databases on their corrosion characteristics had accumulated:
    - HLP-46 is the LD6-5412 glass that was characterized by Kim et al. (1995), Feng et al. (1996), and McGrail et al. (1997a,b).[a] This glass expands the composition ranges of test glasses to higher concentrations of SiO_2, CaO, and K_2O.
    - HLP-47 is the low-activity waste reference material (LRM) glass that was characterized by Wolf et al. (1998) and Ebert and Wolf (1999). This glass increases the range of SiO_2, K_2O, Cl^-, and F^- concentrations in the test glasses.
    - HLP-48 is the LAW-A33 glass that was characterized by McGrail et al. (1999). This glass represents a composition that may be processed by the HVV.
    - HLP-49 is the LAW-B, also known as LAW-B29, that was characterized by Ferrara et al. (1998). It expands the composition ranges of the study to lower Na_2O concentrations and higher CaO and Li_2O concentrations and represents a composition that may be processed by the HVV.
    - HLP-51 is the LAW-ABP1 glass that was characterized by McGrail et al. (1998 and 1999). This glass introduces La_2O_3 as a glass component.

[a] W. L. Ebert, A. J. Bakel, D. M. Strachan, and S. F. Wolf. 1998. *Laboratory Testing of LD6-5412 Glass*, DRAFT, Argonne National Laboratory, Argonne, Illinois.

- HLP-52 is the Han-28 glass that was characterized by McGrail et al. (1999). This glass expands the composition ranges to lower B_2O_3 and Fe_2O_3 concentrations and higher Na_2O and P_2O_5 concentrations.
- HLP-53 is the LAW-A23 glass that was characterized by McGrail et al. (1998 and 1999). This glass represents a composition that may be processed by the HVV and expands the range of composition to higher CaO concentrations.
- HLP-54 is the L4-912 glass that was characterized by Kim et al. (1995) and Feng et al. (1996).[a] This glass expands the composition ranges to higher concentrations of Al_2O_3 and SiO_2 and lower concentrations of many glass components.
- HLP-55 is the L4-99 glass that was characterized by Kim et al. (1995) and Feng et al. (1996).[a] This glass expands the composition ranges to higher SiO_2 concentration and lower concentrations of many glass components.
- HLP-56 is the LAW-A44 glass that was characterized by McGrail et al. (1999). The composition of this glass is proprietary.

[a] W. L. Ebert, A. J. Bakel, D. M. Strachan, and S. F. Wolf. 1998. *Laboratory Testing of LD6-5412 Glass*, DRAFT, Argonne National Laboratory, Argonne, Illinois.

Table 2-1. Target Compositions (in mass% of oxides) of the Hanford LAW Product-Acceptance Glasses

Glass ID[a]	Description[b]	SiO_2	Al_2O_3	B_2O_3	Fe_2O_3	TiO_2	Zn	ZrO_2	MgO	Li_2O	Na_2O	K_2O	Ca	Cl^-	SO	P_2O_5	Cr_2O_3	F	ReO_2	MoO_3	La_2O_3	Total
HLP-01	Center	49.07	7.00	10.00	5.5	3.00	1.5	1.50	1.50	0.00	20.00	0.41	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-02	L Si	36.00	8.79	12.57	6.9	3.77	1.8	1.88	1.88	0.00	25.14	0.52	0.0	0.35	0.0	0.07	0.09	0.0	0.01	0.00	0.00	99.99
HLP-03	H Si	52.00	6.60	9.43	5.1	2.82	1.4	1.41	1.41	0.00	18.85	0.39	0.0	0.26	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.99
HLP-04	I Si	40.00	8.24	11.78	6.4	3.53	1.7	1.77	1.77	0.00	23.57	0.49	0.0	0.33	0.0	0.07	0.09	0.0	0.01	0.00	0.00	100.01
HLP-05	L Al	50.65	4.00	10.32	5.6	3.09	1.5	1.55	1.55	0.00	20.65	0.43	0.0	0.29	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.01
HLP-06	H Al	46.46	11.94	9.47	5.2	2.84	1.4	1.42	1.42	0.00	18.94	0.39	0.0	0.26	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.99
HLP-07	I Al	48.01	9.00	9.79	5.3	2.93	1.4	1.47	1.47	0.00	19.57	0.40	0.0	0.27	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.98
HLP-08	L B	51.25	7.31	6.00	5.7	3.13	1.5	1.57	1.57	0.00	20.89	0.43	0.0	0.29	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.01
HLP-09	H B	47.98	6.84	12.00	5.3	2.93	1.4	1.47	1.47	0.00	19.56	0.40	0.0	0.27	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.99
HLP-10	I B	50.16	7.15	8.00	5.6	3.06	1.5	1.53	1.53	0.00	20.45	0.42	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	99.98
HLP-11	L Fe	51.93	7.41	10.58	0.0	3.17	1.5	1.59	1.59	0.00	21.17	0.44	0.0	0.29	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.01
HLP-12	H Fe	47.25	6.74	9.63	9.0	2.89	1.4	1.44	1.44	0.00	19.26	0.40	0.0	0.27	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.98
HLP-13	I Fe	50.37	7.18	10.27	3.0	3.08	1.5	1.54	1.54	0.00	20.53	0.42	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-14	L Ti	50.59	7.21	10.31	5.6	0.00	1.5	1.55	1.55	0.00	20.62	0.43	0.0	0.29	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.02
HLP-15	H Ti	47.55	6.78	9.69	5.3	6.00	1.4	1.45	1.45	0.00	19.39	0.40	0.0	0.27	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.98
HLP-16	L Zn	49.82	7.10	10.15	5.5	3.04	0.0	1.52	1.52	0.00	20.31	0.42	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	99.99
HLP-17	H Zn	47.82	6.82	9.75	5.3	2.92	4.0	1.46	1.46	0.00	19.50	0.40	0.0	0.27	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.98
HLP-18	L Zr	49.82	7.10	10.15	5.5	3.04	1.5	0.00	1.52	0.00	20.31	0.42	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	99.99
HLP-19	H Zr	46.83	6.68	9.55	5.2	2.86	1.4	6.00	1.43	0.00	19.09	0.39	0.0	0.26	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.99
HLP-20	L Mg	49.82	7.10	10.15	5.5	3.04	1.5	1.52	0.00	0.00	20.31	0.42	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	99.99
HLP-21	H Mg	47.82	6.82	9.75	5.3	2.92	1.4	1.46	4.00	0.00	19.50	0.40	0.0	0.27	0.0	0.05	0.07	0.0	0.01	0.00	0.00	99.98
HLP-22	L Na	51.67	7.37	10.53	5.7	3.16	1.5	1.58	1.58	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	100.00
HLP-23	H Na	47.13	6.72	9.61	5.2	2.88	1.4	1.44	1.44	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	100.00
HLP-24	I Na	50.37	7.18	10.27	5.6	3.08	1.5	1.54	1.54	0.00	18.00	0.37	0.0	0.25	0.0	0.05	0.07	0.0	0.01	0.00	0.00	100.01
HLP-25	Center	49.07	7.00	10.00	5.5	3.00	1.5	1.50	1.50	0.00	20.00	0.41	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-26	Center	49.07	7.00	10.00	5.5	3.00	1.5	1.50	1.50	0.00	20.00	0.41	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-27	HHHH[c]	52.00	11.94	12.00	0.0	0.00	0.0	0.00	0.00	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	99.99
HLP-28	HHHL[c]	52.00	11.94	12.00	3.1	1.69	0.8	0.84	0.84	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	99.99
HLP-29	HHLH[c]	52.00	11.94	6.00	2.5	1.38	0.6	0.69	0.69	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	99.98
HLP-30	HHLL[c]	52.00	11.94	6.00	5.6	3.07	1.5	1.54	1.54	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	100.01
HLP-31	HLHH[c]	52.00	4.00	12.00	3.3	1.83	0.9	0.92	0.92	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	100.00
HLP-32	HLHL[c]	52.00	4.00	12.00	6.4	3.52	1.7	1.76	1.76	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	100.00

Glass ID[a]	Description[b]	SiO_2	Al_2O_3	B_2O_3	Fe_2O_3	TiO_2	Zn	ZrO_2	MgO	Li_2O	Na_2O	K_2O	Ca	Cl^-	SO	P_2O_5	Cr_2O_3	F	ReO_2	MoO_3	La_2O_3	Total
HLP-33	HLLH[c]	52.00	4.00	6.00	5.9	3.21	1.6	1.61	1.61	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	99.99
HLP-34	HLLL[c]	52.00	4.00	6.00	9.0	4.90	2.4	2.45	2.45	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	99.99
HLP-35	LHHH[c]	36.00	11.94	12.00	6.7	3.69	1.8	1.85	1.85	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	100.00
HLP-36	LHHL[c]	36.00	11.94	12.00	9.8	5.38	2.6	2.69	2.69	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	100.00
HLP-37	LHLH[c]	36.00	11.94	6.00	9.3	5.07	2.5	2.54	2.54	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	99.99
HLP-38	LHLL[c]	36.00	11.94	6.00	12.4	6.76	3.3	3.38	3.38	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	99.99
HLP-39	LLHH[c]	36.00	4.00	12.00	10.1	5.52	2.7	2.76	2.76	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	99.98
HLP-40	LLHL[c]	36.00	4.00	12.00	13.2	7.21	3.6	3.61	3.61	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	100.01
HLP-41	LLLH[c]	36.00	4.00	6.00	12.6	6.90	3.4	3.45	3.45	0.00	23.00	0.47	0.0	0.32	0.0	0.06	0.09	0.0	0.01	0.00	0.00	99.97
HLP-42	LLLL[c]	36.00	4.00	6.00	15.7	8.59	4.3	4.30	4.30	0.00	16.00	0.33	0.0	0.22	0.0	0.04	0.06	0.0	0.01	0.00	0.00	100.00
HLP-43	Center	49.07	7.00	10.00	5.5	3.00	1.5	1.50	1.50	0.00	20.00	0.41	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-44	reduced[d]	49.07	7.00	10.00	5.5	3.00	1.5	1.50	1.50	0.00	20.00	0.41	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-45	reduced[d]	49.07	7.00	10.00	5.5	3.00	1.5	1.50	1.50	0.00	20.00	0.41	0.0	0.28	0.0	0.06	0.08	0.0	0.01	0.00	0.00	100.00
HLP-46	LD6-5412[f]	55.91	12.00	5.00	0.0	0.00	0.0	0.00	0.00	0.00	20.00	1.46	4.0	0.35	0.2	0.19	0.04	0.2	0.00	0.15	0.00	99.60
HLP-47	LRM[g]	55.00	10.00	8.00	1.0	0.10	0.0	1.00	0.10	0.10	20.00	1.50	0.5	0.80	0.2	0.50	0.20	1.0	0.00	0.00	0.01	100.01
HLP-48	LAW-A33[e]	38.25	11.97	8.85	5.7	2.49	4.2	2.49	1.99	0.00	20.00	3.10	0.0	0.58	0.1	0.08	0.02	0.0	0.00	0.00	0.00	100.00
HLP-49	LAW-B29[e]	43.93	8.03	8.07	8.0	0.00	3.9	3.04	3.00	4.08	10.00	0.36	7.0	0.29	0.0	0.01	0.10	0.0	0.00	0.00	0.00	99.98
HLP-51	LAW-ABP1	41.89	10.00	9.25	2.5	2.49	2.6	5.25	1.00	0.00	20.00	2.20	0.0	0.58	0.1	0.08	0.02	0.0	0.00	0.00	2.00	100.00
HLP-52	HAN-28[e]	44.46	10.15	0.00	2.5	0.38	0.0	5.00	1.18	0.00	28.62	1.96	2.5	0.13	0.3	1.90	0.08	0.3	0.00	0.00	0.00	99.59
HLP-53	LAW-A23[e]	40.15	9.86	4.23	7.3	0.00	3.2	2.99	2.04	2.04	20.00	3.10	4.3	0.36	0.0	0.08	0.01	0.1	0.00	0.00	0.00	99.98
HLP-54	L4-912	56.78	12.00	9.00	0.0	0.00	0.0	0.00	0.00	0.00	20.00	0.33	0.0	0.09	0.3	1.19	0.04	0.2	0.00	0.00	0.01	99.97
HLP-55	L4-99	59.78	9.00	9.00	0.0	0.00	0.0	0.00	0.00	0.00	20.00	0.33	0.0	0.09	0.3	1.19	0.04	0.2	0.00	0.00	0.01	99.97
HLP-56	LAW-A44[e,h]																					

(a) Glass HLP-50 is reserved for a suitable natural analog glass to be tested once identified.
(b) Levels of glass components are given as L – low, I – intermediate, and H – high for the components following the level.
(c) Levels of glass components are given as L – low, I – intermediate, and H – high for SiO_2, Al_2O_3, B_2O_3, and Na_2O, respectively.
(d) HLP-44 and -45 were melted and heat treated under a reducing atmosphere to increase the ratio of two valent to total iron (Fe(II)/Fe).
(e) Preliminary Hanford LAW glasses developed by the Vitreous State Laboratory at the Catholic University of America for the HVV. Target composition was normalized to 100% during fabrication.
(f) HLP-46, or LD6-5412, contains additional components (target mass%): SrO (0.11), I (0.13), Cs_2O (0.15), and MnO (0.002), see Feng et al. (1996) for details.
(g) HLP-47, or LRM, contains additional components (target mass%): BaO (0.005), CdO (0.2), I (0.002), MnO (0.1), NiO (0.1), and PbO (0.1), see Ebert and Wolf 1999 for details.
(h) Proprietary glass composition.
(i) The entire Fe concentration is listed as Fe_2O_3; except where otherwise noted, no attempt was made to control the oxidation state of Fe.

2.2 Glass Fabrication and Heat Treatment

Matrix glasses were batched from single metal oxide or carbonate precursors for all components except SO_3, P_2O_5, F^-, and Cl^-, which were added as sodium salts, and B_2O_3, which was added as H_3BO_3. Batches sufficient to produce 500 g of glass were melted in covered Pt/Rh crucibles for 1 h, quenched on a steel plate, ground in a tungsten carbide mill, and remelted in a covered Pt/Rh crucible for 1 h. After the second melt, a portion of the melt was quenched on a steel plate. The remainder of the melt was transferred directly into a preheated furnace (in Pt or Pt/Rh containers) and heat-treated according to the HVV box interior cooling schedule shown in Figure 2-1.[a] This cooling schedule was used to simulate the slowest cooling that can be expected during plant operation. Glasses HLP-46, -47, -52, -54, and -55 were not heat treated (to maintain the same thermal history of the glasses previously tested with the same compositions), but bars were cast and annealed for 2 h at roughly 10°C above the glass transition temperature and slow cooled to room temperature. Glasses HLP-44 and -45 were batched with a targeted ratio of FeO to Fe_2O_3 and melted and heat treated in a controlled atmosphere furnace with CO/CO_2 ratios described in Table 2-2. This procedure was used at SRTC to fabricate glasses HLP-13 to HLP-25 and at PNNL to fabricate the remaining glasses.

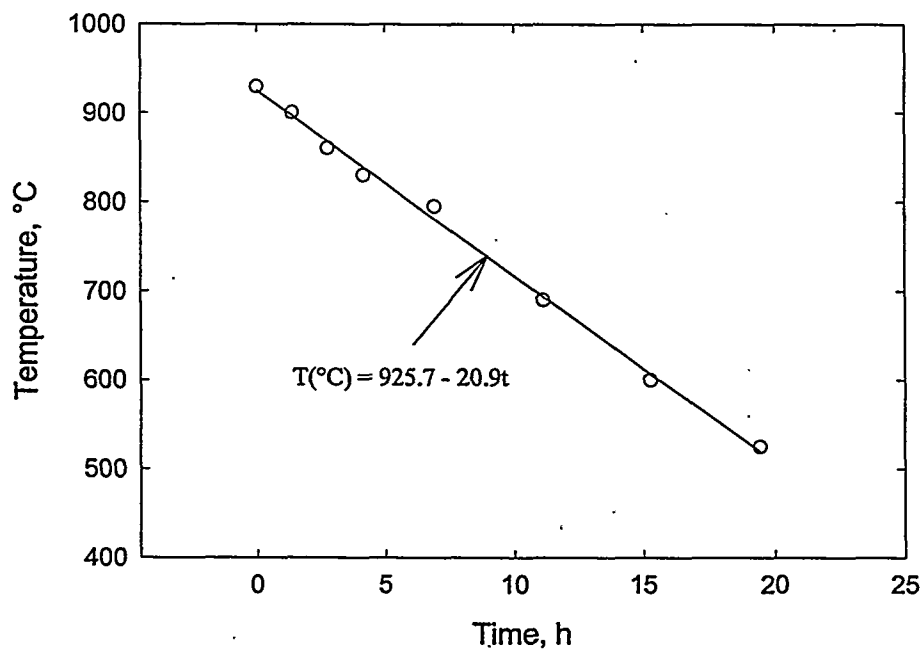

Figure 2-1. Computed Thermal Cooling Curve for 1.2 × 1.2 × 1.8 m Waste Package

[a] Although the HVV no longer plans to cast glass into a box, an updated cooling schedule was not available at the time of this testing. The impacts of a different cooling schedule will have to be assessed after the final schedule is available. However, the impacts are not expected to be significant.

Table 2-2. Melting Parameters for HLP-44 and HLP-45

Fabrication Step	Ratio	HLP-44	HLP-45
Batching	FeO/Fe_2O_3	1.65/3.67	3.87/1.23
Melting	CO/CO_2	0.64/99.36	16.66/82.7
Heat Treatment	CO/CO_2	0/100	0.02/99.97

2.3 Homogeneity

Heat-treated glasses were examined in transmitted-light optical microscopy (OM) at magnifications up to 70×. Selected glasses were examined at high magnification (up to 1000×) OM, scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD). Crystalline fractions of any glass in which secondary crystalline phases were identified with OM were obtained by semiquantitative XRD according to the direct comparison method (Cullity 1978). This method is estimated to have a relative accuracy of ± 50%.

2.4 Density

Densities of all glasses were measured with a gas pycnometer AccuPyc 1330, which uses ultra pure Helium and is equipped with a 1-cm^3 cell. Heat-treated glass samples were ground in a tungsten carbide mill for 1 min to reduce the impact of bubbles on density. The device was calibrated with a tungsten carbide calibration ball before each set of measurements to check the calibration and exclude possible contamination of the instrument by glass powder.[a]

Once the sample was loaded, ten purge cycles were performed in roughly 30 min. The average of 10-volume-displacement measurements on the same sample was used to calculate the density of each glass. A standard deviation was calculated from the 10-volume-displacement measurements. This procedure was found to yield a precision from 0.04 to 0.01 % (relative) when multiple measurements of the same glass were made over a period of roughly 4 months, which is consistent with the reported precision for this instrument.

2.5 Redox Analyses

The Fe(II)/Fe ratio or redox of selected matrix glasses (HLP-26, -44, and -45) were measured according to the colorimetric method. The redox of both quenched and heat-treated samples was measured. For the measurement, roughly 0.1 g of powder (ground in a tungsten carbide mill) was mixed with 2.5 mL of concentrated H_2SO_4 (95–98%) and then with 7.5 mL of concentrated HF (48–51%). Within 15 sec after the powder was mixed with HF, a 250 mL reagent solution composed of phenanthroline, boric acid, and potassium hydrogen phthalate, was immediately added to stabilize the Fe(II). The solution was diluted to 500 mL with DIW and the absorbance of Fe(II) was measured using an ultra-violet/visible/near infrared spectrophotometer. The spectrophotometer was calibrated, and an Fe(II) concentration was calculated from calibration data. The total iron was determined by inductively coupled plasma-emission spectroscopy of the solution.

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[a] Certificate of Calibration, 98-046490, traceable to NIST Test No. 821 25B 592-97 according to ANSI/NCSL 2640-1-94 and ISO 10012-1-92, Precision Ball & Guage Co., Alvadore, Oregon (1998).

2.6 Composition Analyses

To confirm that the "as-fabricated" glass compositions corresponded to the defined targeted compositions (see Table 2-1), a sample from each HLP glass was submitted to the SRTC Mobile Laboratory (SRTC-ML) for chemical analysis. Due to limited quantities of glass, fines (-200 mesh powder) produced during the PCT sample-preparation procedure were submitted for analysis. Concentrations (as mass %) for the cations of interest were measured using inductively coupled plasma-atomic emission spectroscopy (ICP-AES) after preparing the samples using one of two fusion techniques: 1) Na_2O_2/NaOH/HCl or 2) $LiBO_2/HNO_3$. Table 2-3 identifies the elements analyzed, methods of analysis, and typical reportable limits[a]. The target and measured concentrations will be compared below.

Glass standards were not run with these samples as this practice is not required in the SRTC Mobile Laboratory (SRTC-ML) procedures. Instead, a matrix-matched calibration standard was run at the beginning and end of the test blocks as well as after each ten samples. For the analyses of the calibration standard, the expected differences are ± 5% (although the SRTC-ML procedure allow for differences up to ± 10%).

Na_2O_2/NaOH/HCl Fusion Preparation

Approximately 0.25 ± 0.01 g of crushed glass was fused with 1.5 g Na_2O_2 and 1.0 g NaOH at 600°C for 15 min in a Pt crucible. The fused sample was dissolved in water and 25 mL of HCl acid. The fused sample was diluted to 250 mL with deionized water.

ICP-AES was used to measure the concentrations of B, Si, Al, and Li in the Na_2O_2/NaOH/HCl fusion preparation. Before running the solution through the ICP-AES, a 1/10 dilution on the final 250-mL solution was performed. Calibration standards were matrix matched.

$LiBO_2/HNO_3$ Fusion Preparation

Approximately 0.1 ± 0.01 g of crushed glass was fused with 0.3 g of $LiBO_2$ at 900°C for 15 min in a Pt crucible. The fused sample was dissolved in a 4% HNO_3 solution. The dissolved sample was diluted to a final volume of 250 mL. No further dilutions were made before running this solution through the ICP-AES. Again, calibration standards were matrix matched.

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[a] The reportable limits are obtained from a two-point calibration, followed by the analyses of a blank five times with five replicates. The average standard deviation for each element, or detection limit, is then calculated from these results. The reportable limit is the detection limit multiplied by 10.

Table 2-3. Elemental Analysis Based on Dissolution Procedure and Analytical Technique

Element	Dissolution Technique	Analytical Technique	Typical Reportable Limit (μg/mL)
Al	$Na_2O_2/NaOH/HCl$	ICP-AES	< 0.200
B	$Na_2O_2/NaOH/HCl$	ICP-AES	< 0.180
Ca	$LiBO_2/HNO_3$	ICP-AES	< 0.010
Cr	$LiBO_2/HNO_3$	ICP-AES	< 0.030
Fe	$LiBO_2/HNO_3$	ICP-AES	< 0.020
K	$LiBO_2/HNO_3$	ICP-AES	< 0.600
Li	$Na_2O_2/NaOH/HCl$	ICP-AES	< 0.020
Mg	$LiBO_2/HNO_3$	ICP-AES	< 0.001
Na	$LiBO_2/HNO_3$	ICP-AES	< 0.530
Ni	$LiBO_2/HNO_3$	ICP-AES	< 0.060
Si	$Na_2O_2/NaOH/HCl$	ICP-AES	< 0.180
Ti	$LiBO_2/HNO_3$	ICP-AES	< 0.001
Zn	$LiBO_2/HNO_3$	ICP-AES	< 0.400
Zr	$LiBO_2/HNO_3$	ICP-AES	< 0.080

2.7 Product Consistency Testing

Both PCT-A and PCT-B were performed on each test-matrix glass to assess chemical durability as defined in American Society for Testing and Materials (ASTM) C 1285 (ASTM 1985). The PCT-A was conducted in triplicate for each of the LAW glasses. Duplicate blank tests with ASTM Type I water were also run within each test block. Samples were ground, washed, and prepared according to procedure. For PCT-A, 15 mL of ASTM water was added to 1.5 g of glass in stainless steel vessels resulting in a surface area to volume ratio S/V of approximately 2000 m^{-1}. (For this initial examination of the data, small variations in S/V resulting from minor density differences were not considered.) The vessels were closed, sealed, and placed into an oven at 90 ± 2°C where they remained for 7 days. After the 7-day test, vessels were removed from the oven and allowed to cool to room temperature. The final masses of each vessel and the solution pH were recorded on the data sheet. Test solutions were then filtered through a 0.45-μm pore size filter. Six mL of each test solution was then acidified with 4 mL of 0.4 M HNO_3 to ensure that the cations remain in solution. Test solutions and blanks were then analyzed in the SRTC-ML for Si, B, Na, and Li concentrations using ICP-AES. A multi-element solution standard was also submitted with the PCT solutions for control purposes. Data sheets were used to record the vessel identification number, sample ID, mass of vessel (empty), mass of vessel with glass, and the mass of vessel with glass and water.

The PCT-B series was conducted at an S/V value of approximately 20,000 m^{-1} and a temperature of 90°C in Teflon® vessels[a] as defined by Vienna et al. (1999). The durations for the PCT-B tests were: 10, 100, 1000, 5000 (or a time to be determined [TBD]), and 10,000 h (or a time TBD).[b] Samples were ground, washed, and prepared according to procedure. Ten mL of ASTM water was added to 10.0 g of glass in Teflon vessels, resulting in an S/V value of approximately 20,000 m^{-1}. The vessels were closed,

[a] When Teflon® vessels are used, CO_2 diffuses into the test solution so that secondary reactions are not limited by CO_2 concentration. Also for these long test durations, the vessel mass must be tracked and water added when the water mass loss exceeds 10%.

[b] A sixth sample was initiated and will be used as a "pulse-flow" test in which solution concentrations are monitored on, at least, a monthly basis to determine the appropriate times to pull the two TBD tests. Samples will be terminated at a time determined upon review of initial data.

sealed, and placed into an oven at 90 ± 2°C. After the specified test duration, the vessels were removed from the oven and were allowed to cool to room temperature. The final mass of each vessel and the solution pH were recorded on the data sheet. Test solutions were then filtered through a 0.45-μm pore size filter. Generally, 6 mL of each test solution was then acidified with 4 mL of 0.4 M HNO_3 to ensure that the cations remain in solution. Test solutions and blanks were then analyzed in the SRTC-ML for Si, B, Na, and Li concentrations using ICP-AES. A multi-element solution standard was also submitted with the PCT solutions for control purposes. Data sheets were used to record the vessel identification number, sample ID, mass of vessel (empty), mass of vessel with glass, and the mass of vessel with glass and water. Selected glass samples from the PCT-B tests are being evaluated for the formation of secondary phases via electron microscopy.

2.8 Vapor Hydration Testing

In the VHT, monolithic samples are exposed to saturated water vapor at elevated temperatures (typically 100°C to 300°C) in a sealed vessel as shown schematically in Figure 2-2. This environment greatly accelerates the progression of glass corrosion by water and can result in the formation of alteration phases. The principal uses of the test are 1) as a screening tool to quickly determine if a glass is likely to corrode at an extreme rate, 2) as a convenient means of generating alteration phases for analysis within a short period, and 3) for a measure of the alteration rate at elevated temperatures.

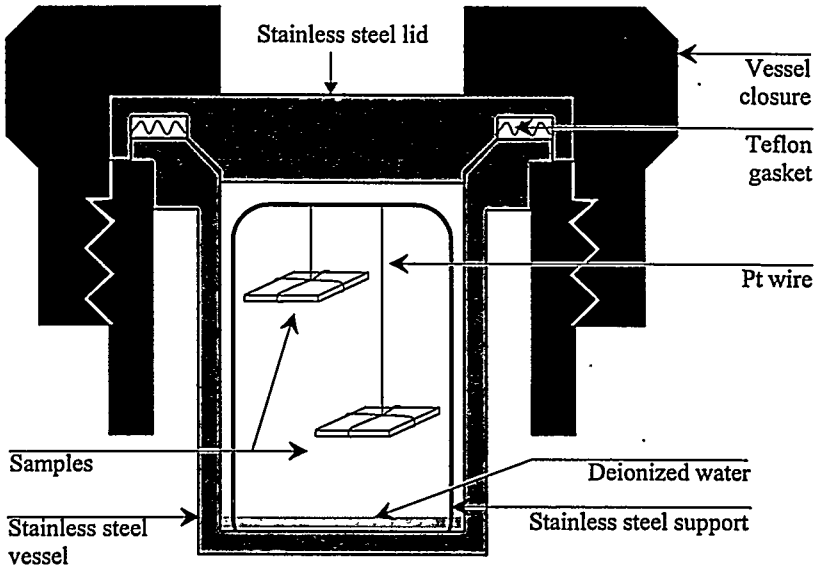


Figure 2-2. Apparatus for Conducting VHTs

The VHTs were performed according to a PNNL technical procedure.[a] Samples with dimensions of 10 × 10 × 1.5 mm are prepared from heat-treated glass bars with a diamond-impregnated saw. All sides are polished to 600-grit surface finishes with silicon carbide paper. Samples, stainless steel vessels, lids, and supports are cleaned, and samples are suspended from stainless steel supports on Pt wire. An

[a] *Vapor-phase Hydration Test Procedure*, GDL-VHT, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington (1999).

amount of deionized water (DIW), predetermined to be appropriate for the vessel size, the temperature, and the number of samples in the vessel, is added to the vessel. The sealed vessel is held at constant temperature in a convection oven for a preset time, removed, weighed, and quenched in water. After the test termination, samples are removed from the vessel and examined for the presence of alteration products with OM. The alteration products are identified with XRD and SEM with EDS.

The amount of altered glass was calculated from the difference between initial glass thickness and remaining glass thickness determined from sample cross sections with OM and image analysis (IA). The thickness of remaining glass layer, d_r, is determined by performing 10 measurements equally distributed across the specimen as shown in Figure 2-3.

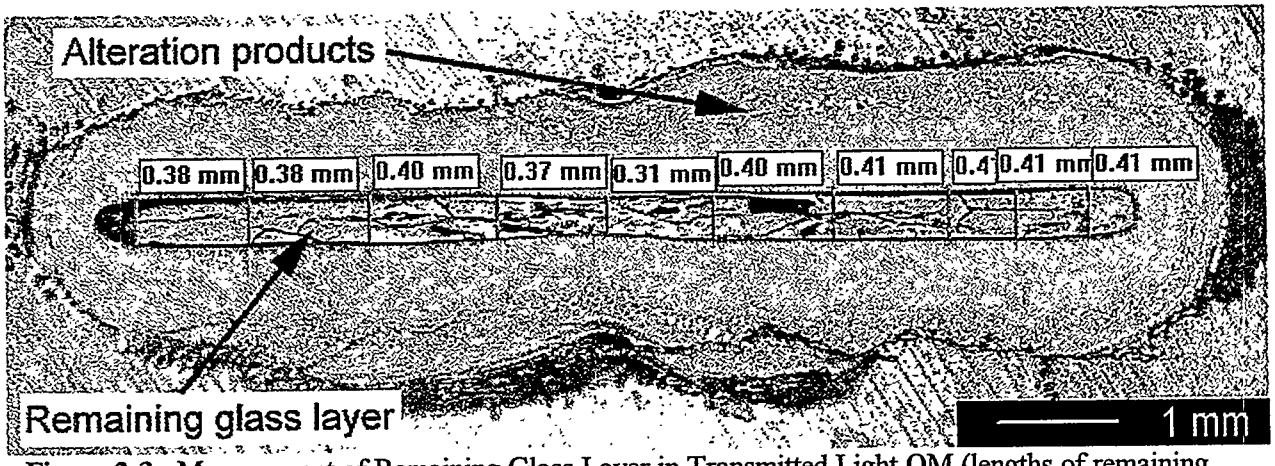


Figure 2-3. Measurement of Remaining Glass Layer in Transmitted Light OM (lengths of remaining glass layer are listed above each measurement)

The alteration extent or the amount of glass converted into alteration products (m_d) per unit surface area, is given by

$$m_d = \frac{m_i}{2w_i l_i}\left(1 - \frac{d_r}{d_i}\right) \tag{2.1}$$

where m_i is the initial sample mass, w_i and l_i are sample width and length, respectively, d_r is the thickness of remaining glass layer, and d_i is the initial glass layer thickness. The alteration rate, r, is then given by

$$r = \frac{\partial m_d}{\partial t} \tag{2.2}$$

where t is time, and the rate is calculated by regression over the linear portion of the $m_d - t$ curve as discussed in Section 3.6.1. This rate is that describing the alteration process, which is known to include leaching (ion exchange), corrosion (matrix dissolution), and precipitation of multiple alteration products. We do not yet know if one of the reactions limits the rate of the overall process or if so, which reaction. This will be a topic of further study.

3.0 Results and Discussion

The testing program described above is still in progress. This section summarizes the current, preliminary results. The final results from this testing program will be reported in a subsequent report.

3.1 Glass Homogeneity

Eight of the 55 matrix glasses formed significant amounts of a crystalline phase during the heat treatment. All other glasses appeared to be homogeneous or single phased by OM. However, additional phases that were not detectable by OM could have formed. Selected glasses were examined with SEM and XRD to confirm their homogeneity (which is still not considered adequate to rule out the presence of additional phases). Of the glasses that formed additional phases—HLP-36, -37, -38, -40, -41, -42, -49, and -53—six were four-component-at-a-time change glasses with low SiO_2, and two were proposed HVV glasses. Examination of the XRD traces of each glass, shown in Figure 3-1, suggests that they all contain crystalline inclusions with the possible exception of HLP-41. Further examination suggests that glasses HLP-38 and -42 have similar patterns. The phase characterization for each of these glasses is described in Sections 3.1.1 through 3.1.6.

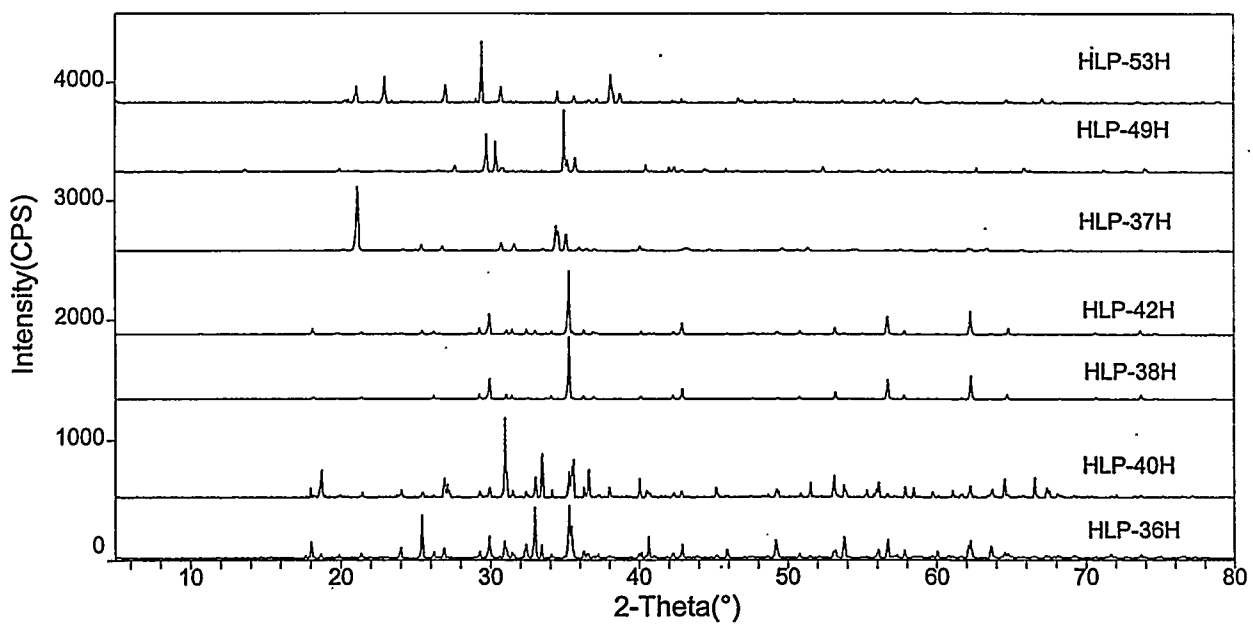


Figure 3-1. XRD Pattern of Inhomogeneous Glasses (with the "amorphous hump" subtracted)

3.1.1 HLP-36 and HLP-40

Glasses HLP-36 and -40 have the same target concentrations of SiO_2, Na_2O, and B_2O_3 with a different concentration of Al_2O_3 and form the same crystalline phases. The phases identified in these glasses along with their estimated concentrations are listed in Table 3-1. Hematite was found in two modifications with a different content of Ti substituting for Fe. Micrographs of these phases, both OM

and SEM, are shown in Figure 3-2 and Figure 3-3 for HLP-36 and Figure 3-4 and Figure 3-5 for HLP-40. Both zinc iron oxide and iron titanium oxide form smaller crystals located usually on the surface of hematite. An additional phase was found in HLP-36 with SEM/EDS; this phase has a high concentration of Ti and a smaller concentration of Mg. It likely accounts for the Loveringite structure found with XRD with Mg substituted for Ca.

Table 3-1. List of Phases Identified in HLP-36 and -40 With XRD

#[a)]	Phase	Concentration in HLP-36	Concentration in HLP-40
1	Zinc Iron Oxide ($ZnFe_2O_4$)	1.74 mass%	0.44 mass%
2	Hematite (Fe_2O_3)	2.40	1.52
3	Iron Titanium Oxide (Fe_2TiO_5)	2.09	10.32
4	Loveringite ($CaTi_{21}O_{38}$)	4.85	1.02

a) Numbers refer to the labels in figures.

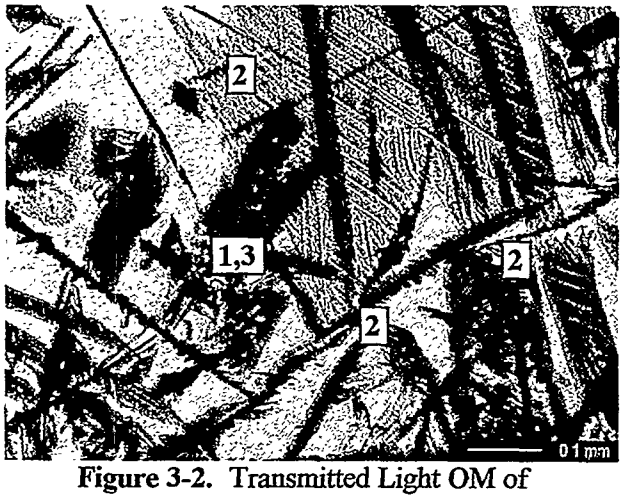


Figure 3-2. Transmitted Light OM of HLP-36 (200×)

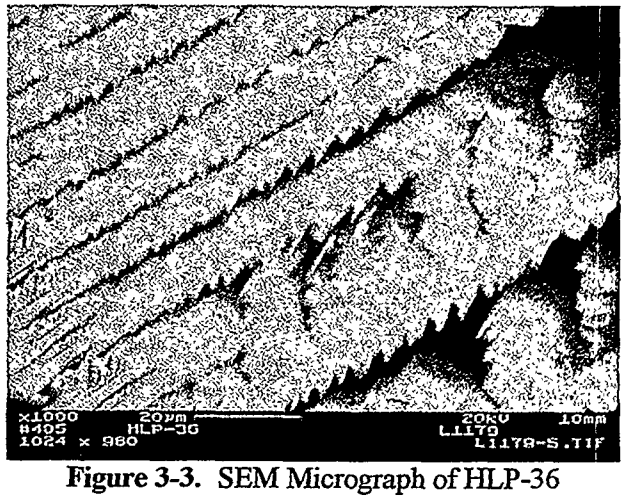


Figure 3-3. SEM Micrograph of HLP-36

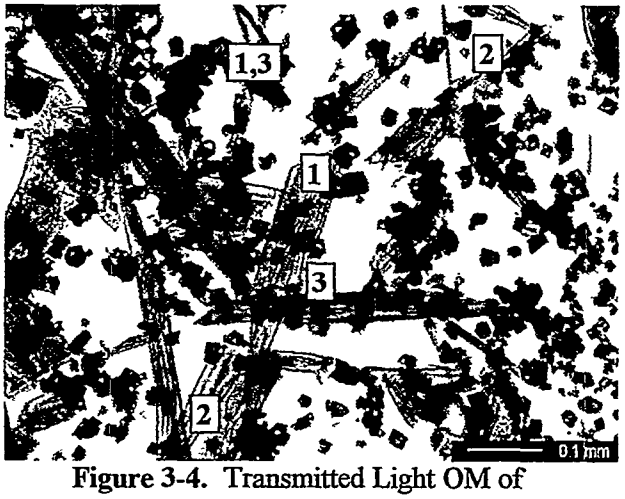


Figure 3-4. Transmitted Light OM of HLP-40 (200×)

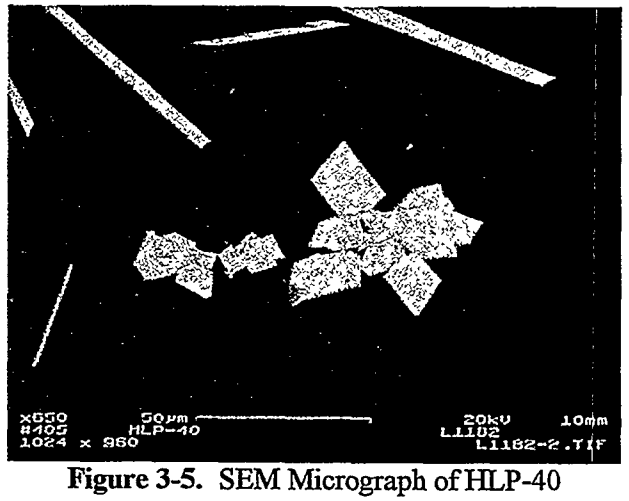


Figure 3-5. SEM Micrograph of HLP-40

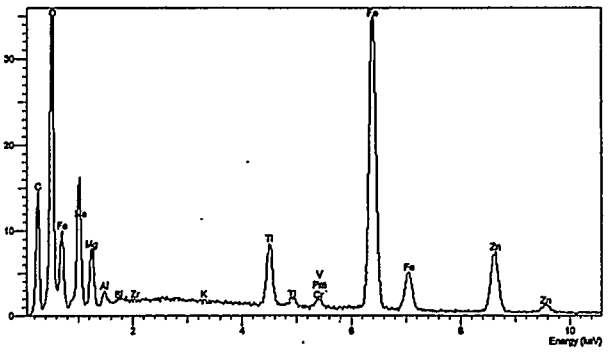


Figure 3-6. SEM/EDS of Zinc Iron Oxide ($ZnFe_2O_4$)

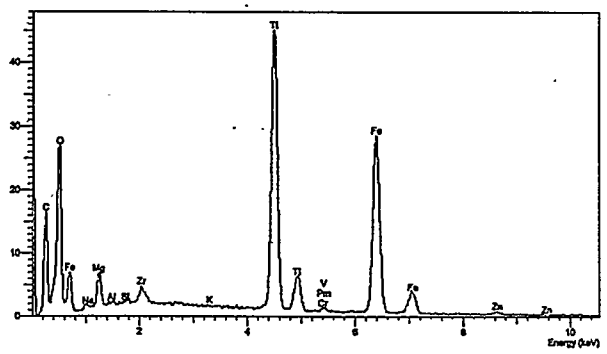


Figure 3-7. SEM/EDS of Hematite (Fe_2O_3), where Iron is Substituted by Ti

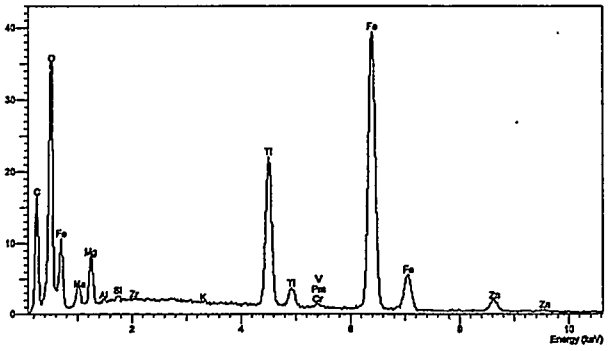


Figure 3-8. SEM/EDS of Iron Titanium Oxide (Fe_2TiO_5)

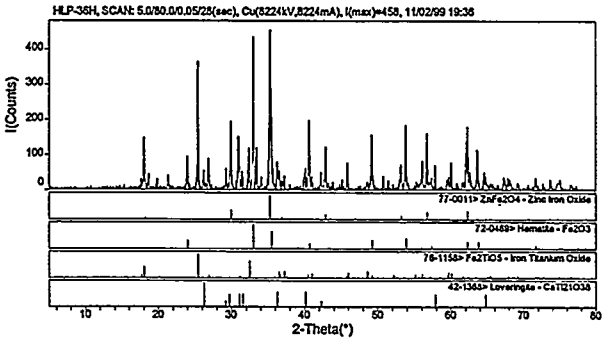


Figure 3-9. XRD Pattern of HLP-36

3.1.2 HLP-37

Carnegeite and chromite were identified in HLP-37 glass, with concentrations listed in Table 3-2. The leaf-like crystals in Figure 3-10 were identified as two distinct carnegieite phases. The light gray phase in Figure 3-11 has higher Si concentration, while the darker phase has higher concentrations of Al and Na. The second phase was identified with OM as spinel. An EDS spectra of this phase indicates high concentrations of Cr and Fe, likely chromite. This structure cannot be verified by XRD because of its minor content in glass (Figures 3-12 through 3-14).

Table 3-2. List of Phases Identified in HLP-37

#[a)]	Phase	Concentration
1	Carnegieite low ($Na(AlSiO_4)$)	49.28 mass%
2	Chromite ($FeCr_2O_4$)	≥ 0.5

a) Numbers refer to the labels in figures.

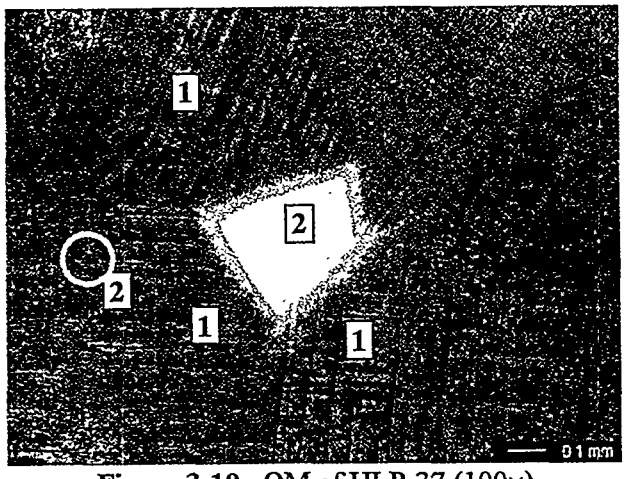


Figure 3-10. OM of HLP-37 (100×)

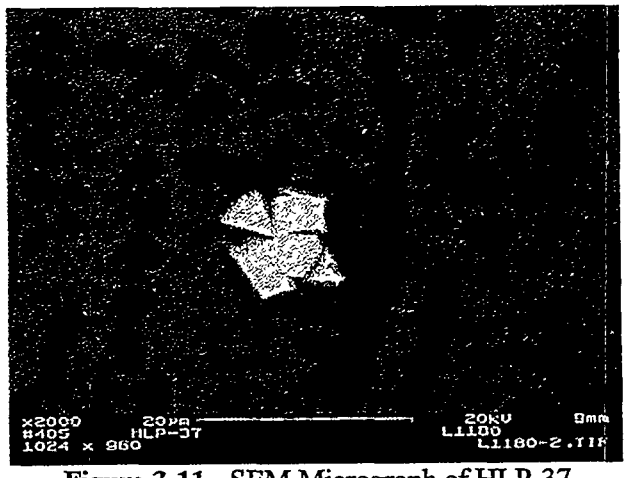


Figure 3-11. SEM Micrograph of HLP-37

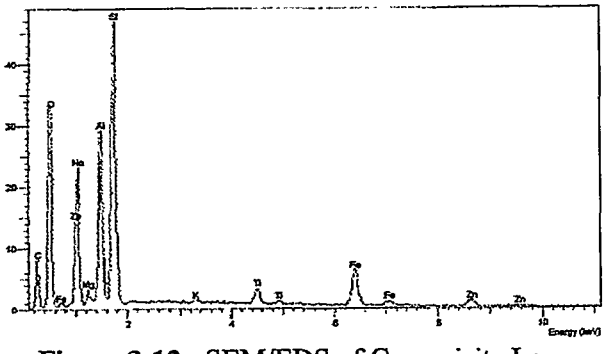


Figure 3-12. SEM/EDS of Carnegieite Low [$Na(AlSiO_4)$] – Dark Gray Phase

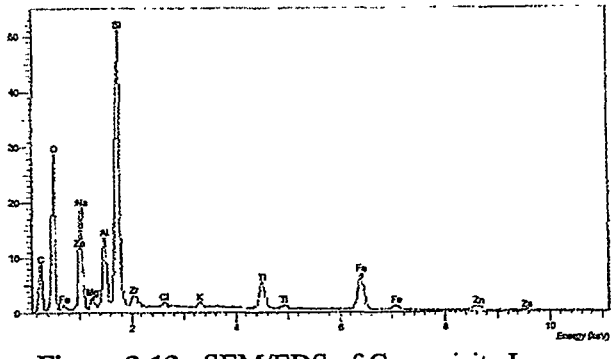


Figure 3-13. SEM/EDS of Carnegieite Low [$Na(AlSiO_4)$] – Light Gray Phase

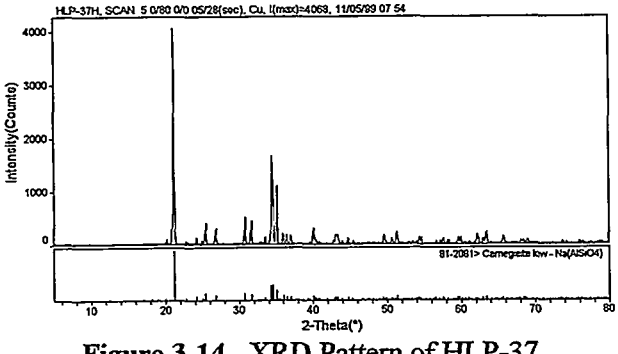


Figure 3-14. XRD Pattern of HLP-37

3.1.3 HLP-38 and HLP-42

Like glasses HLP-36 and -40, HLP-38 and -42 have the same target concentrations of SiO_2, Na_2O, and B_2O_3 with a different concentration of Al_2O_3 and form the same crystalline phases. Titanomagnetite and mathiasite were identified in these glasses with their estimated concentrations listed in Table 3-3. Figure 3-15 and Figure 3-16 show SEM micrographs of these phases in HLP-38.

Table 3-3. Phases Identified in HLP-38 and HLP-42 With XRD

#[a)]	Phase	Concentration in HLP-38	Concentration in HLP-42
1	Titanomagnetite ($Fe_{2.50}Ti_{0.50}O_4$)	~12.78 mass%	13.41 mass%
2	Mathiasite [(K, Ba)(Ti,Cr,Fe,Mg)$_{21}$O$_{38}$]	6.04	5.42

a) Numbers refer to the labels in figures.

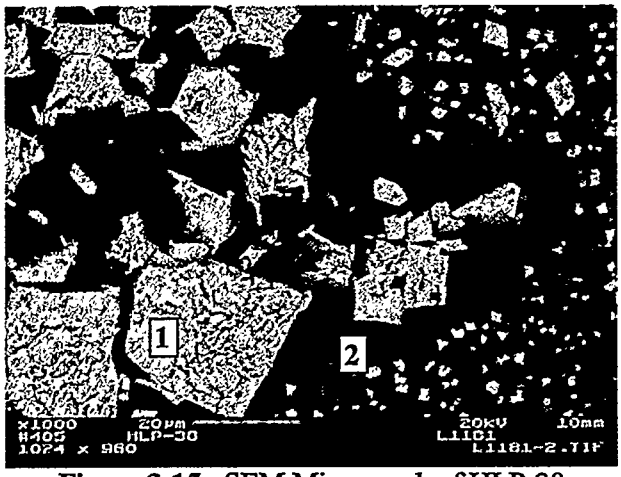


Figure 3-15. SEM Micrograph of HLP-38

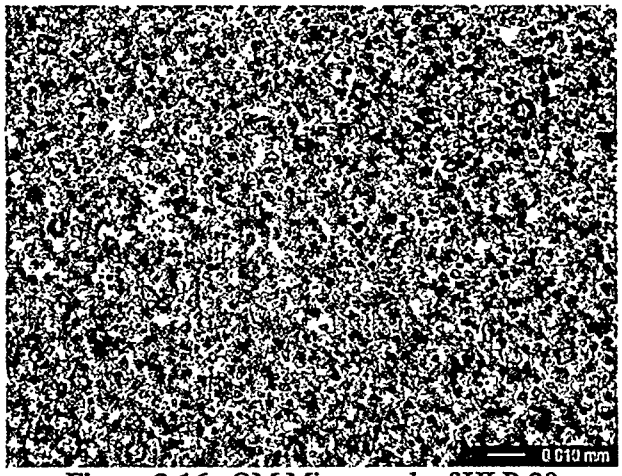


Figure 3-16. OM Micrograph of HLP-38

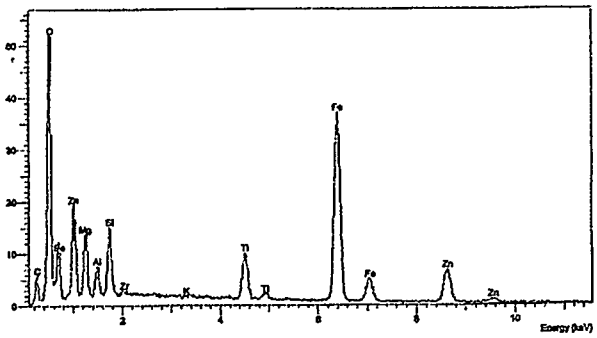


Figure 3-17. SEM/EDS of Titanomagnetite ($Fe_{2.50}Ti_{0.50}O_4$)

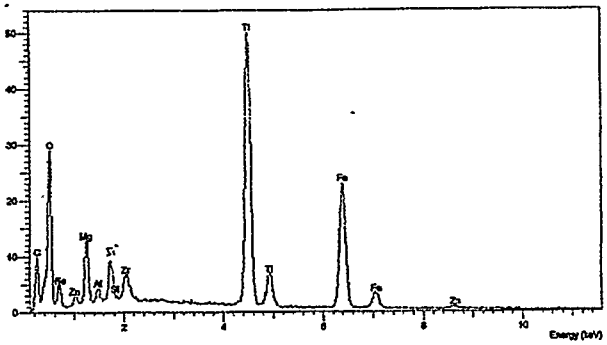


Figure 3-18. SEM/EDS of Mathiasite [(K, Ba)(Ti,Cr,Fe,Mg)$_{21}$O$_{38}$]

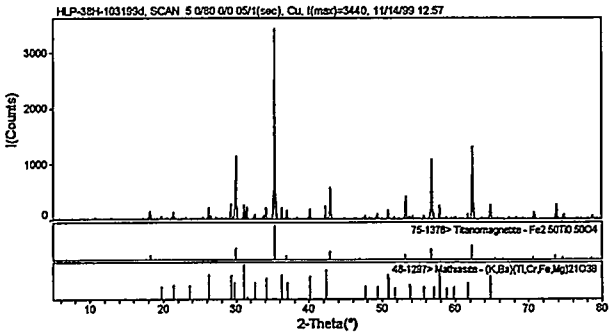


Figure 3-19. XRD Pattern of HLP-38

3.1.4 HLP-41

Zinc Iron Oxide ($ZnFe_2O_4$) was identified in HLP-41 with a combination of OM (which showed spinel like crystals as shown in Figure 3-20) and EDS (which showed high concentrations of Fe and Zn as shown in Figure 3-21). We were not able to identify the crystalline phases with XRD because of the low concentration of crystals. The detection limit of crystalline phases by the XRD method used is estimated at roughly 0.5 mass%.

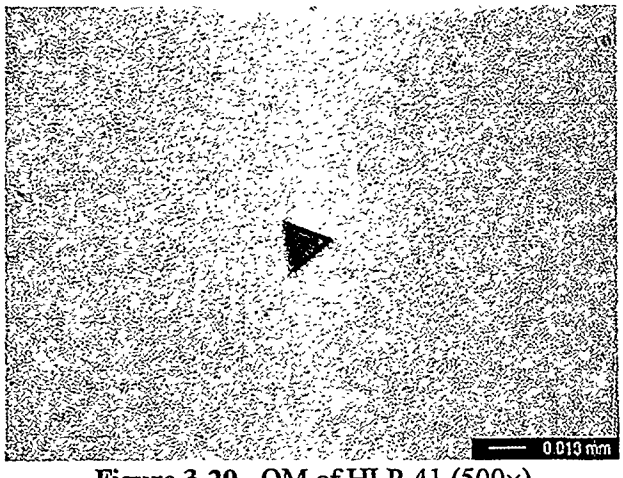


Figure 3-20. OM of HLP-41 (500×)

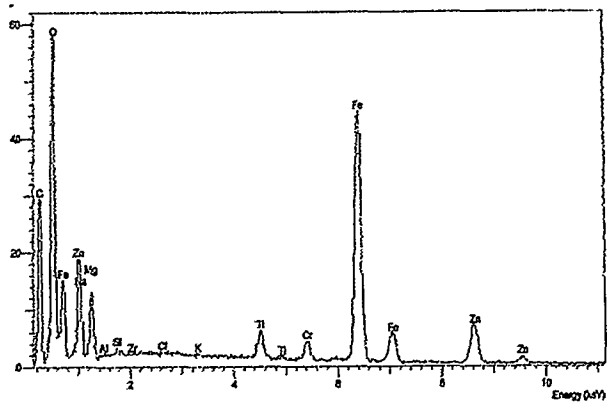


Figure 3-21. EDS Spectra of a Crystal in HLP-41

3.1.5 HLP-49

The phases identified in HLP-49 glass with XRD are listed in Table 3-4. Only one type of crystal was identified in HLP-49 with OM as shown in Figure 3-22. The composition of the crystal was calculated with SEM/EDS to be $Ca_{0.88}Mg_{0.49}Fe_{0.49}(SiO_3)_2$, which is very close to a Ca-clinopyroxene named augite. Some Zr impurities were also found via SEM/EDS of these crystals. XRD identified two types of these clinopyroxene with a different ratio of Fe substituting for Mg. Further SEM investigation identified chromite at the center of a clinopyroxene crystal and Pt in the center of one chromite crystal (see Figure 3-26 and Figure 3-27). Platinum was introduced into the glass, probably during the melting process, and may have served as a nucleation center for growth of the chromite, which in turn may have served as a nucleation site for the growth of clinopyroxene.

Table 3-4. List of Phases Identified in HLP-49 with XRD

#[a)]	Phase	Concentration
1	Calcium Magnesium Silicate [$Ca_{0.8}Mg_{1.2}(SiO_3)_2$]	2.24 mass%
2	Augite [$Ca_{0.61}Mg_{0.76}Fe_{0.49}(SiO_3)_2$]	3.51
3	Zinc Iron Oxide ($ZnFe_2O_4$)	≤0.5

a) Numbers refer to the labels in figures.

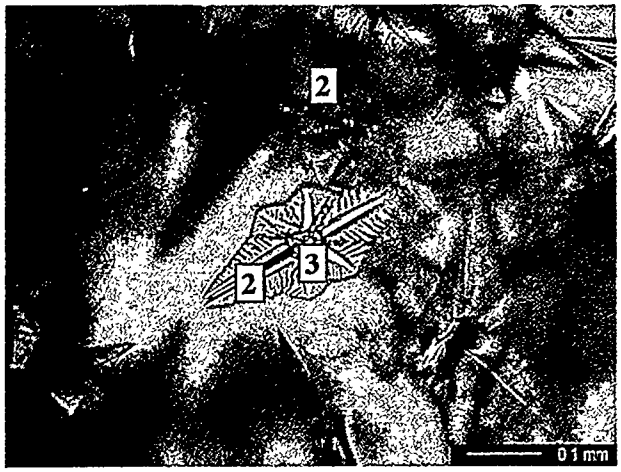


Figure 3-22. OM of Augite in HLP-49 (200×)

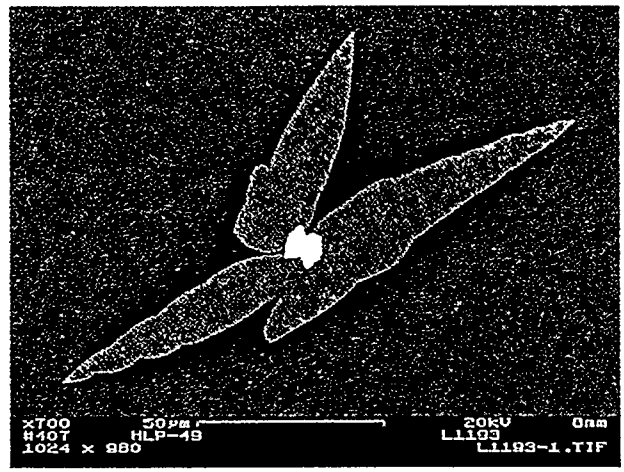


Figure 3-23. SEM Micrograph of Augite and Zinc Iron Oxide (on top) in HLP-49

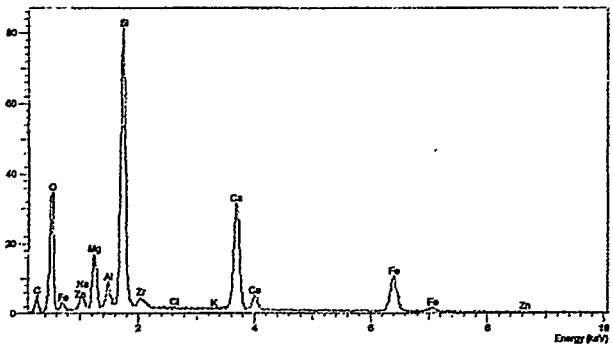


Figure 3-24. SEM/EDS of Augite $[Ca_{0.61}Mg_{0.76}Fe_{0.49}(SiO_3)_2]$

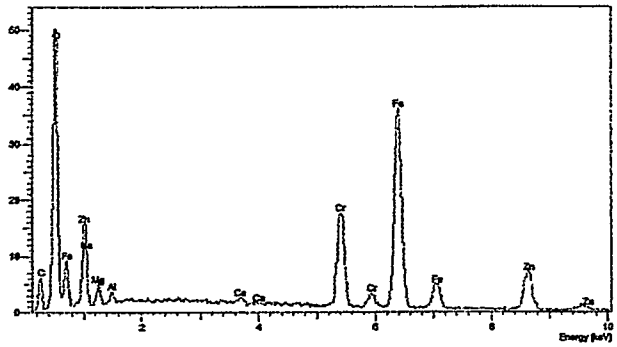


Figure 3-25. SEM/EDS of Zinc Iron Oxide $(ZnFe_2O_4)$

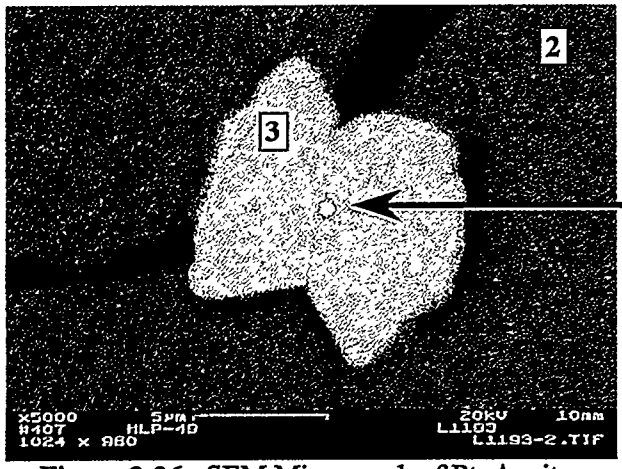


Figure 3-26. SEM Micrograph of Pt, Augite (background), and Zinc Iron Oxide in HLP-49

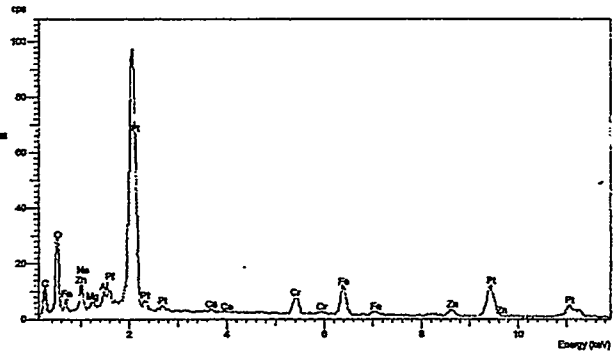


Figure 3-27. EDS Spectra of a Pt particle in HLP-49

3.1.6 HLP-53

During the heat treatment of HLP-53, a second phase appeared to segregate on all surfaces of the melt (for example, see Figure 3-28). The segregated materials or "phases" were easy to mechanically separate. OM analyses of each individual "phase" (given in Figure 3-30 and Figure 3-31) showed densely packed small crystals on the surface phase and a few large crystals in the bulk phase. XRD analyses identified only nepheline ($NaAlSiO_4$) in both the surface and bulk. The measured compositions of the bulk-quenched glass and the surface layer and bulk layer of the heat-treated glass are compared in Table 3-5. The differences are too small to suggest that the two layers are of different composition. These data suggest massive surface crystallization of nepheline in HLP-53 during heat treatment. The inhomogeneity of this sample precluded the testing of heat-treated samples by VHT; however, a sample representative of the material was ground and used for PCT along with a quenched sample. The content of nepheline measured in HLP-53 glass with XRD was 2.11 mass%.

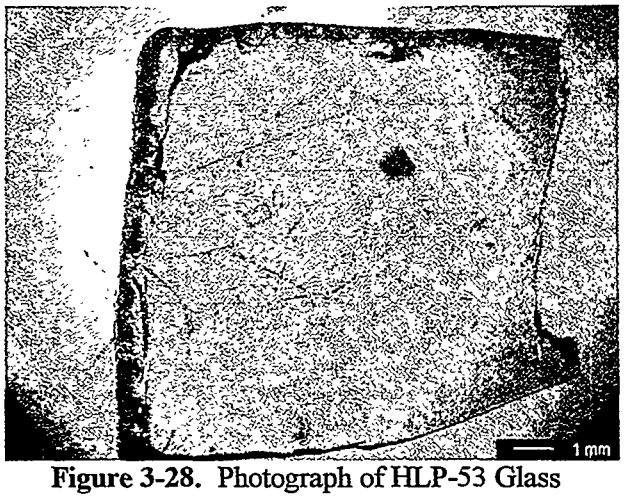


Figure 3-28. Photograph of HLP-53 Glass Monolith after Heat Treatment

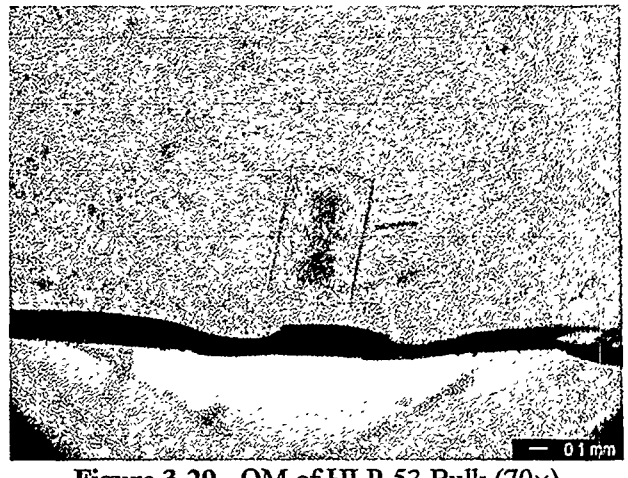


Figure 3-29. OM of HLP-53 Bulk (70×)

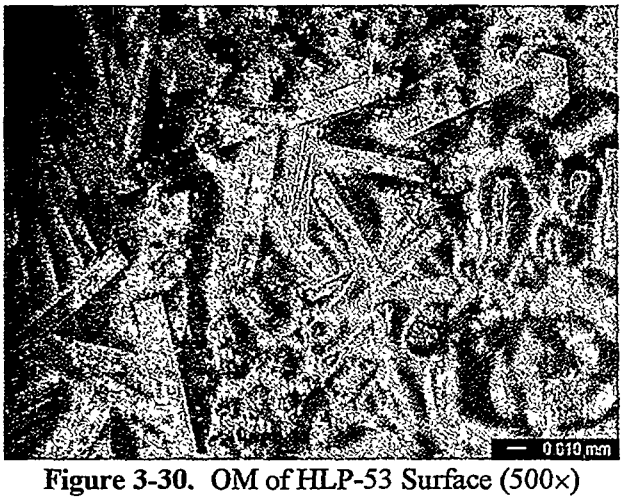


Figure 3-30. OM of HLP-53 Surface (500×)

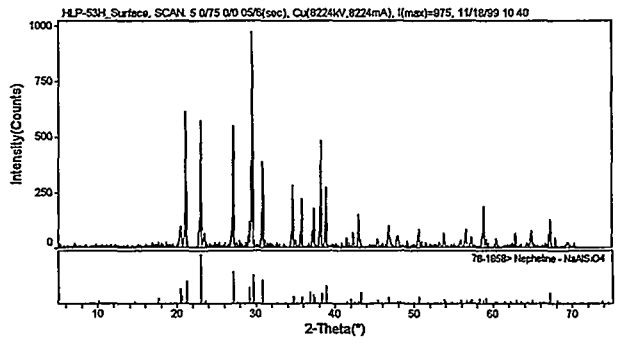


Figure 3-31. OM of HLP-53 Bulk (70×)

Table 3-5. Comparison of Composition for Different Samples of HLP-53 (mass %)

	Target	Quench	HT (PCT)	Bulk	Surface
SiO_2	40.15	40.8	39.5	42.2	43.5
Al_2O_3	9.86	9.79	9.31	9.59	9.49
B_2O_3	4.23	4.54	5.46	4.34	4.26
Fe_2O_3	7.30	7.52	7.67	7.99	8.12
ZnO	3.28	3.24	3.09	3.07	3.26
ZrO_2	2.99	2.82	2.76	2.79	2.67
MgO	2.04	1.84	1.93	1.85	1.89
Li_2O	2.04	2.13	2.29	2.11	2.09
Na_2O	20.00	20.4	18.6	18.7	19.3
K_2O	3.10	3.08	2.75	2.98	2.93
CaO	4.38	4.33	4.21	4.27	4.32
Cl^-	0.36	NM	NM	NM	NM
SO_3	0.04	NM	NM	NM	NM
P_2O_5	0.08	NM	NM	NM	NM
Cr_2O_3	0.01	BD	0.14	BD	BD
F^-	0.12	NM	NM	NM	NM
Total	99.98	100.49	97.71	100.19	101.83

NM = not measured, BD = below detection limits

3.2 Density of HLP Glasses

The measured glass densities (ρ) are listed in Table 3-6 along with standard deviations. The densities of all matrix glasses range from 2.45 g/cm^3 to 2.95 g/cm^3.[a] However, on average, the crystallized glasses have higher densities, ranging from 2.71 g/cm^3 to 2.95 g/cm^3 as compared to the homogeneous glasses, which range in density from 2.45 g/cm^3 to 2.81 g/cm^3.

[a] The units of g/cm^3 are used in this report to allow direct comparison with existing data on glass density. To convert to the SI units of kg/m^3, the reader can multiply reported values by 1000.

Table 3-6. Density of HLP Glasses (heat treated and powdered unless otherwise noted)

Glass[a]	ρ [g/cm^3]	St.Dev.	Glass[a]	ρ [g/cm^3]	St.Dev.	Glass[a]	ρ [g/cm^3]	St.Dev.
HLP-01	2.6493	0.0020	HLP-24	2.6087	0.0006	HLP-21	2.6148	0.0009
HLP-02	2.7022	0.0020	HLP-25	2.6409	0.0018	HLP-22	2.5900	0.0018
HLP-03	2.6364	0.0011	HLP-26	2.6418	0.0018	HLP-23	2.6285	0.0033
HLP-04	2.6828	0.0009	HLP-27	2.5048	0.0008	HLP-43	2.6354	0.0026
HLP-05	2.6756	0.0002	HLP-27QP	2.4869	0.0008	HLP-44	2.6391	0.0018
HLP-06	2.5609	0.0025	HLP-28	2.5165	0.0021	HLP-45	2.6572	0.0024
HLP-07	2.6027	0.0015	HLP-29	2.5691	0.0028	HLP-46	2.5389	0.0006
HLP-08	2.6915	0.0030	HLP-30	2.5990	0.0006	HLP-47	2.5233	0.0015
HLP-09	2.6014	0.0009	HLP-31	2.6244	0.0011	HLP-48	2.6872	0.0014
HLP-10	2.6229	0.0009	HLP-32	2.6249	0.0010	HLP-48HG	2.6556	0.0007
HLP-11	2.5630	0.0025	HLP-33	2.6351	0.0018	HLP-48QP	2.6515	0.0015
HLP-12	2.6819	0.0018	HLP-34	2.6729	0.0031	HLP-48QG	2.6428	0.0009
HLP-13	2.6074	0.0011	HLP-35	2.6437	0.0060	HLP-49	2.7712	0.0006
HLP-14	2.588	0.003	HLP-36	2.7437	0.0011	HLP-51	2.7218	0.0006
HLP-15	2.6275	0.0032	HLP-37	2.7056	0.0010	HLP-51HG	2.6751	0.0011
HLP-16	2.5919	0.0034	HLP-38	2.7828	0.0020	HLP-52	2.6539	0.0007
HLP-17	2.6574	0.0039	HLP-39	2.7304	0.0018	HLP-53	2.7258	0.0007
HLP-18	2.5997	0.0027	HLP-40	2.8250	0.0005	HLP-54	2.4897	0.0030
HLP-19	2.6692	0.0012	HLP-41	2.8140	0.0015	HLP-55	2.4545	0.0025
HLP-20	2.6258	0.0002	HLP-42	2.9520	0.0012	HLP-56	2.6804	0.0015

(a) H = Heat-treated, Q = Quenched, P = Powdered, G = Grain (i.e., not powdered)

3.3 Glass Compositions

The targeted and measured glass compositions are shown in Table A-1. Comparison of the targeted and measured compositions indicates that there were no gross batching errors. That is, the differences between the target and measured concentrations for most of the major components (i.e., SiO_2, Al_2O_3, B_2O_3, TiO_2, and Na_2O) were less than 5%. Furthermore, the initial review of these data suggested that no gross laboratory-to-laboratory variation in glass preparation appeared to have occurred. (Glasses HLP-13 to HLP-25 were prepared at SRTC while the remainder of the glasses were fabricated at PNNL.) A more detailed statistical analysis (including appropriate components of variance) of the composition data is planned for the final Hanford ILAW data package.

It should be noted that the Fe_2O_3 and Cr_2O_3 measured values were higher than the targeted values for all the glasses. Since a significant amount of glass was needed for testing (i.e., VHT, PCT-A, and PCT-B), only ground PCT fines (-200 mesh) were available for composition analyses. Therefore, contamination from the stainless steel grinding vessel is suspected to be the primary cause of the elevated Fe_2O_3 and Cr_2O_3 values. This contamination has the effect of relatively decreasing the other measured concentrations for the glass. A number of the glasses may be resubmitted for nickel analyses so that the glass concentrations can be corrected for the suspected stainless steel contamination.

The sum of the oxides was greater than 95%[a] for all but one glass (i.e., HLP-46). For another four glasses (HLP-9, HLP-11, HLP-26 and HLP-32), the sum of the oxides was approximately 95%. The

[a] A sum of oxides greater than 95% is a heuristic metric used at SRTC to ensure that the measured glass compositions are valid.

resulting lower-than-expected sums of oxides may be either the result of an analytical bias or normal random variation in the measured concentrations.

In almost all cases, the measured Na_2O values were lower than targeted. The maximum deviation was observed in HLP-11 where the measured Na_2O value was 14% lower than targeted. There is currently insufficient data to resolve the source(s) of these differences; further examination is necessary.

Batching and analytical errors were further examined by comparing the chemical composition data for the repeated glasses. This analysis will be discussed in Section 4.17.

3.4 Redox

Glasses HLP-44 and -45 have the same target composition as the center glass (HLP-01). However, they were melted and heat treated under reducing conditions to progressively increase the redox (ratio of two valent to total iron—Fe(II)/Fe) as discussed in Section 2.2. The measured redox of these glasses is compared to that of HLP-26 in Table 3-7. The redox of these heat-treated glasses ranges from 1% to nearly 59%, which is expected to bracket the redox of glasses to be produced by the HVV.

Figure 3-32 shows the relationship between the natural logarithm of oxygen partial pressure above the glass melt and the measured redox of the quenched glasses. Our measurements show that ln[Fe(II)/Fe(III)] is related to $\ln[p_{O2}]$ by a straight line with slope of 0.253, which closely matches the expected slope of 0.25. This relationship allows the reader the ability to interpolate the effects of p_{O2} on corrosion characteristics of the glass.

Table 3-7. Melting Oxygen Partial Pressure and Measured Redox of HLP-26, -44, and -45

Sample[a]	$-\ln(p_{O2})$	Fe(II)/Fe	Fe(II)/Fe	ave.
HLP-26Q	1.56	0.0115	0.0119	0.0117
HLP-26H		0.0099	0.0102	0.0101
HLP-44Q	13.8	0.195	0.1856	0.1903
HLP-44H		0.2029	0.2066	0.2048
HLP-45Q	20.7	0.6199	0.5924	0.6062
HLP-45H		0.581	0.59	0.5855
SRM-278[b]		0.711	0.686	0.6985

(a) Q = quenched and H = heat treated
(b) Obsidian Rock with certified Fe(II)/Fe = 0.74 ± 0.01[a]

[a] Standard Reference Material #278 – Obsidian Rock, National Bureau of Standard, Washington, D. C., 1992.

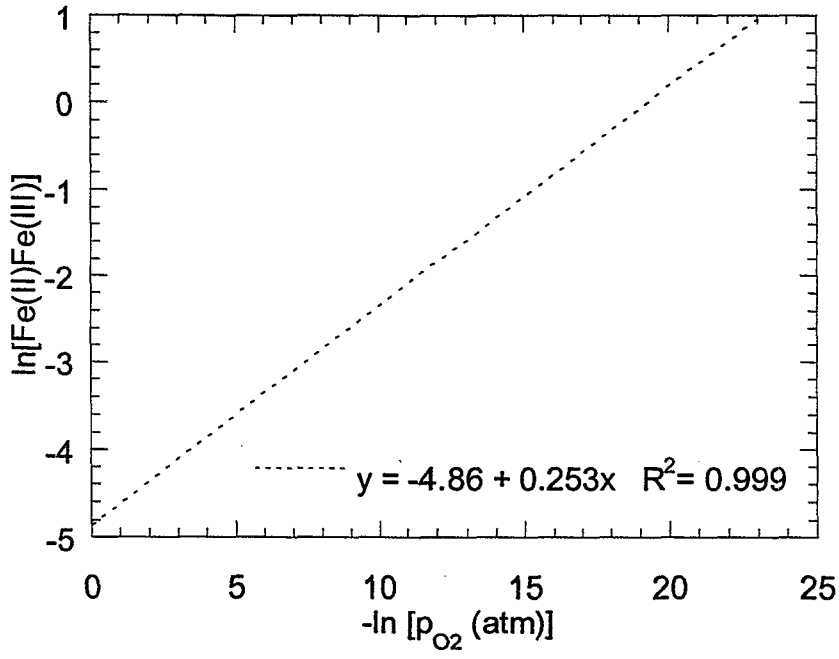


Figure 3-32. Effect of p_{O2} on Measured Glass Redox

3.5 Product Consistency Test

3.5.1 PCT-A

A PCT-A series (i.e., 7 day, 90°C, 2000 m^{-1}) was run in triplicate on the glasses whose compositions are provided in Table 2-1. The raw, measured concentrations resulting from these tests are provided in Table B-1. (Those for the PCT-B series are provided in Table B-2 through Table B-4.) The release values corresponding to these PCT-A results (and the appropriate target concentrations from Table 2-1) are provided in Table B-5. The expression for the normalized release, NC_i in g/L, is normally given as

$$NC_i = \frac{p_i}{10x_i} \tag{3.1}$$

where p_i is the test solution concentration in mg/L (adjusted for dilution), and x_i is the target cation concentration in grams of i per 100 grams glass for the cation in question. A lognormal distribution was assumed appropriate for the data.[a] Under this assumption, the normalized release value, or NC_i in (g/L), for a glass is

$$NC_i = \exp\left[\overline{\ln(p_i)} - \ln(10) - \ln(x_i)\right] \tag{3.2}$$

[a] A lognormal distribution was assumed, since the test solution concentrations cannot be less than zero and many are close to zero in terms of expected errors, the assumption is made that the measured test solution concentrations, p_i, and thus NC_i, will likely follow a lognormal distribution. In addition, some experience from PCT data suggested lognormal behavior.

where the term $\overline{\ln(p_i)}$ represents the mean of the three $\ln(p_i)$ results for a glass. The data in Appendix B can be used to recalculate the average release assuming a normal distribution if desired. The difference in average releases calculated under the two assumptions is considered to be of little practical consequence as shown in Table 3-8.

Table 3-8. Comparison of Mean NC_B for Selected Glasses Calculated with the Assumptions of Lognormal and Normal Distributions of Data

Glass ID	Normal	Lognormal
HLP-01	10.13	10.13
HLP-10	10.47	10.46
HLP-20	14.30	14.21
HLP-30	3.51	3.51
HLP-40	40.23	40.21

These values were measured for an S/V value of approximately 2000 m^{-1}. (For this initial data examination, small differences in S/V resulting from minor density and other differences were not considered.) The release values obtained from Equation 3.2 were normalized by this test parameter to provide releases, $NL_i = NC_i/(S/V)$, with units of g/m^2. The B and Na release values for the PCT-A tests are provided in Table B-5.

3.5.1.1 Gross Check of the PCT-A Release Data

For PCT-A data (i.e., at seven days), the more soluble constituents (e.g., boron and sodium) often release into the test solution at comparable rates. Accordingly, a comparison of these releases can provide a rough check on the analytical errors in the PCT data. Figure 3-33 provides such a comparison for the PCT-A releases computed using Equation 3.2. From this figure, only glass HLP-46 appears to deviate appreciably from the 45° line shown on the figure; however, sodium ion exchange from this glass is known, and this result is not surprising and no additional tests on this glass are warranted. The gross check in Figure 3-33 indicates no obvious errors in the PCT-A analytical data provided in Table B-5. However, such a check may be even more important for the PCT-B data from this study where only a single measurement is available for each glass at each time.

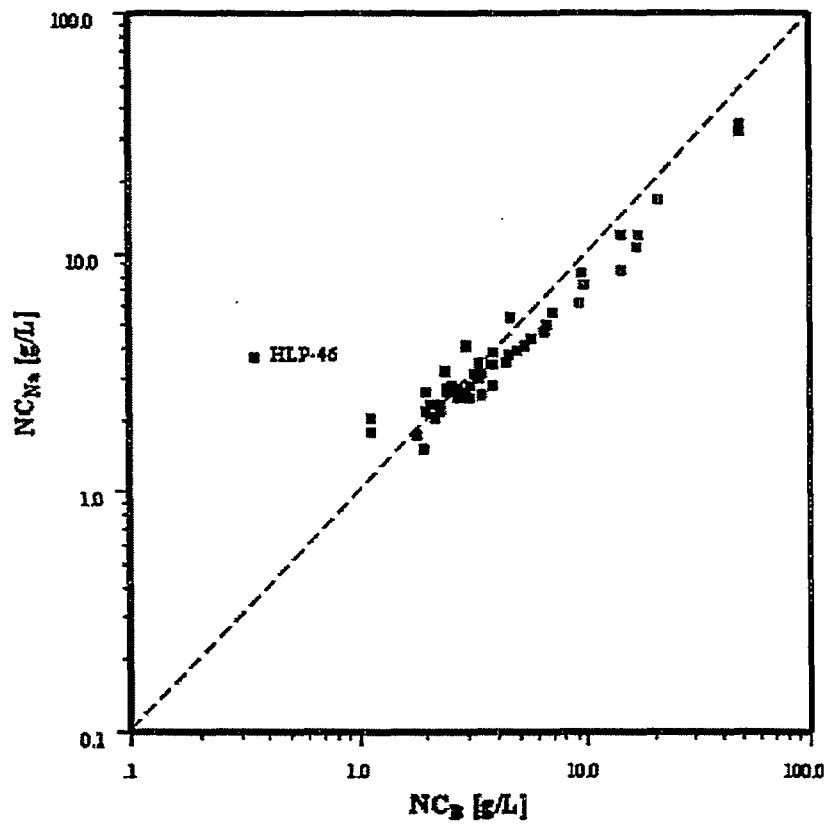


Figure 3-33. Log-Log Plot Illustrating the Normalized Sodium versus Boron Releases for the PCT-A data. Note that glass HLP-46 exhibits known sodium ion exchange. (The dotted line is the 45° line representing a one-to-one correspondence between the test results.)

3.5.2 PCT-B

A PCT-B series was also run on the HLP glasses whose compositions are provided in Table 2-1. These tests differed from the aforementioned PCT-A series in that S/V was increased from 2000 m^{-1} to 20 000 m^{-1}, and the tests were carried out at intervals of 10, 100, and 1000 h. However, due to budgetary constraints, only single tests were performed for the PCT-B experiments (vis-à-vis the triplicate tests run for the PCT-A series). Thus the random variations in the PCT-B results for a glass are likely higher than those in the PCT-A values (which are based upon the means of three replicate tests) for the same glass. The PCT-B release data for boron and sodium are provided in Table B-6. These PCT-B values were computed using Equation 3.1 because only a single test-solution measurement was available for each glass for each set of conditions.

3.5.2.1 Gross Check of the PCT-B Release Data

Figure 3-34 shows the relationship between the log-normalized releases for sodium and boron for the PCT-B data collected at 10, 100, and 1000 h. The three lines provided on this figure represent the least-squares fits for the data at each time. (The uncertainties in the parameters describing these lines suggest that these lines are indistinguishable from each other.) Figure 3-34 indicates that only the 10-h values for glasses HLP-04 and HLP-46 may need to be reevaluated based upon this gross examination.

Similar plots will be used to identify glasses for additional testing. Thus the gross checks illustrated in Figure 3-33 and Figure 3-34 suggest that the PCT data can be used for further short-term examinations.

The differences in the NC_B/NC_{Na} with corrosion extent are generally consistent with the currently accepted model of glass corrosion. At short times the values of NC_{Na} are higher than the values NC_B because ion exchange occurs to some depth in the glass surface. After longer times, NC_B values approach the NC_{Na} values because the amount of additional Na in solution from ion exchange becomes a progressively lower fraction of the total Na in solution.

3.5.3 Release Rates

The PCT releases were measured for four different time intervals (i.e., 7 days and 10, 100, and 1000 h, respectively). Figure 3-35 shows the relationship between the release, $NL_i = NC_i/(S/V)$, and time, t, in hours for the HLP-01 glass. When a log-log transformation of these data is made, the relationship for the resulting HLP-01 values (i.e., that for the 10, 100, and 1000-h data) appears to be fairly linear over the range of time considered for this glass.[a] That is, the relationship between the normalized concentrations and time (up to 1000 h) can be described by

$$NL_i = NC_i/(S/V) \approx \exp\{a + b \ln(t)\} = \exp(a)\, t^b \qquad (3.3)$$

for the HLP-01 glass. Using the data in Table B-6, this relationship appears reasonable for many of the HLP glasses for times up to 1000 h. However, because there are PCT-B data at only three time intervals for each glass, any release rates estimated based upon the expression in Equation 3.3 will have very large uncertainties associated with them, and any comparisons made using these release-rate estimates will also be fraught with uncertainty. Finally, because the relationship in Equation 3.3 cannot be shown to be fundamental to the short-term PCT-B behavior, release rates will instead be estimated using the PCT-B release information in Table B-6. However, because Equation 3.3 appears to be descriptive for many of the short-term HLP data, further examination of this relationship may become warranted when more data become available.

[a] The PCT-A NL_i values in g/m^2 exceed the corresponding values that would be predicted from the PCT-B values for the same cation and glass. This behavior is well-known, and thus only the PCT-B data are used to estimate short-term corrosion rates for the HLP glasses.

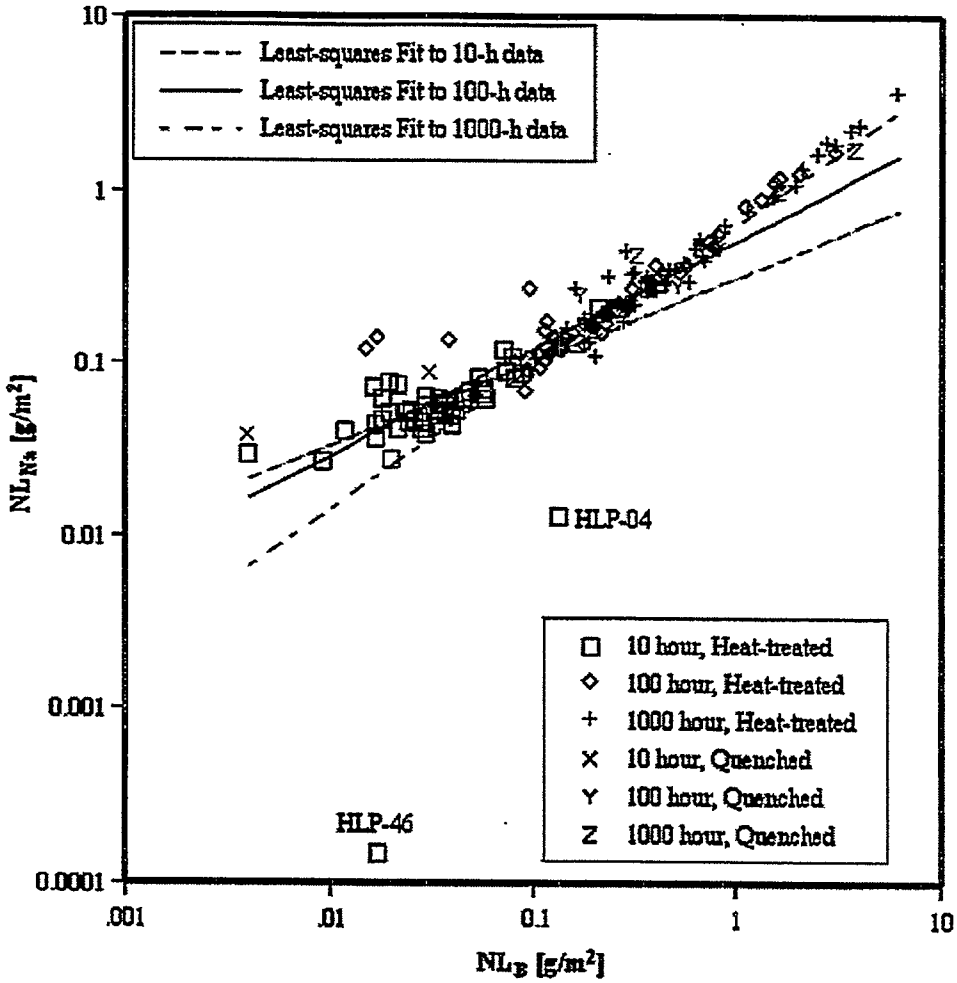


Figure 3-34. Log-Log Plot Illustrating the Normalized Sodium versus Boron Releases for the PCT-B data. This gross examination suggests that the 10-h tests for HLP-04 and HLP-46 may need to be measured again. The lines represent the three least-squares fits through the 10, 100, and 1000-h data (excluding the 10-h values for HLP-04 and HLP-46).

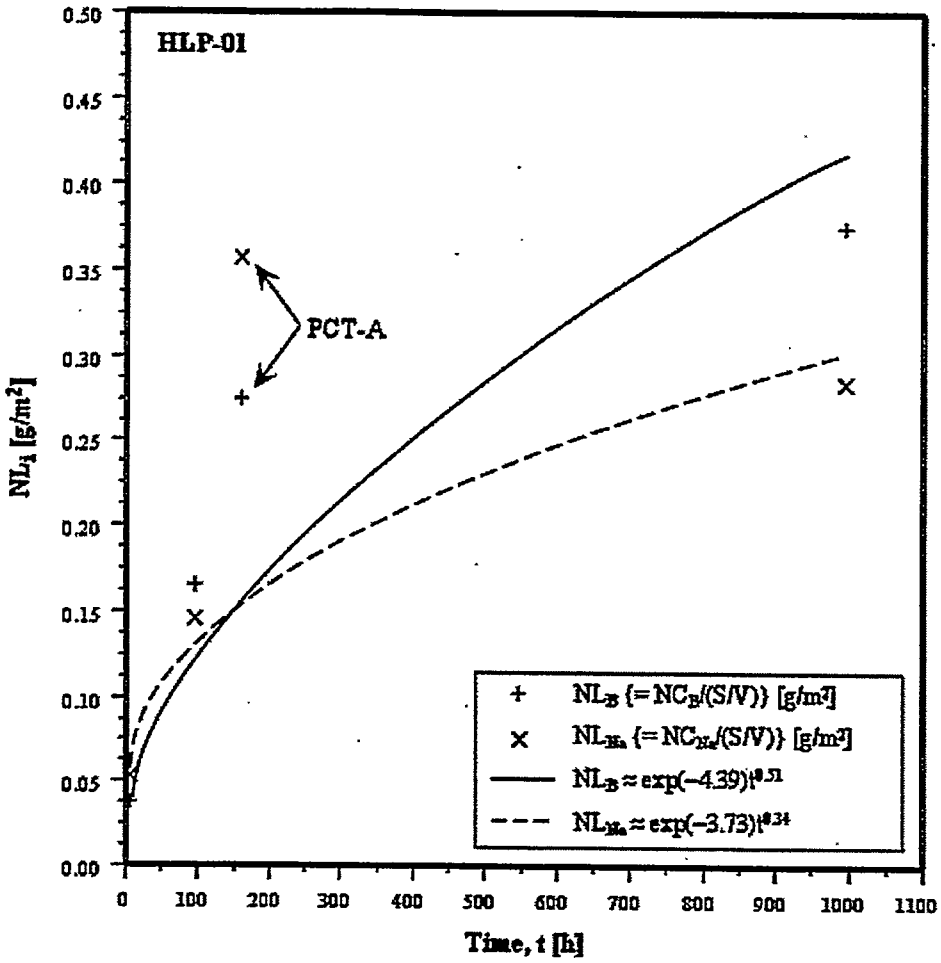


Figure 3-35. Illustration of the Relationship Between the Boron and Sodium Normalized Releases, NL_i in g/m^2, and Time, t in h, for the HLP-01 Glass. The PCT-A results are indicated; the remaining data are the PCT-B results. Lines on this figure indicate the least-squares fits between $\ln(NL_i)$ and $\ln(t)$ (i.e., from Equation 3.3) for the PCT-B data and are for indication only.

At any given time, the release, NL_i in g/m^2, represents the concentration of constituent i in the test solution at time t in hours. Thus a release rate, r in $g/m^2/d$,[a] can be obtained by dividing the measured NL_i value (at the time tested) by the time tested, t, or

$$r = 24\left(\frac{NL_i(i)}{t}\right) \tag{3.4}$$

where t is in hours. A differential release rate, r_Δ in $g/m^2/d$, can also be computed by taking differences in measured values at successive times, or

[a] The units of $g/m^2/d$ are used in this report to allow direct comparison with existing data on glass alteration rates. To convert to the SI units of $kg/m^2/s$, the reader can multiply reported values by 1.1574×10^{-8}.

$$r = 24\left(\frac{NL_i(t_{i+1}) - NL_i(t_i)}{t_{i+1} - t_i}\right) = 24\left(\frac{\Delta(NL_i)}{\Delta t}\right). \tag{3.5}$$

The bases for the release rates are presented in Figure 3-36.[a]

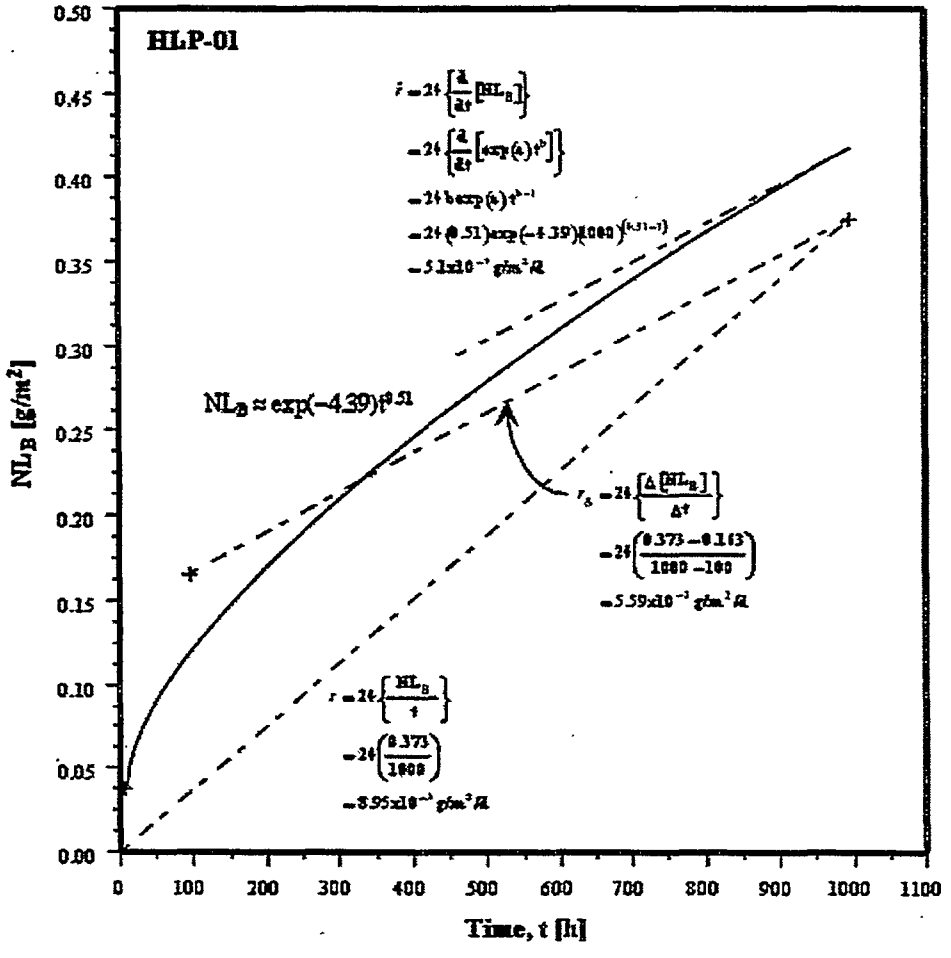


Figure 3-36. Boron Release Rate Estimates for the HLP-01 Glass. The solid line represents the fit from the boron data based upon Equation 3.3 (as shown in). The three dotted lines in this figure represent the estimated boron release rates for the HLP-01 glass, based upon the relevant PCT-B data.

There are errors associated with the values obtained from any of the proposed methods of estimating the release rate from PCT-B data. For example, the errors for the boron release rates obtained from Equation 3.3 for the HLP-01 glass would be large and would make any sort of comparison amongst glasses difficult. The errors in the release-rate estimates from either Equation 3.4 or Equation 3.5 (assuming that the error in t is negligible) are functions of the errors in the NL_i values. However, the NL_i values are computed from various measured and assumed values, and the components of variance for the

[a] For completeness, the least-squares fit line (i.e., the solid line) and corrosion rate, $\hat{r}$ in g/m²/d, that would be obtained from the expression in Equation 3.3 has been provided on Figure 3-36.

terms used to compute the NL_i values are confounded and cannot be estimated from the PCT-B data in this study. In addition, no single rate can be determined from PCT-B glass because the corrosion extent (as measured by NL_i) is not a linear function of time.

Some insight may be obtained by inspecting the PCT-A data (as provided in Table B-1), which were collected in triplicate. It is true that these data were from samples with S/V values different from those of the PCT-B data and that the ranges of measured PCT-A concentrations did not completely cover those of the PCT-B data; however, the tests were carried out by the same personnel, and the resulting test-solution concentrations were measured in the same laboratory as those used to compute the PCT-B data. As illustrated in Exhibit B-1,the PCT-A data suggest that the magnitude of the errors in the measured boron and sodium concentrations in the test solutions are relative to the magnitude of the corresponding concentrations. As also illustrated in this exhibit, there does not appear to be a similar trend in these PCT-A values under the natural logarithm transformation (i.e., for $\ln[p_i]$ where p_i is the concentration in ppm). The PCT-A error estimates, obtained from components of variance analysis, were used for this initial examination of the release-rate estimates from PCT-B data.

Using error propagation and assuming that the errors in the various glass composition and S/V terms are negligible (for this initial examination of the data), the error in an NL_i value, represented by s_{NL_i}, is estimated from the error in the corresponding $\ln(p_i)$, represented by $s_{\ln(p_i)}$, using the following:

$$s_{NL_i} \approx (NL_i) s_{\ln(p_i)} \tag{3.6}$$

where (NL_i) is computed from a release measurement (as in the PCT-B data).

Equation 3.6 indicates that the error obtained from the transformed concentrations is an estimate of the relative error in the NL_i value. Using the PCT-A data in Table B-1, the relative errors in the NL_B and NL_{Na} values are approximately 17.5 and 8.7%, respectively. Furthermore, the correlations between successive NL_i (or $\ln[NL_i]$) values were very large and positive (i.e., all are greater than 0.70). These results will be used to examine likely errors in the release rates estimated from PCT-B data. Additional examinations of the likely error structure will be made when additional data have been collected and analyzed.

Using Equation 3.4, Equation 3.5, and Equation 3.6, the release rates, r and r_Δ, and their relative errors were estimated for the HLP glasses. These release-rate estimates, r and r_Δ, based upon the boron and sodium release data, are provided in Table B-7 and Table B-8, respectively. Using estimates of 17.5 and 8.7% relative errors in the NL_B and NL_{Na} values, respectively (and assuming the error in measured time is negligible), the relative percent errors in the release rates were estimated and placed in Table 3-9.[a]

Table 3-9. Estimated Relative Percent Standard Deviations in Release Estimates

	Boron		Sodium	
Time (h)	r	r_Δ	r	r_Δ
10	42	42	20.8	20.8
100	4.2	6.6	2.08	3.28
1000	0.42	0.66	0.21	0.33

[a] The errors for the corrosion rates, r_Δ, obtained from successive differences, were estimated, neglecting the correlations between successive NL_i values; this should provide conservative estimates of the errors.

For the boron release rates, r, represented in Table B-7, the glasses with the five largest values at 10 h were HLP-31, -02, -39, -41, and -27. The glasses with the five smallest boron release rates at 10 h were HLP-30, -38Q (or the quenched HLP-38 glass), -22, -34, and -29. For the sodium release rates presented in Table B-8, the five glasses with the largest values at 10 h were HLP-31, -02, -41, -39, and -27, which agrees with the five largest boron release rates at 10 h. For the sodium release rates, the glasses with the five smallest values at 10 h were HLP-46, -04, -52, -22, and -28. Thus, the same five HLP glasses have the largest boron and sodium release rates at 10 h; however, this is not the case for the glasses with the lowest release rates at 10 h. This could be due to a number of possible reasons, including the large analytical error expected (as suggested in Table 3-9).

The glasses with the five largest and smallest release rates, r and r_Δ, from the boron and sodium PCT-B data are presented in Table 3-10 for 10, 100, and 1000 h. As illustrated in this table, the rank ordering of the boron and sodium release rates appears to be fairly consistent. One exception is glass HLP-52, which for 10 h has some of the smallest release rates, whereas at 100 h and 1000 h, this glass has one of the largest release rates. This may be due to the large relative errors expected at short leach times and low test-solution concentrations. These results may be confirmed with further experiments.

From the information in Table 3-10, no clear delineation in composition space (as presented in Table 2-1) can be made between glasses tending to have large short-term release rates from those tending to have small release rates. It appears that the target sodium concentrations in those HLP glasses that tend to have the largest short-term release rates based upon the PCT-B data have relatively high target Na_2O concentrations in glass. However, many of the glasses that tend to have low short-term release rates also have relatively high sodium concentrations. More work will be needed to make such a distinction based upon glass compositions.

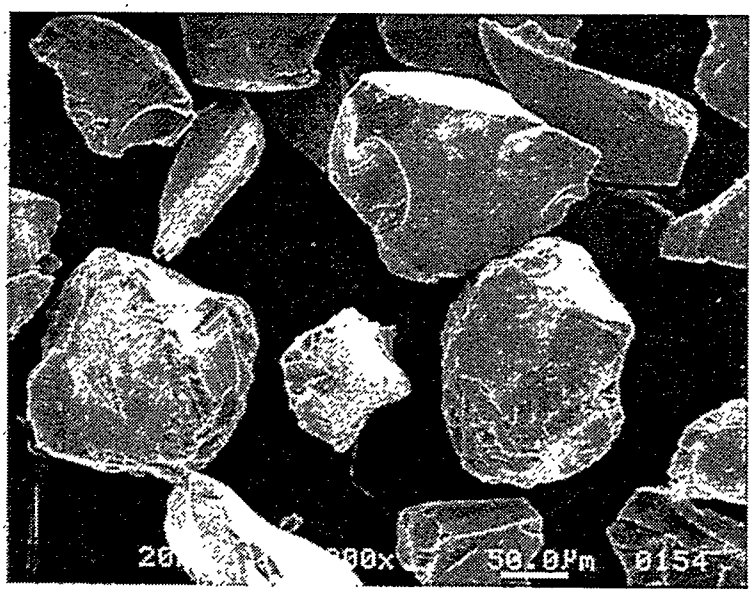
Table 3-10. Rank Ordering of Release Rates for the HLP Glasses Based Upon PCT-B Data

		Release Rate Rank Ordering by HLP Glass Number			
		Release rates, r		Release rates, r_Δ	
Time (h)	Cation	Largest Five	Smallest Five	Largest Five	Smallest Five
10	B	31>02>39>41>27	30<38Q<22<34<29	31>02>39>41>27	30<38Q<22<34<29
	Na	31>02>41>39>27	46<04<52[†]<22<28	31>02>41>39>27	46<04<52[†]<22<28
100	B	41>39>33>31>05	44<45<51<30<38Q	41>39>33>05>31	44<45<51<30<28
	Na	52[(a)]>41>39>33>31	30<28<22<06<49	52[(a)]>41>33>39>31	30<28<54<06<49
1000	B	33>41>42Q>42>05	30<06<49<08<38	51>41>33>39>31	30<28<54<06<49
	Na	52[(a)]>33>41>42>31	30<28<22<06<49	52[(a)]>33>42>42Q>05	30<28<22<06<34

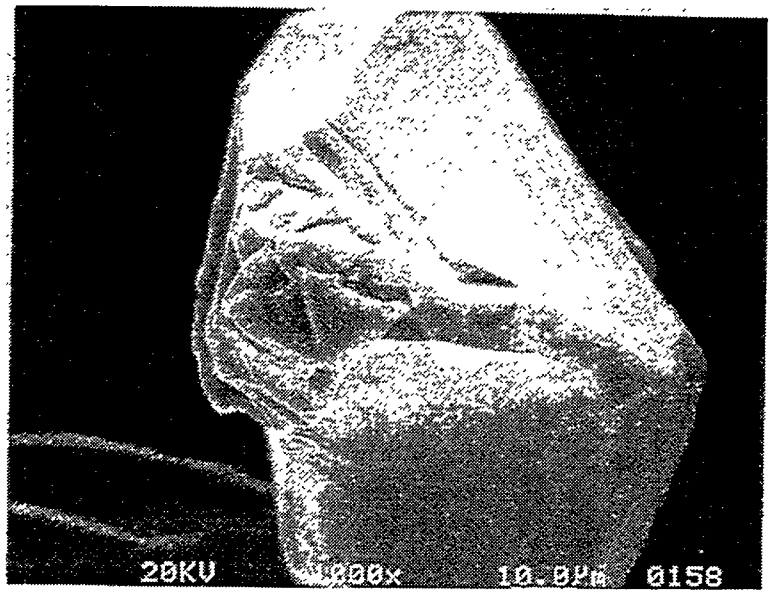
(a) There was no boron added to glass HLP-52.

3.5.4 Alteration Products

Reacted grains of glass from the PCT conducted for 1000 h with glass HLP-39 at 20,000 m^{-1} was examined with SEM to determine if alteration phases had formed during the test. Representative photomicrographs are shown in Figure 3-37. No alteration of the glass could be detected during examination of a large number of grains. The surface of the glass appeared unreacted, with no evidence of alteration phases or pitting of the surface. This is consistent with the very low values of NL_B and NL_{Na} measured in the test: $NL_B = 2.52$ and $NL_{Na} = 1.56$ g/m^2 (see Table B-6). The amount of glass dissolved (in terms of thickness) can be calculated from the measured values of NL_i and glass density. The density of HLP-39 was measured to be 2.73 (see Table 3-6). The amount of glass that must have dissolved to generate the measured solution concentration is (2.52 g/m^2)/(2.73 g/cm^3) = 0.923 μm based on the boron



a.



b.

Figure 3-37. SEM Images of Reacted HLP-39 Glass from PCT Conducted 1000 h at 90°C and 20,000 m^{-1}. (a) Moderate magnification showing uniform size and appearance of particles and (b) High magnification showing pristine appearance of surface.

concentration and (1.56 g/m^2) / (2.73 g/cm^3) = 0.571 μm based on the sodium concentration. The appearance of the reacted particles in the photomicrographs suggests that the actual amount of glass that dissolved from the surface is much less than 1 μm and that a significant proportion of dissolved material may result from the dissolution of fines.

3.6 Vapor Hydration Test

The resistance of matrix glasses to corrosion in the VHT was measured over the temperature range from 150°C to 300°C. Preliminary rates at 200°C are reported for most glasses in Section 3.6.2. The initial plan (Vienna et al. 1999) called for measuring the rate at 150°C. However, after initial scoping tests, it became clear that the time required to sufficiently alter most matrix glasses to estimate rate would be prohibitively long. In other words, most of the matrix glasses were far more resistant to the VHT than initially expected. The impact of this temperature increase, or the use of elevated temperatures in general, on the reaction mechanisms is not yet well understood. The alteration products are reported for many VHT samples in Section 3.6.3, and the impacts of temperature on rate are discussed in Section 3.6.4 for selected glasses.

3.6.1 "Incubation"

An incubation time is a time needed for the hydration process to establish suitable conditions for precipitation of secondary alteration phases. These phases start to form on the surface of samples from nucleation centers, usually at the Pt wire-sample interface (in samples polished to a 600 grit finish), and extend across the sample, eventually forming a continuous layer, typically 50 μm to 300 μm thick. A characteristic dissolution curve of LAW glasses is displayed in Figure 3-38. The process of conversion of glass to alteration products by VHT can be divided into three stages: 1) incubation time, 2) precipitation of first alteration products indicated by a dramatic increase in rate, and 3) a linear $m_d - t$ region with constant rate. In Figure 3-38, the incubation time is roughly 10% of the total dissolution time (the time to dissolve the entire sample which is at roughly 1950 g/m^2 in Figure 3-38). The incubation time was found to range from 2% to 10% of the total dissolution time for all matrix glasses for which both values could be obtained. However, due to lack of data measured during the incubation time, the comparison was made only for 12 glasses form the entire test matrix. Although the incubation time presumably depends on test temperature and glass composition, it was not possible to predict these effects, due to lack of experimental data.

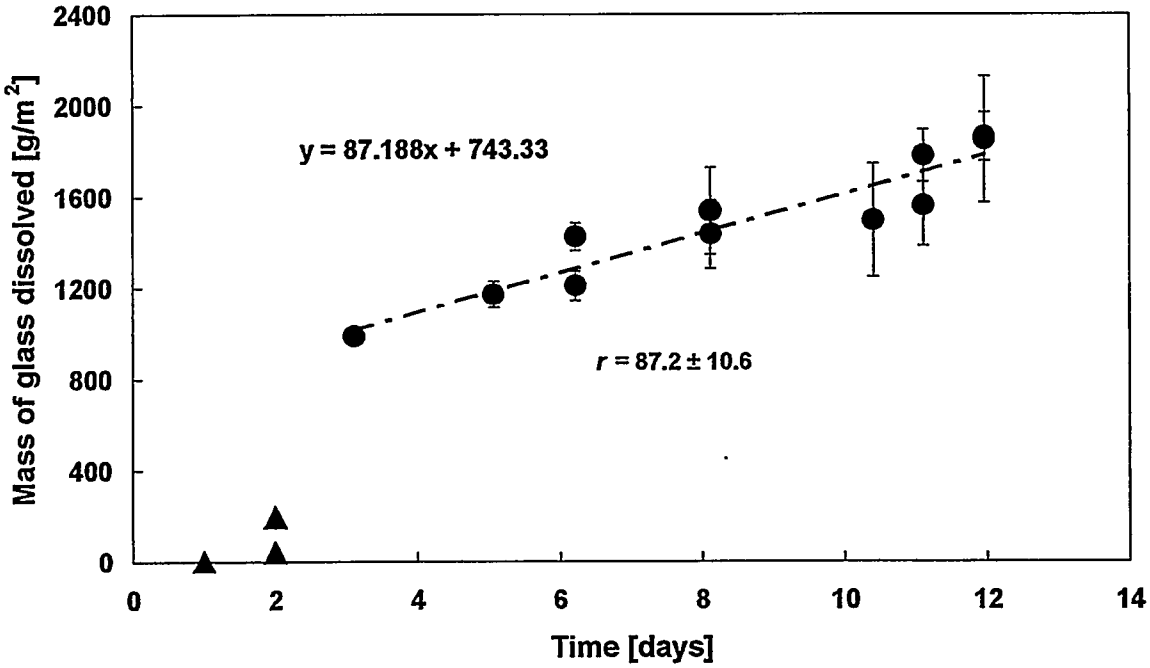
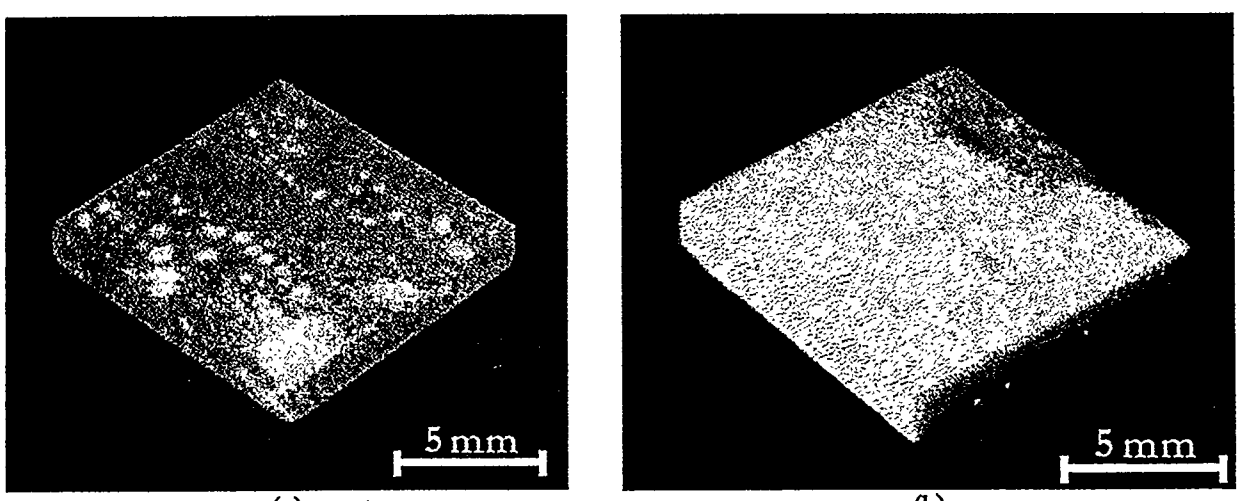


Figure 3-38. VHT Tests on HLP-46 Glass at 175°C up to 12 Days; Triangles Represent Data in the Incubation Time that Were Excluded from Linear Regression

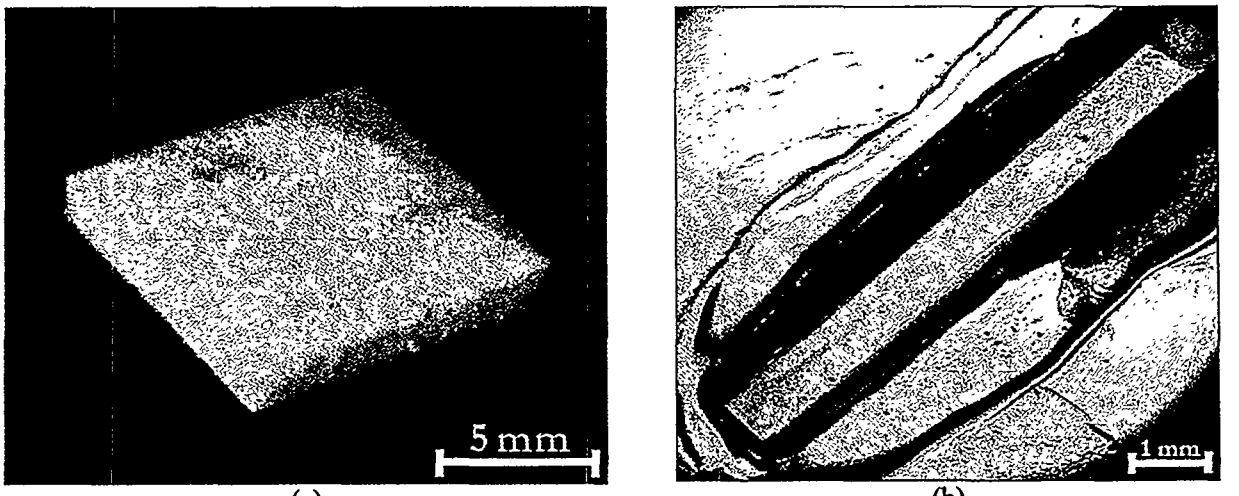
An example of the progression through different reaction stages in duplicate samples of HLP-46 glass after 2 days of VHT at 175°C is displayed in Figure 3-39. Sample (A) has a thin, 30-μm layer partially covering the glass surface, whereas the secondary phases start to precipitate in the form of white dots. Sample (B) has a continuous alteration layer roughly 100 μm thick.



(a) (b)

Figure 3-39. Duplicate Samples of HLP-46 Glass after 2 Days of VHT at 175°C

A sample of HLP-46 glass after 3 days of VHT at 175°C is displayed in Figure 3-40. Although the test period was only 1 day longer, the sample shows a continuous layer of alteration products about 600 μm thick, see cross section in Figure 3-40 (B). It can be concluded that rapid acceleration of dissolution occurred between the 2nd and 3rd day of the test. As shown in Figure 3-38, rate increases rapidly after alteration products begin to precipitate on the sample surface and becomes approximately constant after the alteration products form continuous layer/layers (i.e., after 3 days). Therefore, the rate for test glasses was determined by regression over the linear portion of the dissolution curve from 3 to 12 days.



(a) (b)

Figure 3-40. Photograph of a Sample of HLP-46 Glass after 3 days of VHT at 175°C (a) and Optical Micrograph of the Cross Section of the Same Sample (b)

3.6.2 Alteration Rate at 200°C

The initial alteration rates of most glasses have been determined at 200°C. These rates, listed in Table 3-11, are preliminary and are expected to change as further data are generated.[a] The glasses with high resistance to VHT (e.g., $r \leq 14$ g/m^2/d)[b] take long times to sufficiently corrode to accurately determine a rate; for example, Figure 3-41 shows m_d as a function of time for HLP-03. The estimated rate is clearly subject to change as longer-term tests are completed. Conversely, Figure 3-42 shows m_d as a function of time for HLP-29 for which the rate is well established.

[a] Considering the preliminary nature of the rates, uncertainties and intercepts were not estimated.
[b] The units of g/m^2/d are used in this report to allow direct comparison with existing data on glass alteration rates. To convert to the SI units of kg/m^2/s, the reader can multiply reported values by 1.1574×10^{-8}.

Table 3-11. Preliminary VHT Alteration Rates and Major Alteration Products at 200°C

Glass ID	r [g/m²/d]	Glass ID	r [g/m²/d]	Glass ID	r [g/m²/d]
HLP-01	4.3	HLP-20	8.7	HLP-39	id
HLP-02	264.7	HLP-21	4	HLP-40	1
HLP-03	1	HLP-22	1.5	HLP-41	14.1
HLP-04	18.3	HLP-23	15.9	HLP-42	0.2
HLP-05	2.5	HLP-24	3.1	HLP-43	id
HLP-06	1.6	HLP-25	5.7	HLP-44	id
HLP-07	13.8	HLP-26	0.6	HLP-45	id
HLP-08	7.2	HLP-27	84.2	HLP-46	254.6
HLP-09	0.9	HLP-28	1.7	HLP-47	36.4
HLP-10	3.6	HLP-29	55.4	HLP-48	50.5
HLP-11	5.4	HLP-30	11.5	HLP-49	0.6
HLP-12	14.4	HLP-31	78.3	HLP-51	4.4
HLP-13	1.3	HLP-32	4.5	HLP-52	1219.4
HLP-14	13.2	HLP-33	18.2	HLP-53	552.6
HLP-15	1.1	HLP-34	id	HLP-54	57
HLP-16	1.4	HLP-35	17.8	HLP-55	24.7
HLP-17	9.6	HLP-36	13.5	HLP-56	id
HLP-18	16.1	HLP-37	10.7		
HLP-19	0	HLP-38	6.7		

id = insufficient data

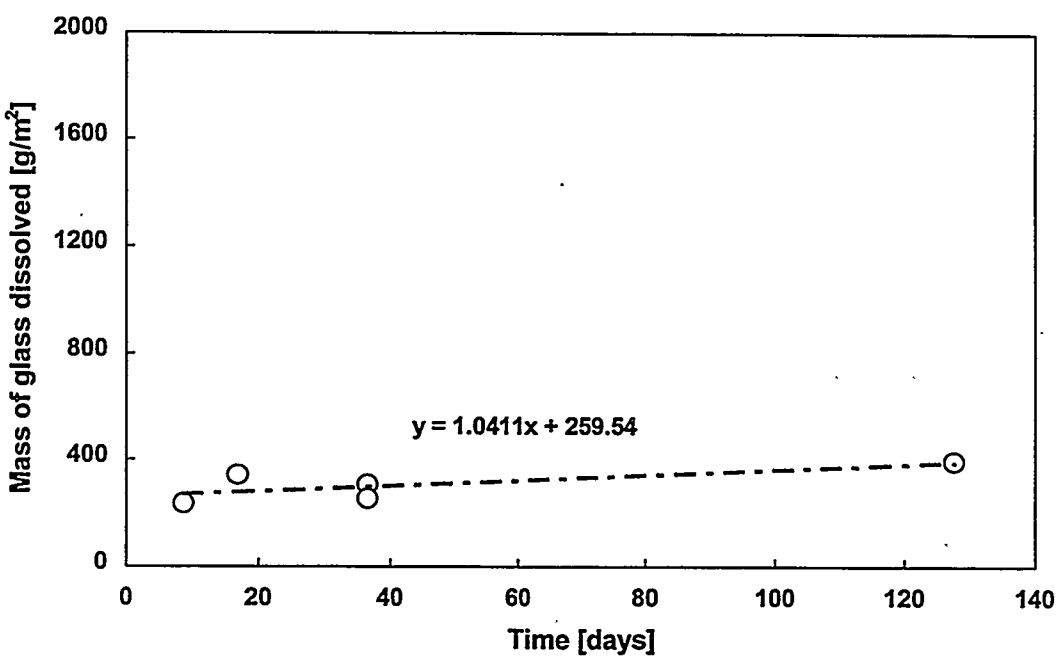


Figure 3-41. The m_d as a Function of t for HLP-03 at 200°C

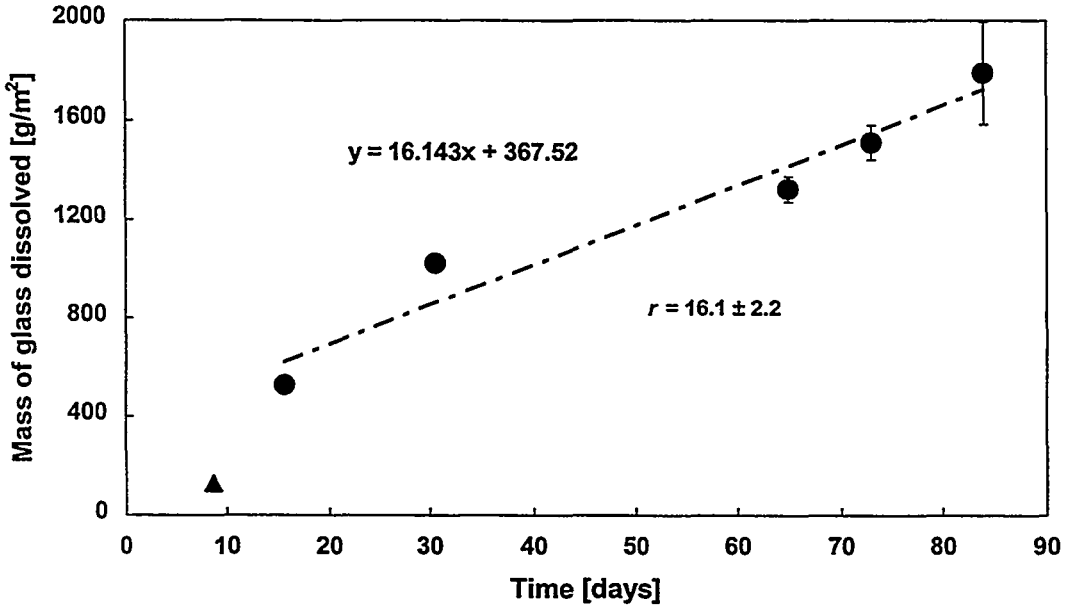


Figure 3-42. The m_d as a Function of t for HLP-18 at 200°C

The preliminary *rates* ranged from 0.0 to 1219 g/m^2/d and covered at least three orders of magnitude. The glasses can be categorized into four groups:

1. Glasses with low resistance to VHT – rate at 200°C between 14 and 1219 g/m^2/d. For these glasses, we have good estimates of rate since the samples in this group are completely dissolved in roughly 100 days or less. This group contains 18 glasses, listed in Table 3-12.
2. Glasses with medium resistance to VHT – rate at 200°C between 6 and 14 g/m^2/d. For these glasses, we have poor estimates of rate. The ranking of glasses within this category is likely to change; however, these glasses are clearly more resistant to VHT than glasses in Group 1 and less resistant to VHT than glasses in Group 3. This group has 9 glasses.
3. Glasses with high resistance to VHT – rate at 200°C less than 6 g/m^2/d. For these glasses, we have poor estimates of rate. The ranking of glasses within this category is likely to change; however, these glasses are clearly more resistant to VHT than glasses in Groups 1 and 2. This group contains 22 glasses.
4. Glasses with insufficient data to estimate rate or, more generally, their resistance to VHT. This group has six glasses, not listed in Table 3-12.

The demarcation of these categories is largely arbitrary. The value of 14 g/m^2/d was selected because those glasses with *rates* higher than 14 are completely dissolved in roughly three months and therefore sufficient data to accurately measure the rate for these glasses were obtained. The value of 6 g/m^2/d, separating Category 2 and 3 glasses, was selected after examination of m_d vs. t plots for glasses in each category. Those glasses with *rates* above 6 g/m^2/d could be clearly distinguished from those with *rates* below 6 g/m^2/d.

Table 3-12. HLP Glasses Listed in Order of rate and Grouped into Three Categories

Group 1			Group 2			Group 3		
Glass ID	Descr.	r ($g/m^2/d$)	Glass ID	Descr.	r ($g/m^2/d$)	Glass ID	Descr.	r ($g/m^2/d$)
HLP-52	HAN 28	1219.4	HLP-07	I Al	13.8	HLP-25	Center	5.7
HLP-53*	LAW-A23	552.6	HLP-36*	LHHL	13.5	HLP-11	L Fe	5.4
HLP-02	L Si	264.7	HLP-14	L Ti	13.2	HLP-32	HLHL	4.5
HLP-46	LD6-5412	254.6	HLP-30	HHLL	11.5	HLP-51	LAW-ABP1	4.4
HLP-27	HHHH	84.2	HLP-37*	LHLH	10.7	HLP-01	Center	4.3
HLP-31	HLHH	78.3	HLP-17	H Zn	9.6	HLP-21	H Mg	4.0
HLP-54	L4-912	57.0	HLP-20	L Mg	8.7	HLP-10	I B	3.6
HLP-29	HHLH	55.4	HLP-08	L B	7.2	HLP-24	I Na	3.1
HLP-48	LAW-A33	50.5	HLP-38*	LHLL	6.7	HLP-05	L Al	2.5
HLP-47	LRM-1	36.4				HLP-28	HHHL	1.7
HLP-55	L4-99	24.7				HLP-06	H Al	1.6
HLP-04	I Si	18.3				HLP-22	L Na	1.5
HLP-33	HLLH	18.2				HLP-16	L Zn	1.4
HLP-35	LHHH	17.8				HLP-13	I Fe	1.3
HLP-18	L Zr	16.1				HLP-15	H Ti	1.1
HLP-23	H Na	15.9				HLP-03	H Si	1.0
HLP-12	H Fe	14.4				HLP-40*	LLHL	1.0
HLP-41*	LLLH	14.1				HLP-09	H B	0.9
						HLP-26	Center	0.6
						HLP-49*	LAW-B29	0.6
						HLP-42*	LLLL	0.2
						HLP-19	H Zr	0

(*) Crystallized glass

Since the *rates* of 37 out of 55 glasses are expected to change, it is premature to describe glass-composition effects on VHT response. However, the following generalities can be made:

- Glasses with a high concentration of Na_2O are more likely to have low resistance to VHT than those with lower concentrations.
- Those glasses with low concentrations of SiO_2, ZrO_2, or TiO_2 are less resistant to VHT than those with high concentrations.

A more thorough evaluation of composition impacts on VHT resistance of matrix glasses will be made when the *rates* of more glasses become final.

3.6.3 Alteration Products

The alteration products formed during VHT of selected glasses were characterized with XRD and SEM/EDS. Table 3-14 lists the phases identified in VHT glasses and their content in mass percent. Most tested samples altered to form analcime and sodium aluminum silicate hydrate. Unlike in other tests,

none of the glass components are removed to the solution, and therefore all elements are available for reaction. The typical soluble component used to characterize glass dissolution is boron. Although boron was expected to be found in crystalline alteration products, only two boron-containing phases were found (6, 12 in Table 3-13). Another boron-containing phase is sodium aluminum silicate boron hydroxide hydrate. However, its pattern is practically identical to sodium aluminum silicate hydrate, so its presence could not be confirmed yet.

Some selected minerals formed on the surface of VHT samples are shown in Figure 3-43 and Figure 3-44. Sodium Zinc Silicate is frequently was found in other test methods. Both minerals were not detected by XRD, probably because of their low content.

Table 3-13. Crystalline Phases Identified in VHT Samples with XRD

#	Phase	Formula	JCPDF#	Formed in Glasses
1	Analcime-C	$Na(Si_2Al)O_6 \cdot H_2O$	41-1478	All Except 52 and 53
2	Sodium Titanium silicate	$NaTiSi_2O_6$	29-1280	All Except 06, 11, 21, 23, 27, 29, 31, 35-38, 46, 48-55
3	Sodium Aluminum Silicate Hydrate Sodium Aluminum Silicate Boron Hydroxide Hydrate	$Na_6[AlSiO_4]_6 \cdot 4H_2O$ $Na_{7.55}(AlSiO_4)_6(B(OH)_4)_{1.685}$-$(H_2O)_{1.97}$	42-216 83-550	02, 29, 35, 38, 48, 51, 53-55
4	Sodium Aluminum Silicate Hydrate	$Na_6Al_6Si_{10}O_{32} \cdot 12H_2O$	39-219 44-103	23, 51
5	Sodium Aluminum Silicate Hydrate	$Na_{5.7}Al_{5.7}Si_{10.3}O_{32} \cdot 12H_2O$	34-524	27
6	Tincalconite	$Na_2B_4O_7 \cdot 5H_2O$	7-277	30, 36
7	Spinel	$[Fe,Zn,Ni][Fe,Ti,Cr]_2O_4$	86-509	38, 42
8	Gobbinsite	$Ca_{0.6}Na_{2.6}K_{2.2}Al_6Si_{10}O_{32}(H_2O)_{12}$	75-1464	46
9	Sodium Aluminum Silicate Hydrate	$Na_3Al_3Si_3O12(H_2O)_2$	84-590	09
10	Sodium aluminum silicon oxide	$Na_{2.12}Al_2Si_2O_{8.06}$	47-716	56
11	Phillipsite	$(K,Na)_2(Si, Al)_8O_{16} \cdot 4H_2O$	46-1427	51
12	Pinakiolite	$(Mg,Mn)_2Mn(BO_3)_2$	36-413	04, 37, 43, 48
13	Calcium silicate hydroxide hydrate	$Ca_{4.5}Si_6O_{15}(OH)_3 \cdot 2H_2O$	43-1488	53
14	Sodium Zirconium silicate	$Na_{14}Zr_2Si_{10}O_{31}$	29-1459	52
15	Hydroxycancrinite	$Na_8Al_6Si_6O_{24}(OH)_2 \cdot 2H_2O$	46-1457	52
15	Sodium aluminum silicate hydrate	$Na_{14}Al_{12}Si_{13}O_{51} \cdot 6H_2O$	28-1036	52

Table 3-14. Crystalline Phases from Table 3-13 and Their Content (%) in Analyzed VHT Samples

Sample ID	Crystalline phase															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	(a)
HLP-01-200-125-surface	97	3														
HLP-02-200-30	16	15	69													
HLP-03-200-125-surface	90	10														
HLP-04-200-016	46	44										10				
HLP-06-200-106-surface	100															
HLP-07-200-100	94	6														
HLP-08-200-100-surface	95	5														
HLP-09-300-005-surface	93	4							3							

Sample ID	Crystalline phase															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	(a)
HLP-10-200-129-surface	98	2														
HLP-11-200-068-surface	100															
HLP-12-200-105	82	18														
HLP-12-300-002	45	55														
HLP-13-200-080-surface	97	3														
HLP-15-200-075-surface	99	1														
HLP-16-200-075-surface	98	2														
HLP-17-200-075-surface	98	2														
HLP-18-200-032	93	7														
HLP-20-200-075-surface	87	13														
HLP-21-200-032-surface	85															15
HLP-23-200-007-surface	95			5												
HLP-24-200-032-surface	95	5														
HLP-27-200-004	88				12											
HLP-27-200-100	100															
HLP-29-200-013	39	60	1													
HLP-30-200-023-surface	94					6										
HLP-31-200-002-surface	100															
HLP-31-200-010	68	32														
HLP-32-200-024-surface	85	15														
HLP-33-200-129-surface	93	7														
HLP-33-300-005	29	71														
HLP-35-200-021	61		39													
HLP-36-200-032-surface	86					14										
HLP-37-200-024-surface	76											24				
HLP-38-200-024	38		2				60									
HLP-38-200-064	24		10				66									
HLP-41-200-120-surface	90	10														
HLP-42-200-068-surface	33	5					62									
HLP-43-200-033	53	6										41				
HLP-46-200-001	97							3								
HLP-46-200-004b	95							5								
HLP-47-200-024	97	3														
HLP-48-200-020	41		51									8				
HLP-49-200-050-surface	47															53
HLP-51-150-187-surface	13										87					
HLP-51-200-075	19			81												
HLP-51-250-003b-surface	70		30													
HLP-52-200-013														38	62	
HLP-53-200-003			94										6			
HLP-54-200-041	65		45													
HLP-55-200-014	40		60													
HLP-56-250-005-surface	96	4														
HLP-56-300-003	21	72								7						

(a) Unidentified crystalline phase

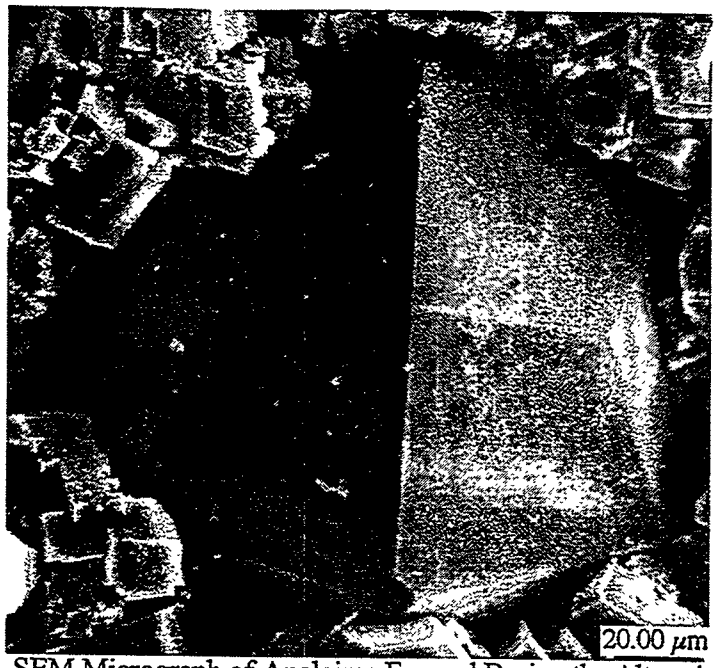


Figure 3-43. SEM Micrograph of Analcime Formed During the Alteration of HLP-48 at 175°C After 28 Days

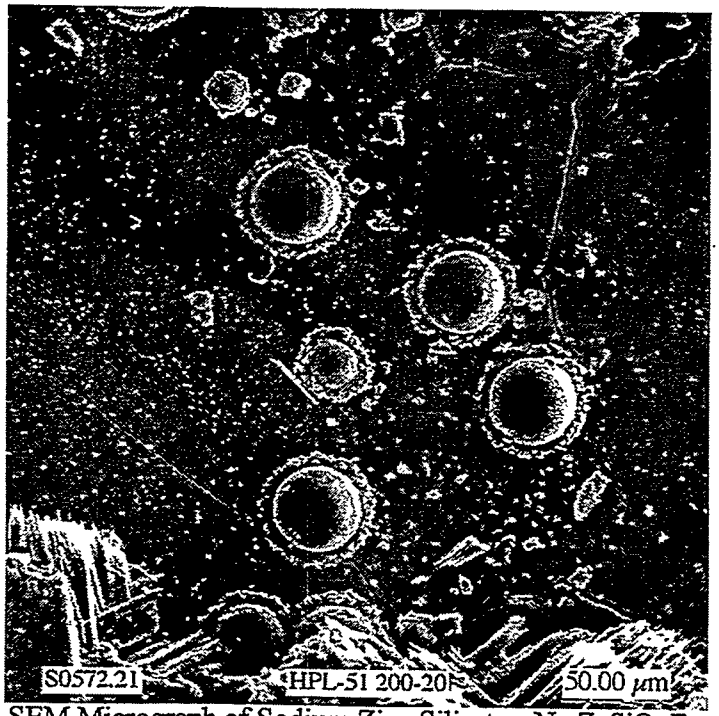


Figure 3-44. SEM Micrograph of Sodium Zinc Silicate – Na_2ZnSiO_4 Formed During the Alteration of HLP-51 at 200°C

3.6.4 Effects of Temperature

VHT's were initiated over the temperature range from 90°C to 300°C for selected glasses to determine the impact of temperature on rate and the alteration products formed. However, only tests from 150°C to 300°C are sufficiently progressed to discuss their results. Table 3-15 lists the rates for glasses tested at multiple temperatures. Figure 3-45 through Figure 3-47 show the $m_d - t$ relationships for HLP-46, -48, and -51 at various temperatures. There are insufficient data to examine the effects of temperature on rate of the remaining test-matrix glasses. Figure 3-48 shows the effect of temperature on rate for these glasses. The apparent activation energies (E_a) for the rate of HLP-46, -48, and -51 were 87.3 kJ/mol, 94.2 kJ/mol, and 97.6 kJ/mol, respectively. The term "apparent activation energy" is considered appropriate because the dissolution of even a simple mineral consists of several reaction steps (five steps in case of quartz) (Lasaga 1995); in VHT, we have changing solution chemistry with reaction extent, dissolution processes, and precipitation processes that must be considered. It should be noted that the validity of the Arrhenius empirical relationship does not imply that the mechanism is the same over the temperature interval in question and that the same alteration products are formed at high- and low-temperatures. These E_a values are at the high end of the range commonly reported for glass corrosion by other test methods, which generally range from 32 kJ/mol (for low SiO_2 glasses) to 100 kJ/mol (Lutze and Ewing 1988, Jercinovic and Ewing 1992, Westsik and Peters 1981, and Abraitis et al.1998). It is uncertain if our measured E_a values will remain constant with decreasing temperature. Mazer (1991) suggests caution in use of temperature as an accelerating parameter until more is understood about the rate-determining mechanism at test and disposal-site temperatures.

Leturcq et al. (1998) summarized corrosion rate data for R7T7 glass within the temperature interval from 25°C to 300°C and confirmed the validity of Arrhenius behavior with a constant $E_a = 60 \pm 5$ kJ/mol. Likewise, Westsik and Peters (1981) showed that E_a of 76-68 glass corrosion remained constant at 53 kJ/mol over the temperature range from 50°C to 150°C; however, the corrosion was found to change below 50°C and above 150°C. A possible explanation for the change in corrosion behavior at the extreme temperature was a change in the stage of corrosion. In the initial stage of corrosion, ion exchange occurs and pH increases rapidly; Westsik and Peters (1981) found the normalized Na release was significantly higher than the normalized boron release for samples tested at temperatures below 50°C. In the second stage, corrosion is roughly congruent, as was found by Westsik and Peters (1981) between 50°C and 150°C, and the rate of corrosion drops as the concentration of aqueous species increases, decreasing the driving force for dissolution. In the third stage of corrosion, mineral phases precipitate from solution allowing the driving force for dissolution to increase and the dissolution rate to accelerate; we suspect that this stage was achieved in the Westsik and Peters (1981) tests at temperatures above 150°C.

Insufficient data are available to determine if the mechanisms that determine rate at 200°C are similar to those that would determine rate at 15°C. Therefore, we cannot predict 15°C rates for these glasses with the data generated at 200°C, even with estimated E_a values.

Table 3-15. Preliminary *r*s (in g/m^2/d) of Test Glasses Subjected to VHT at Various Temperatures

Glass ID	300°C	275°C	250°C	200°C	175°C	150°C
HLP-01	505.0			4.3		
HLP-09	409.3			0.9		
HLP-10	541.8			3.6		
HLP-12	1126.0			14.4		
HLP-25	655.0			5.7		
HLP-26	685.8			0.6		
HLP-46				254.6	87.2	18.6
HLP-48			522.2	50.5	13.7	3.1
HLP-51	336.4	129.3	42.3	4.4		
HLP-56	603.0		78.3			

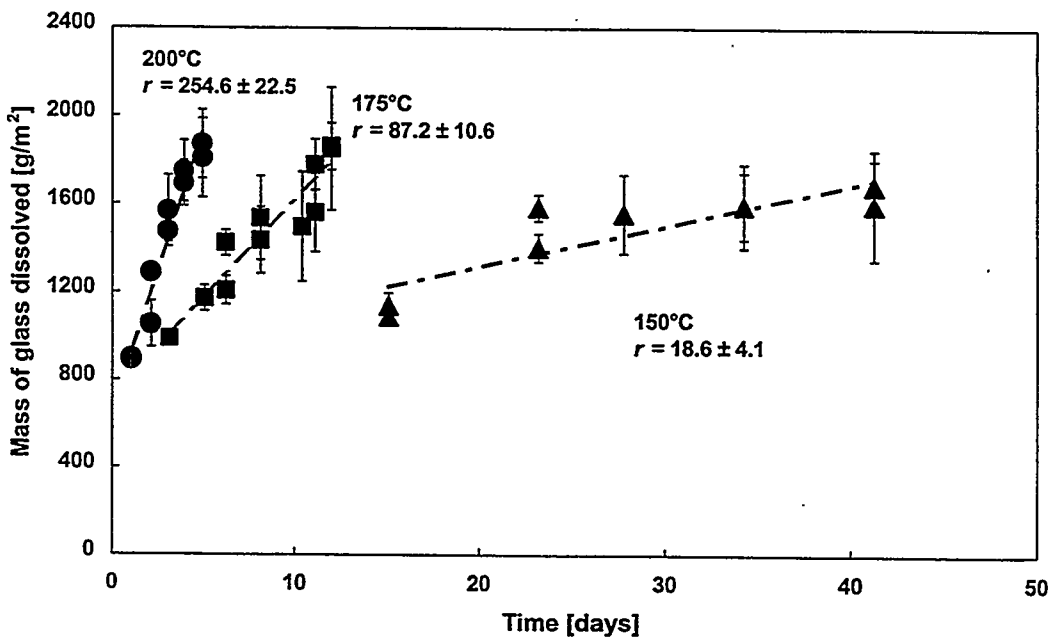


Figure 3-45. Amount of HLP-46 Dissolved in VHT at 150°C, 175°C, and 200°C as Functions of *t*

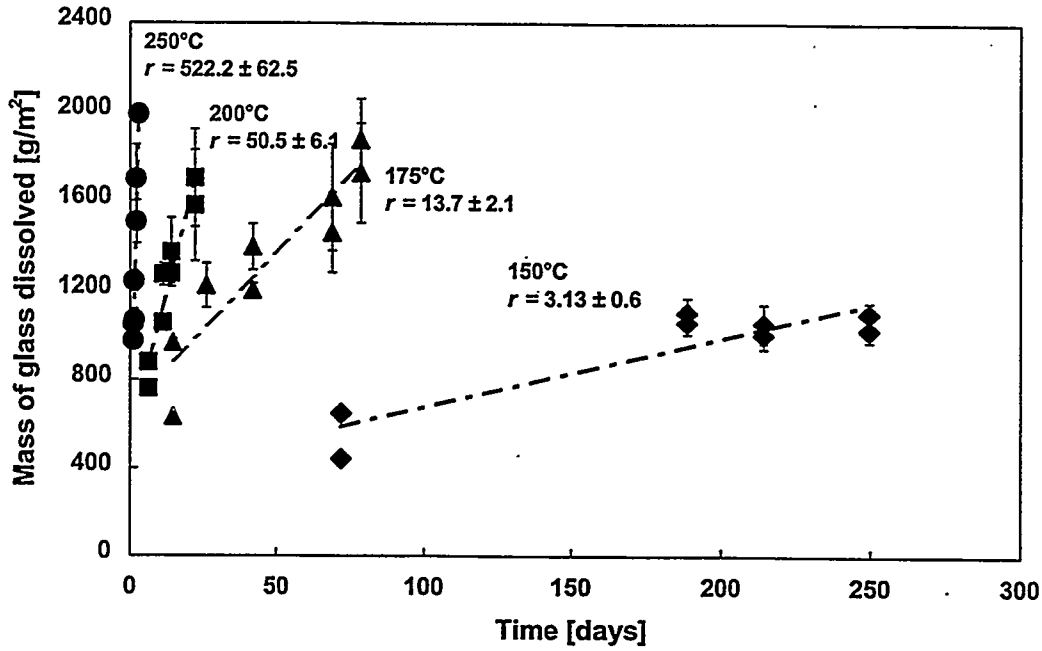


Figure 3-46. Amount of HLP-48 Dissolved in VHT at 150°C, 175°C, 200°C, and 250°C as Functions of *t*

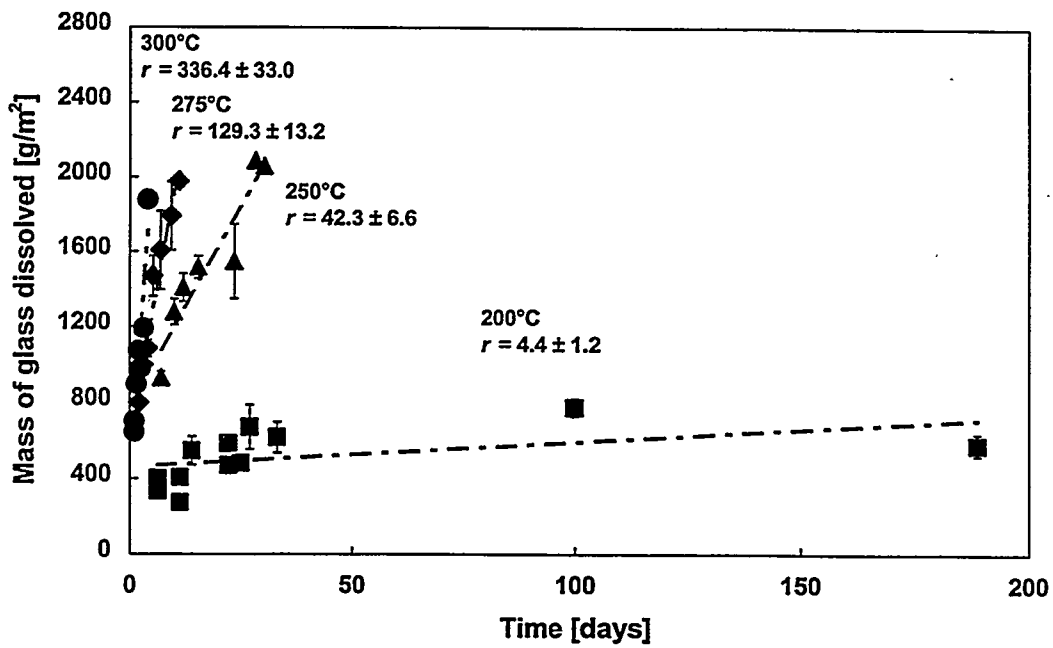


Figure 3-47. Amount of HLP-51 Dissolved in VHT at 200°C, 250°C, 275°C, and 300°C as Functions of *t*

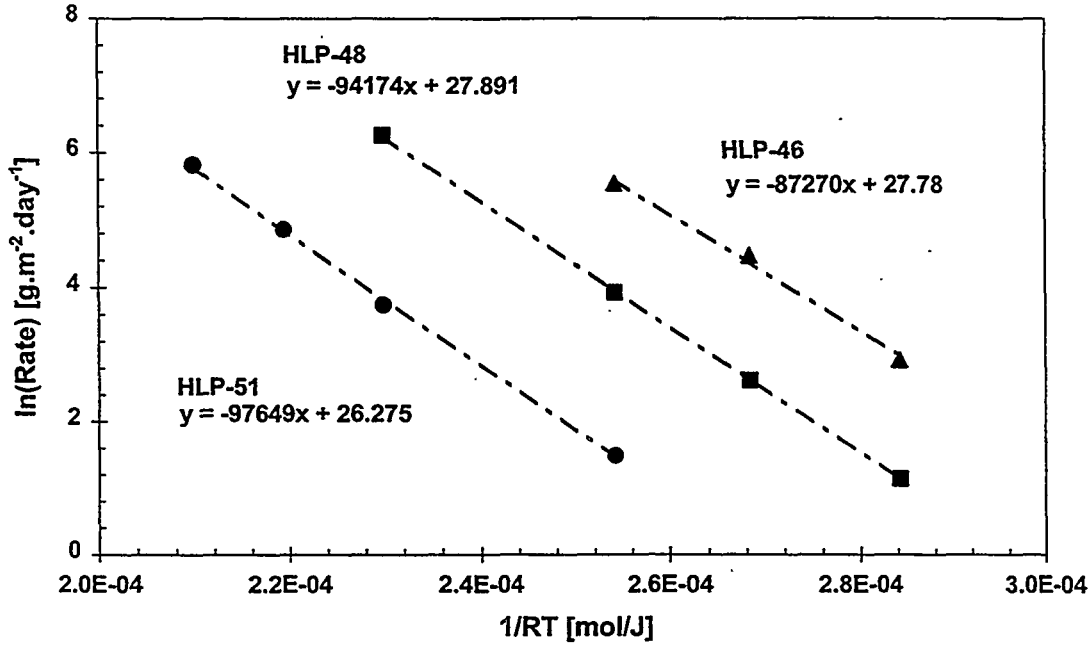


Figure 3-48. Effect of Temperature on rate for HLP-46, HLP-48, HLP-51

Jercinovic and Ewing (1992) found that different alteration products were formed on natural high silica glass at different temperatures of corrosion. Temperature was also found to affect the alteration products formed during VHT of selected HLP glasses. Figure 3-49 shows that the XRD pattern of HLP-46 reacted at increasing temperatures. While the location of major peaks does not change, it is clear that peaks 21.645 and 28.108 decrease while peaks 15.809 and 25.978 increase with increasing temperature. Since each of these has a different amount of alteration, we compare the XRD pattern of HLP-46 at 200°C as a function of alteration time in Figure 3-50. The lack of change in relative peak heights with alteration extent suggests that the change in the XRD pattern in Figure 3-49 must be due to temperature. The peaks in these XRD patterns are identified in Figure 3-51. This identification led us to the conclusion that as temperature is increased, the concentration of analcime is increased relative to that of sodium aluminum silicate hydrate.

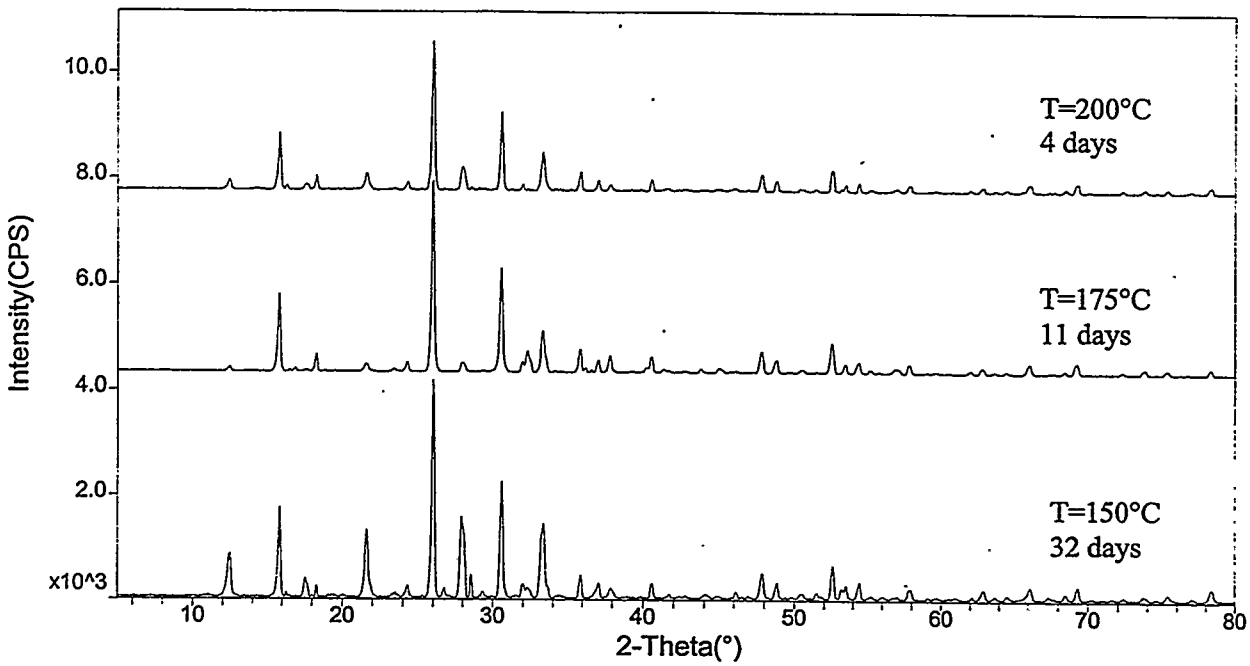


Figure 3-49. Comparison of XRD Patterns for HLP-46 Subjected to VHT at Different Temperatures

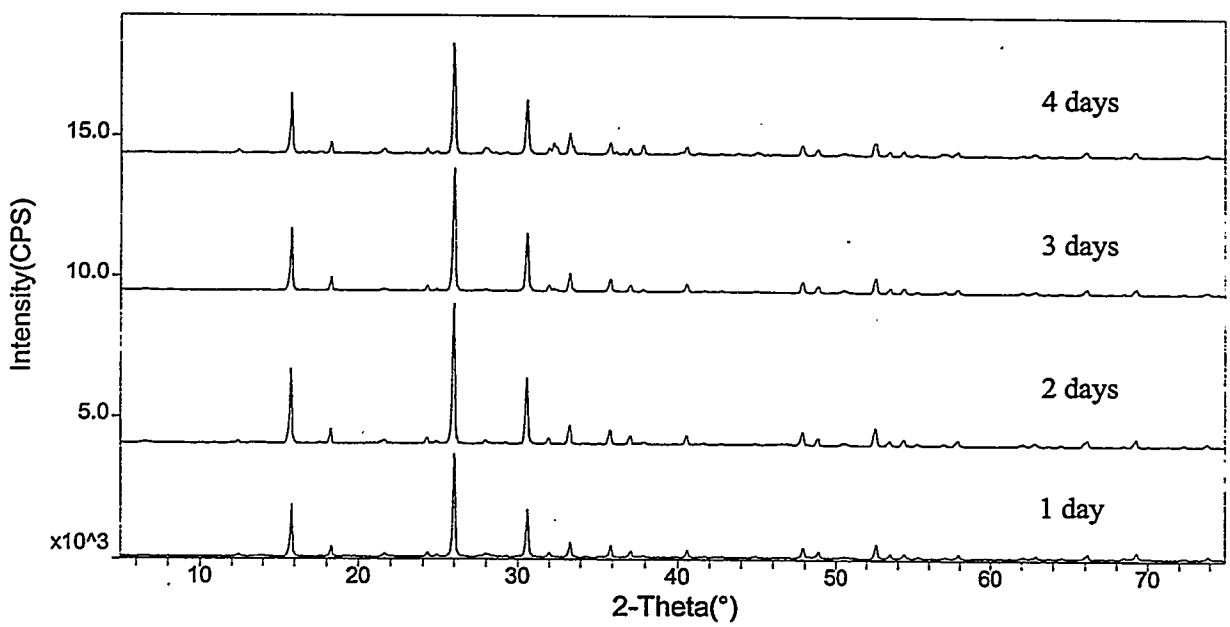


Figure 3-50. Comparison of XRD Patterns for HLP-46 Subjected to VHT at 200°C for 1, 2, 3, and 4 Days

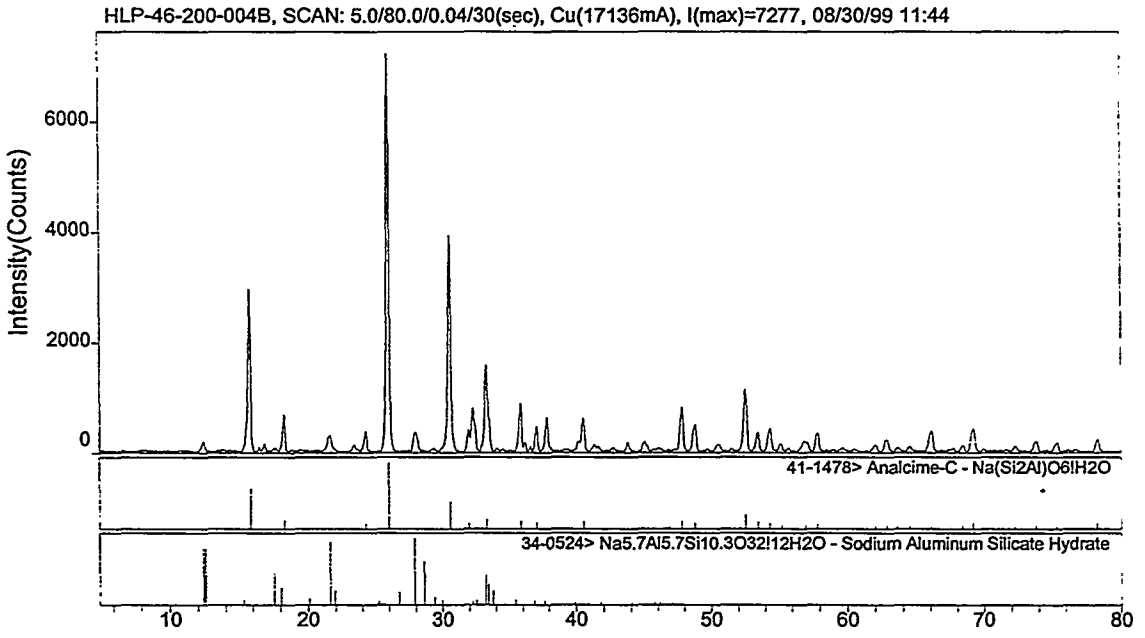


Figure 3-51. XRD Pattern of HLP-46 Subjected to VHT at 200°C for 4 Days

A similar analysis was performed on VHT samples of HLP-48. Figure 3-52 shows that the XRD pattern of HLP-46 reacted at increasing temperatures. While the location of major peaks does not change, it is clear that the peak at 25.865 decreases while the peak at 24.155 increases with increasing temperature. Since each of these has a different amount of alteration, we compare the XRD pattern of HLP-48 at 200°C as a function of alteration time in Figure 3-53. The lack of change in relative peak heights with alteration extent suggests that the change in XRD pattern in Figure 3-52 must be due to temperature. The peaks in these XRD patterns are identified in Figure 3-54. This identification led us to the conclusion that as temperature is increased, the concentration of sodium aluminum silicate boron hydroxide hydrate is increased relative to that of analcime. Surprisingly, the concentration of analcime increases with temperature in HLP-46 and decreases with temperature in HLP-48. A more thorough examination of the stability of alteration products as a function of temperature should be conducted when more data are available.

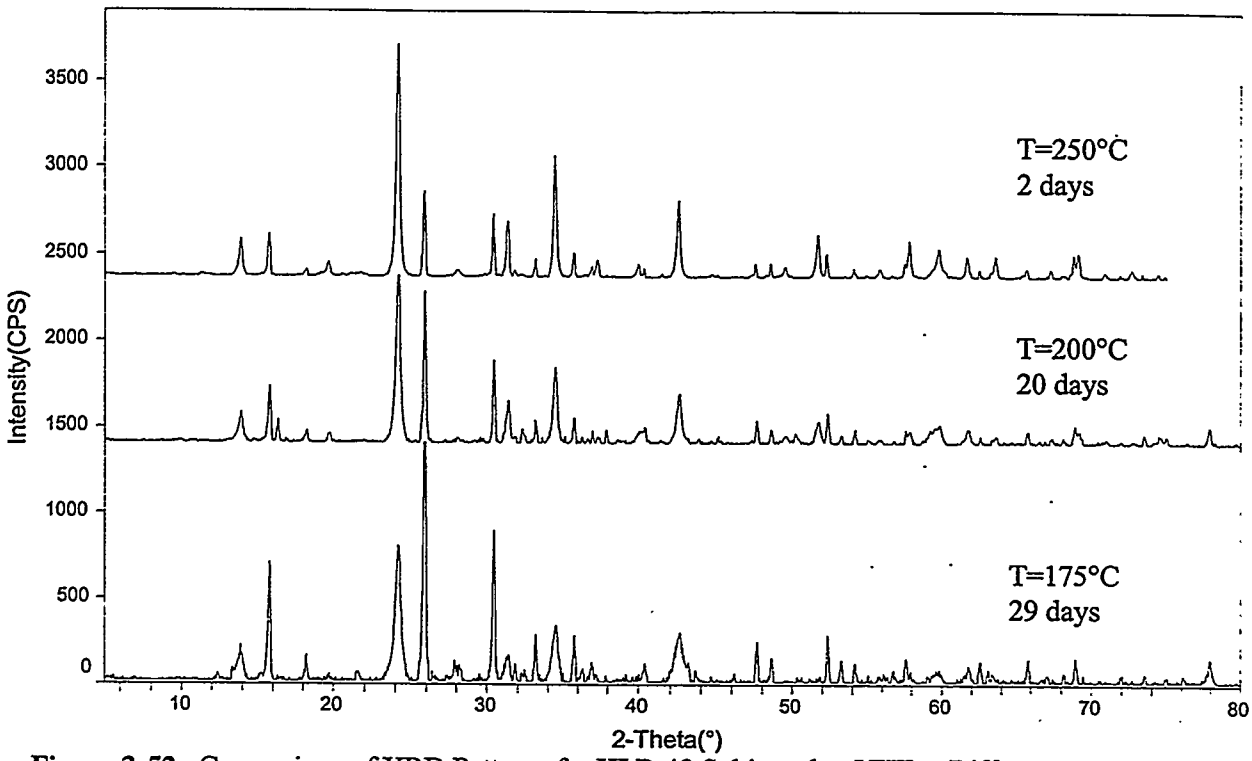


Figure 3-52. Comparison of XRD Patterns for HLP-48 Subjected to VHT at Different Temperatures

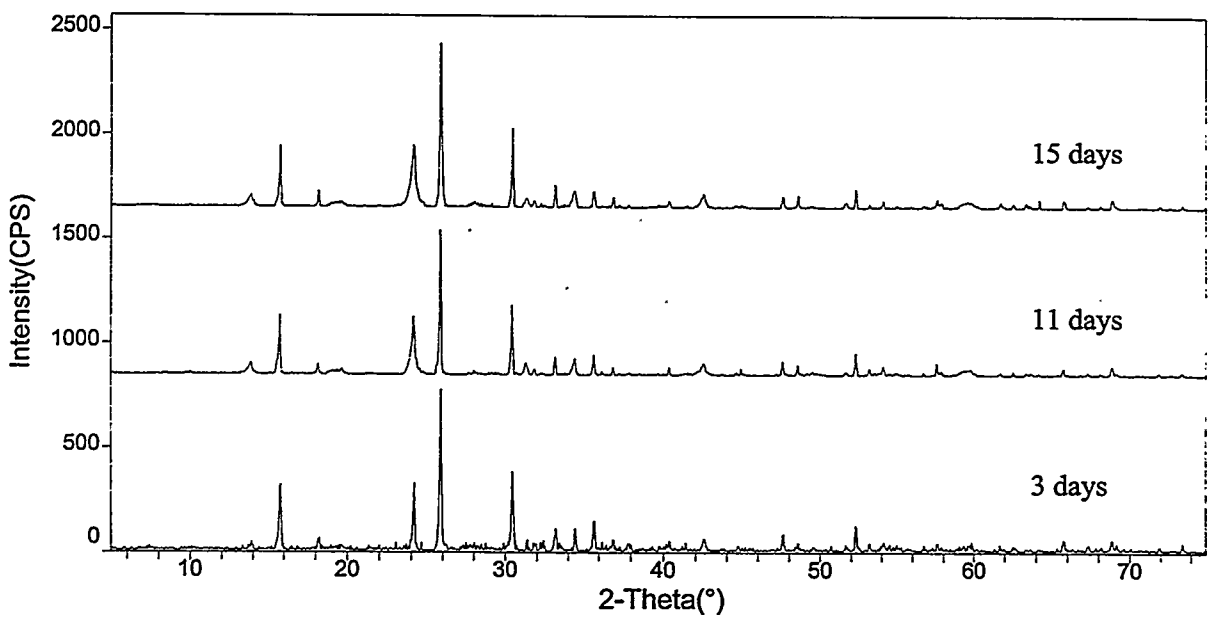


Figure 3-53. Comparison of XRD Patterns for HLP-48 Subjected to VHT at 200°C for 3, 11, and 15 Days

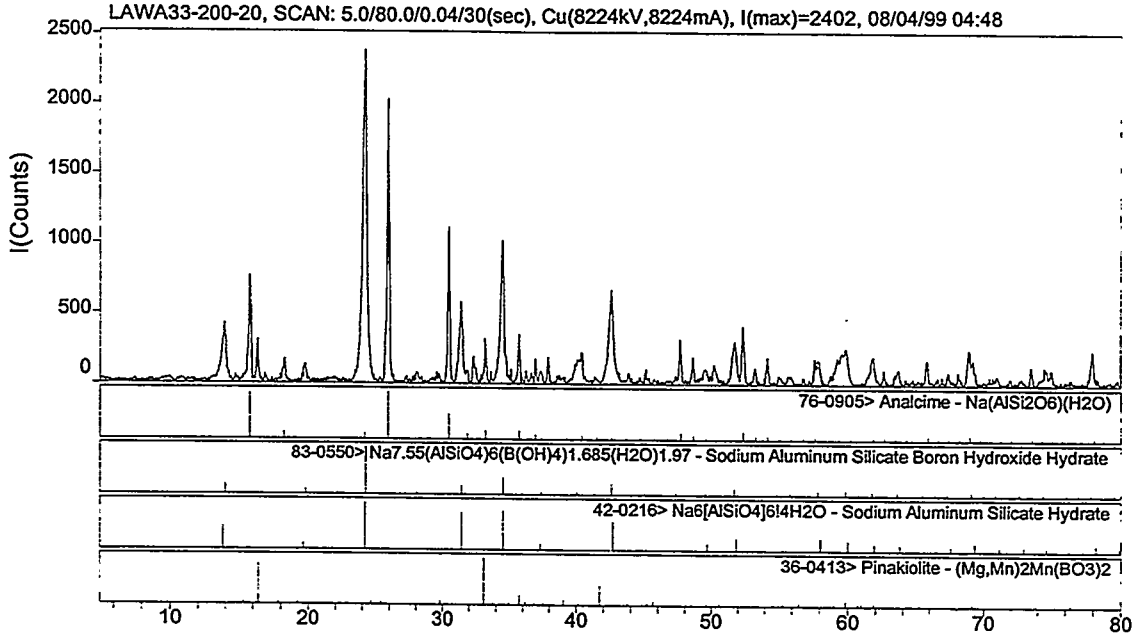


Figure 3-54. XRD Pattern of HLP-48 Subjected to VHT at 200°C for 20 Days

4.0 Data Reproducibility

Results from repeated glass testing and property values of test-matrix glasses reported in the literature were compared to assess the reproducibility of the testing program employed in this study. The literature results compared to those in this study are presented in Section 4.1 for PCT and in Section 4.2 for VHT. The results from repeated test glasses are compared in Section 4.3.

4.1 PCT Data

As part of these research activities, PCT-A (i.e., T = 90°C, S/V ≈ 2000 m^{-1}, and t = 7 days) and PCT-B (i.e., T = 90°C, S/V ≈ 20 000 m^{-1}, and t = 10, 100, and 1000 h) tests were run at SRTC on the HLP glasses whose compositions are provided in Table 2-1. However, a number of these glasses were previously fabricated and tested for the PCT at other laboratories. These historical data were examined to indicate whether they corroborated the SRTC data under the realization that these data were subject to laboratory-to-laboratory, glass-to-glass, and other variations that have not been characterized. Thus, results from these comparisons will be necessarily qualitative; however, work is planned to perform a more rigorous statistical evaluation of the data before the final Hanford ILAW data-package submission.

4.1.1 HLP-46

The first glass examined was HLP-46. A series of tests was run by PNNL on this glass to examine the potential effects of S/V and time on the PCT results. These results are summarized in Table 4-1. Argonne National Laboratory (ANL) also performed the PCT on this same glass.[a] The SRTC, PNNL, and ANL boron and sodium releases, NC_i in g/L, are plotted against the (S/V)t term on Figure 4-1. (This is a convenient way to plot results with different S/V values on the same graph.) The PNNL results also include historic PCT-A data (Kim et al. 1995). For the boron results, it is evident that corrosion has accelerated in the PCT experiments with (S/V)t values beginning at approximately 10^8 h/m. Thus deviation of the long-term data from the least-squares fit to short-term PCT responses is not surprising and indicates that, under these conditions, the short-term data will not provide insight into the long-term data. Figure 4-1 indicates a similar short-term relationship for the sodium release (where no long-term ANL data were available). Additional examinations of these data will be made as long-term PCT-B data become available. However, the information in Figure 4-1 suggests that there is no reason to believe that the SRTC, ANL, or PNNL data are invalid for the HLP-46 glass.

4.1.2 HLP-47

Additional PCT data for the HLP-47 glass were previously collected from a round-robin study of this glass conducted by ANL (Ebert and Wolf 1999). Since these additional data were all from PCT-A on a single glass, only the test solution concentrations (in mg/L) were examined (as the glass-to-glass effects should have been insignificant). As illustrated in Figure 4-2, the individual PCT-A measurements from this study do not appear prone to either larger than expected random or systematic variation when compared to the results from the round-robin study. Additional work is planned to closely examine the appropriate components of variance to which these measurements are subject. This will allow more rigorous statistical methods to be used to provide more objective comparisons.

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[a] W. L. Ebert, A. J. Bakel, D. M. Strachan, and S. F. Wolf. 1998. *Laboratory Testing of LD6-5412 Glass*, DRAFT, Argonne National Laboratory, Argonne, Illinois.

Table 4-1. PNNL PCT-B Test Results for HLP-46

Glass (g)	H_2O (mL)	S/V (m^{-1})	Time, t (h)	(S/V)t (h/m)	B (mg/L)	Na (mg/L)	NC_B (g/L)	NC_{Na} (g/L)
0.1	100	2×10^1	1	2×10^1	0.073	0.35	0.0047	0.0023
0.5	50	2×10^2	1	2×10^2	0.063	1.9	0.0040	0.012
1	10	2×10^3	1	2×10^3	0.52	13.5	0.033	0.089
10	10	2×10^4	1	2×10^4	2.5	57	0.16	0.38
0.1	100	2×10^1	10	2×10^2	0.068	1.3	0.0043	0.0086
0.5	50	2×10^2	10	2×10^3	0.72	8.9	0.046	0.059
1	10	2×10^3	10	2×10^4	1.9	37	0.12	0.24
10	10	2×10^4	10	2×10^5	5.0	150	0.32	0.99
0.1	100	2×10^1	100	2×10^3	0.785[(a)]	7.4	0.050	0.049
0.5	50	2×10^2	100	2×10^4	1.6	22	0.10	0.15
1	10	2×10^3	100	2×10^5	3.3	88	0.21	0.58
1	10	2×10^3	100	2×10^5	3.0	74	0.19	0.49
10	10	2×10^4	100	2×10^6	13.0	120	0.83	0.79
0.1	100	2×10^1	1000	2×10^4	1.4	14	0.089	0.092
0.5	50	2×10^2	1000	2×10^5	2.4	35	0.15	0.23
1	10	2×10^3	1000	2×10^6	5.4	171	0.34	1.1
10	10	2×10^4	1000	2×10^7	No analyses were available			

(a) The last digit was estimated.

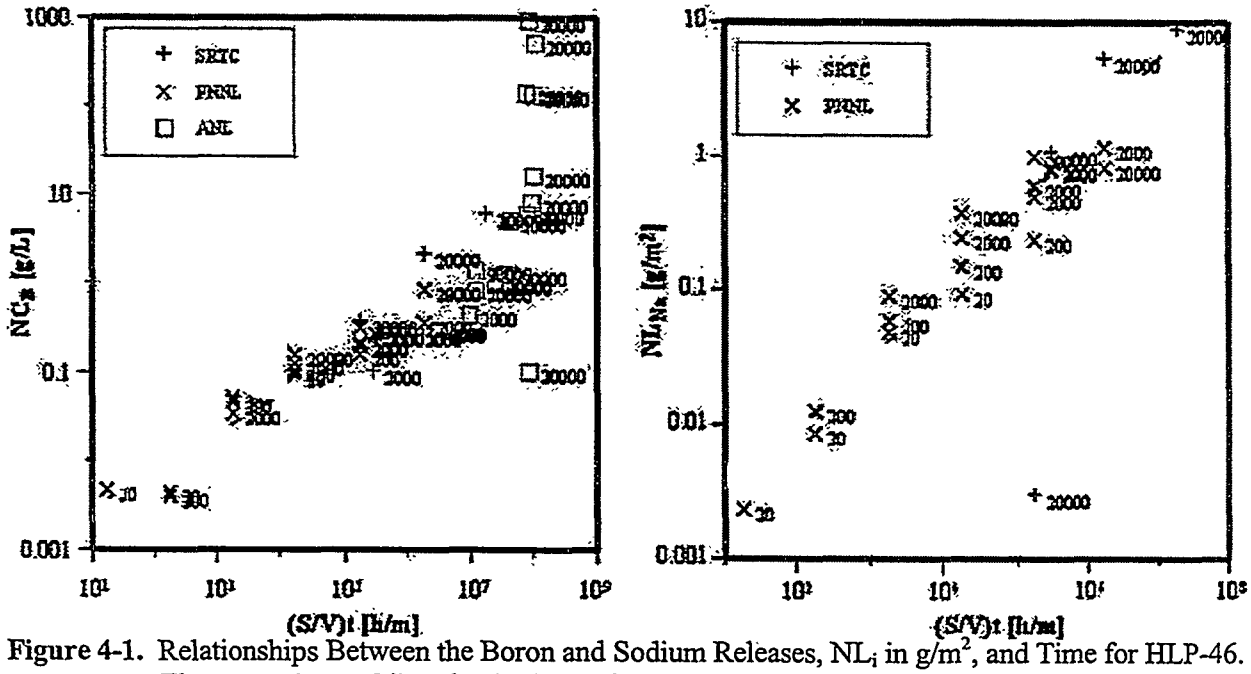


Figure 4-1. Relationships Between the Boron and Sodium Releases, NL_i in g/m^2, and Time for HLP-46. The approximate S/V value is shown for each sample. The dotted lines represent the least-squares fits for the respective boron and sodium data with (S/V)t values up to approximately 10^8 h/m.

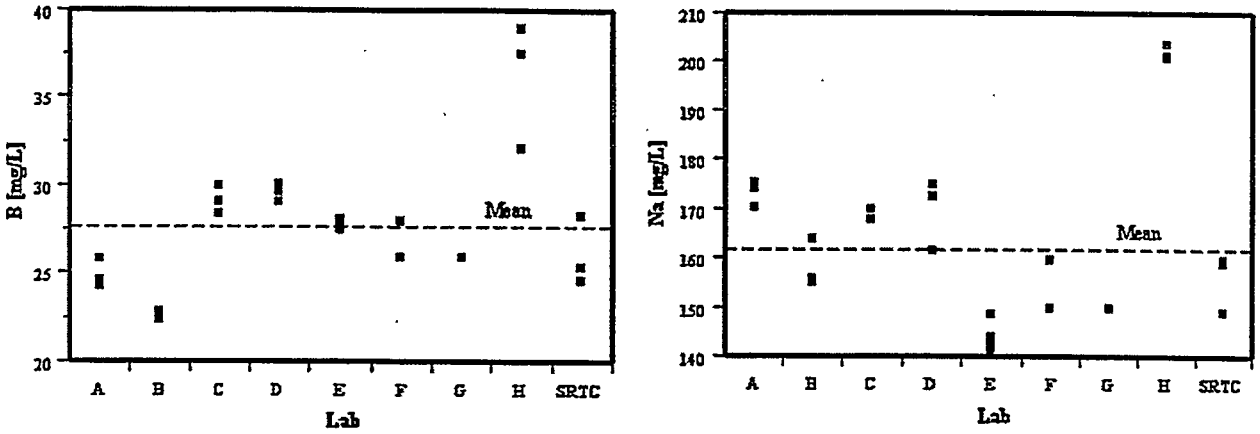


Figure 4-2. Boron (on the left) and Sodium (on the right) PCT-A Measurements for HLP-47 (or LRM-1). Data sets titled "A" through "H" are from round-robin testing, and the set entitled "SRTC" represents the measurements taken as part of this study. The dotted lines represent overall mean concentrations.

4.1.3 HLP-48

Additional data for the HLP-48 glass were also previously collected by ANL (McGrail 1999). Figure 4-3 illustrates the relationships between normalized boron and sodium releases, NC_i, and (S/V)t for the SRTC and ANL data. This figure appears to indicate that the SRTC and ANL data agree fairly well, and thus there is no reason to believe that either set is invalid. Additional work is planned to more closely examine the appropriate components of variance to which these measurements are subject. This will allow more rigorous statistical methods to be used for future comparisons.

4.1.4 HLP-54

A series of tests was run at PNNL on the HLP-54 glass to examine the potential effects of S/V and time on PCT-B results. These results are summarized in Table 4-2. These PNNL data (including previously run PCT-A measurements [Kim et al. 1995]) and the SRTC data from this study are plotted on Figure 4-4. In this context, there is no reason to believe that either the SRTC data from this study or the previous PNNL results are invalid.

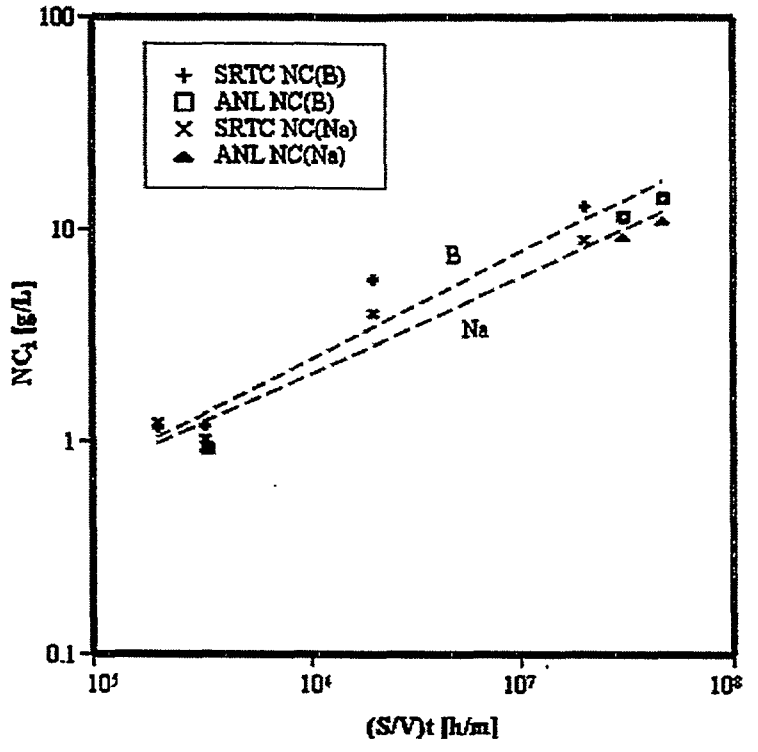


Figure 4-3. Relationships Between Normalized Boron and Sodium Releases, NC_i in g/L, as Functions of (S/V)t in h/m for HLP-48 Glass. The dotted lines represent the least-squares fits through the respective boron and sodium data.

Table 4-2. PNNL PCT-B Test Results for HLP-54

Glass (g)	H_2O (mL)	S/V (m^{-1})	Time, t (h)	(S/V)t (h/m)	B (mg/L)	Na (mg/L)	NC_B (g/L)	NC_{Na} (g/L)
0.1	100	2×10^1	1	2×10^1	0.019	0.27	0.0007	0.0018
0.5	50	2×10^2	1	2×10^2	0.12	1.1	0.0043	0.0074
1	10	2×10^3	1	2×10^3	0.72	6.3	0.026	0.042
10	10	2×10^4	1	2×10^4	4	30	0.14	0.20
0.1	100	2×10^1	10	2×10^2	0.12	0.86	0.0043	0.0058
0.5	50	2×10^2	10	2×10^3	0.47	3.4	0.017	0.023
1	10	2×10^3	10	2×10^4	2.9	22	0.10	0.15
10	10	2×10^4	10	2×10^5	11.5	80	0.412	0.54
0.1	100	2×10^1	100	2×10^3	0.648[a]	3	0.023	0.020
0.5	50	2×10^2	100	2×10^4	1.9	12	0.068	0.081
1	10	2×10^3	100	2×10^5	9.7	64	0.35	0.43
1	10	2×10^3	100	2×10^5	9.4	60	0.34	0.40
10	10	2×10^4	100	2×10^6	55	312	1.97	2.10
0.1	100	2×10^1	1000	2×10^4	2.3	10	0.082	0.067
0.5	50	2×10^2	1000	2×10^5	8	38	0.29	0.26
1	10	2×10^3	1000	2×10^6	37	160	1.32	1.08
10	10	2×10^4	1000	2×10^7	207	742	7.41	5.00

(a) The last digit was estimated.

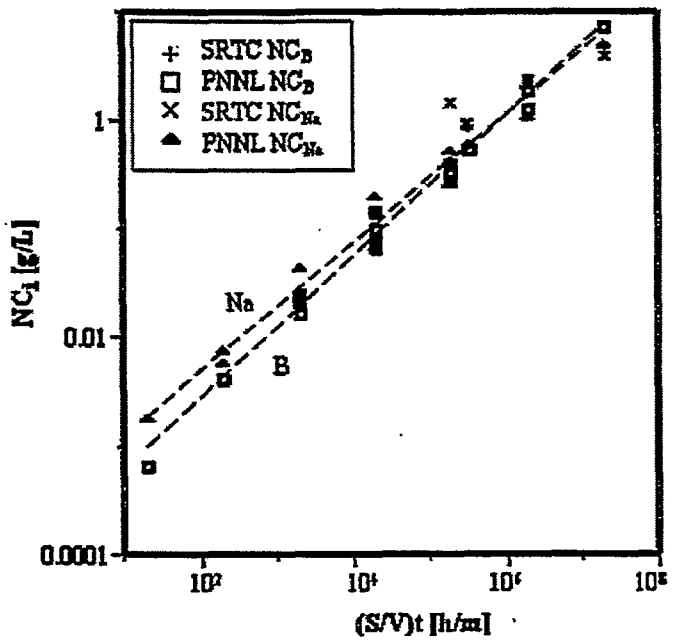


Figure 4-4. Relationships Between Normalized Boron and Sodium Releases, NC_i in g/L, as Functions of (S/V)t in h/m for HLP-54 Glass. The dotted lines represent the least-squares fits through the respective boron and sodium data.

4.1.5 HLP-55

A series of tests was also run at PNNL on the HLP-55 glass to examine the potential effects of S/V and time on PCT-B results. These results are summarized in Table 4-3. These PNNL data (including previously run PCT-A measurements [Kim et al. 1995]) and the SRTC data from this study are plotted on Figure 4-5. In this context, there is again no reason to believe that either the SRTC data from this study or the previous PNNL results are invalid.

Table 4-3. PNNL PCT-B Test Results for HLP-55

Glass (g)	H_2O (mL)	S/V (m^{-1})	Time, t (h)	(S/V)t (h/m)	B (mg/L)	Na (mg/L)	NC_B (g/L)	NC_{Na} (g/L)
0.1	100	2×10^1	1	2×101	0.024	0.33	0.0009	0.0022
0.5	50	2×10^2	1	2×10^2	0.2	1.7	0.0072	0.012
1	10	2×10^3	1	2×10^3	1.5	10.5	0.054	0.071
10	10	2×10^4	1	2×10^4	11	57	0.39	0.38
0.1	100	2×10^1	10	2×10^2	0.17	1.2	0.0061	0.0081
0.5	50	2×10^2	10	2×10^3	0.65	4.2	0.023	0.028
1	10	2×10^3	10	2×10^4	4.7	31	0.17	0.21
10	10	2×10^4	10	2×10^5	49	220	1.75	1.48
0.1	100	2×10^1	100	2×10^3	0.851(	3.9	0.030	0.026
0.5	50	2×10^2	100	2×10^4	2.8	16	0.10	0.11
1	10	2×10^3	100	2×10^5	27	134	0.97	0.90
1	10	2×10^3	100	2×10^5	23.2[a]	106	0.83	0.714
10	10	2×10^4	100	2×10^6	166	708	5.94	4.77
0.1	100	2×10^1	1000	2×10^4	3.2	14	0.11	0.094
0.5	50	2×10^2	1000	2×10^5	12	53	0.43	0.36
1	10	2×10^3	1000	2×10^6	74	277	2.65	1.87
10	10	2×10	1000	2×10^7	474	1580	17.0	10.6

(a) The last digit was estimated.

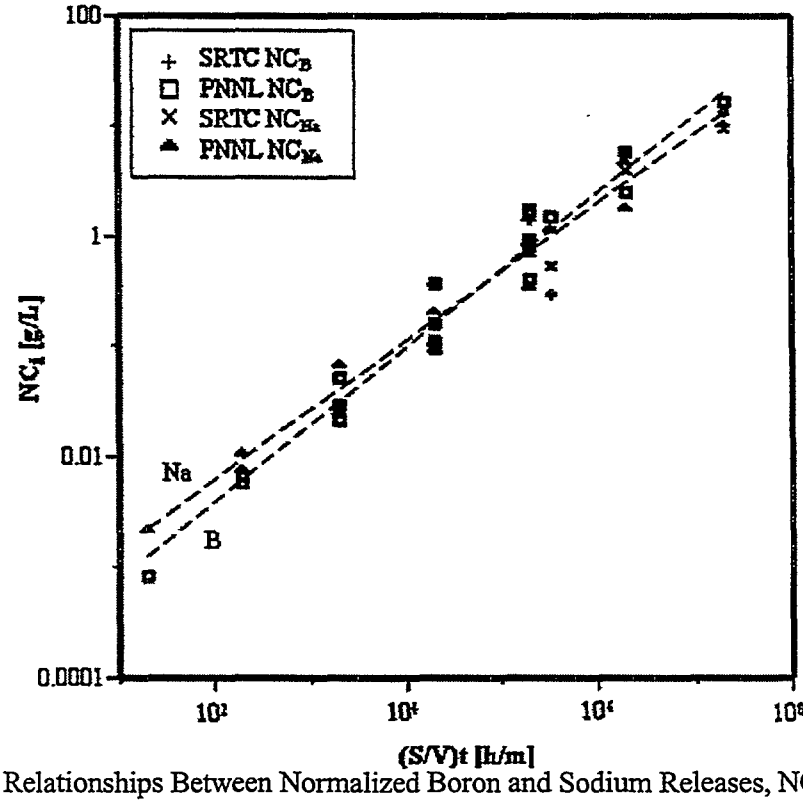


Figure 4-5. Relationships Between Normalized Boron and Sodium Releases, NC_i in g/L, as Functions of (S/V)t in h/m for HLP-55 Glass. The dotted lines represent the least-squares fits through the respective boron and sodium data.

4.2 VHT Data

The response of HLP-46, -47, and -48 to the VHT were measured at PNNL at the beginning of the test program (starting in April 1999) and again at the end of the program (January 2000). The response of HLP-46, -47, -48, -54, and -55 to the VHT were measured at Argonne National Laboratory (ANL). These data are compared in this section. However, to add the appropriate context under which the data can be compared, we first discuss some key parameters of the test.

The amount of water available in the VHT reaction vessel for glass corrosion was found to be very important to the m_d of test samples. Tests with different amounts of water were conducted at 250°C and 300°C with the aim to determine the appropriate amount of water needed to conduct the test. The appropriate amount of water was defined as an amount of water that is

- sufficient to fully dissolve the amount of glass present during the test
- below the amount of water that would cause reflux and dripping of water from sample during the test (indicated by elevated pH in solution at the base of the vessel after test termination)[a].

Figure 4-6 shows the impact of water content on the m_d of HLP-48 subjected to the VHT for 1, 1.5, and 2 days at 250°C. Tests were conducted with amount of water ranging from 0.4 mL to 0.6 mL (0.6 mL is the amount calculated from steam tables for 100% RH plus 0.05 mL per sample in the vessel). There is an increase in m_d as the amount of water increases until 0.45 mL and then a decrease. The amount, 0.45 mL, was selected as the optimum amount of water for conducting the test at 250°C since it is the highest amount of water that did not show a pH rise. However, the rates were found to be relatively constant over a range of water contents from 0.45 mL to 0.6 mL, as shown in Figure 4-7.

[a] A pH rise in the solution at the bottom of the reaction vessel after termination of the VHT may indicate reflux has occurred during testing. However, there are other mechanisms that can cause a pH rise, such as a drop of H_2O from the sample during or after test termination and particles falling from the sample during the test or after termination. Therefore, we cannot conclude that reflux has occurred without additional evidence.

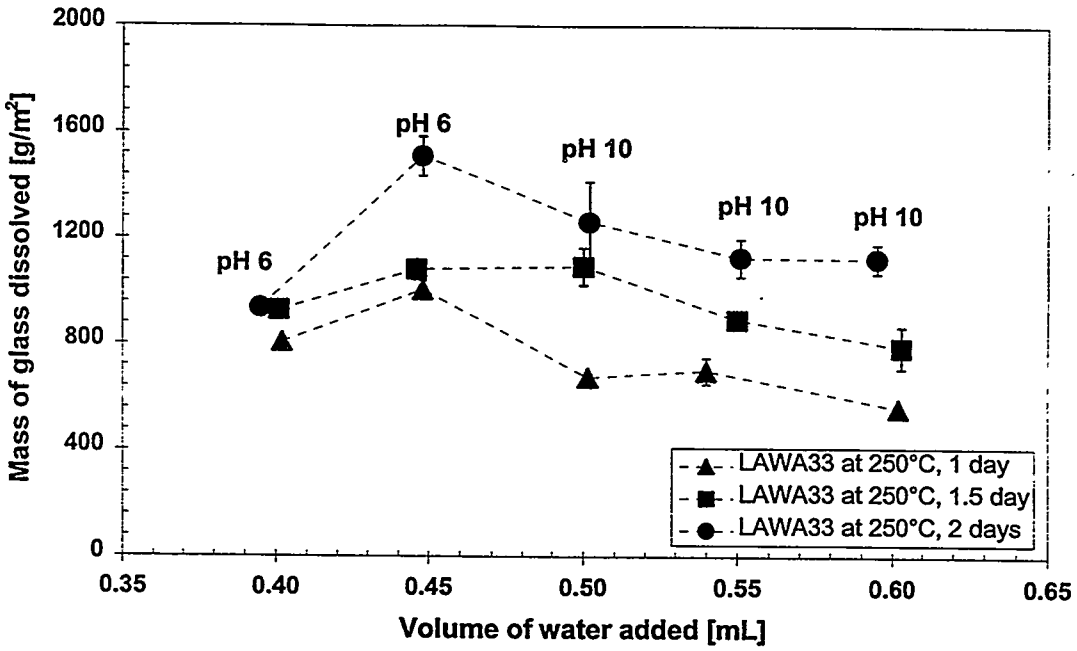


Figure 4-6. The m_d of HLP-48 as a Function of Volume of Water in the Vessel

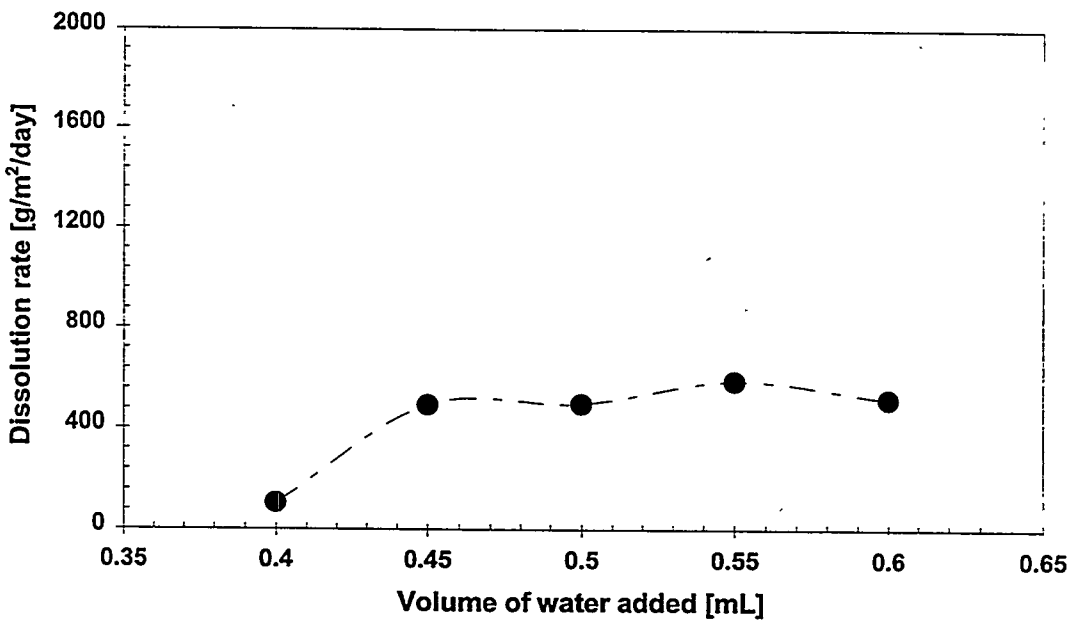


Figure 4-7. The rate of HLP-48 as a Function of Volume of Water in the Vessel

Since the rate is almost independent of the amount of added water, the only variable that changed during the test is the incubation time, which resulted in a change of the intercept in m_d vs. t, as shown in Figure 4-8. The intercept is decreased with increasing amount of water used in the test (except 0.4 mL, which had a significantly different rate).

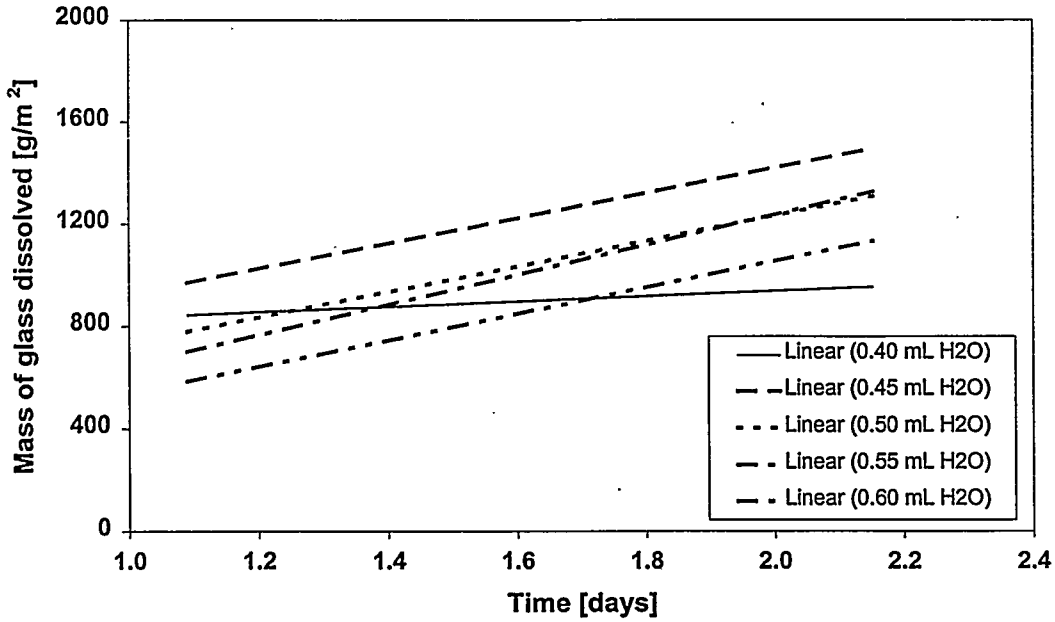


Figure 4-8. The m_d of HLP-48 as a Function of t for Different Volumes of Water

Figure 4-9 shows the impact of water content on the m_d of HLP-51 subjected to the VHT for 2 days at 300°C. Tests were conducted with the amount of water ranging from 0.7 mL to 1.5 mL (1.4 mL is the amount calculated from steam tables for 100% RH plus 0.05 mL per sample).

There is an increase in m_d as the amount of water increases towards 1 mL and then m_d values are constant even with different reaction times. This may be caused by a change in dissolution mechanism because the alteration layers on samples from tests with greater than 1 mL of water flaked off during the test. The difference in reaction layers formed with 1.4 mL and 0.9 mL can be seen visually in Figure 4-10.

The amount of 0.8 mL was selected as the optimum amount of water for conducting the test at 300°C since it is the highest amount of water that did not have elevated pH in the post-test solution. Again, the rates were found to be relatively constant over a range of water contents (from 0.8 mL to 1.2 mL), as shown in Figure 4-11.

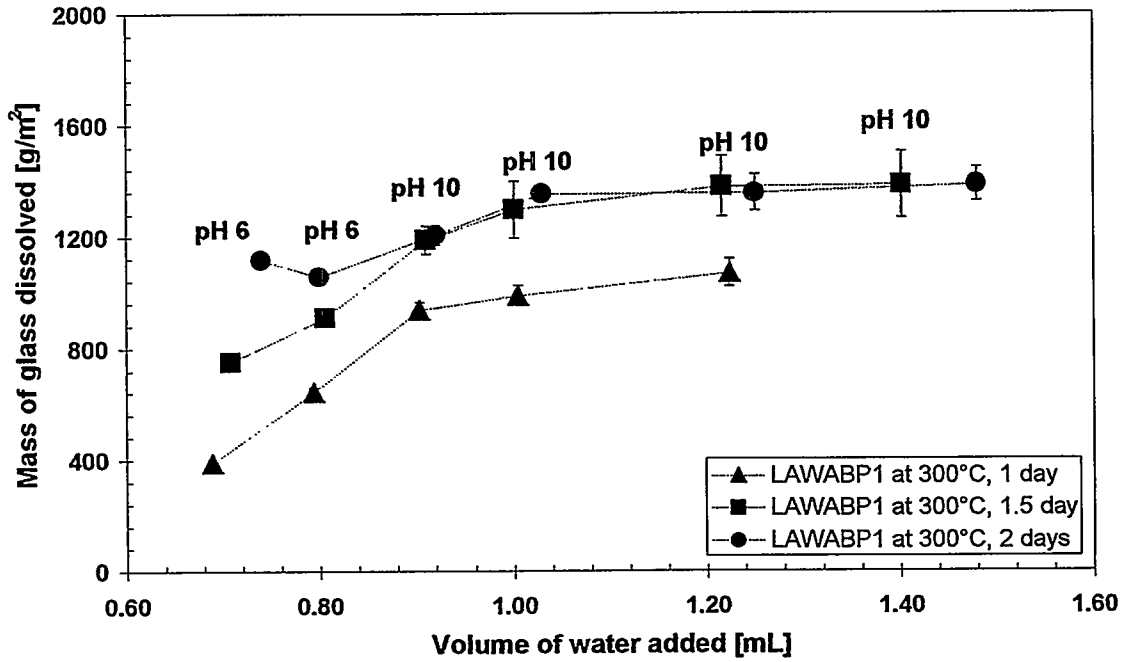
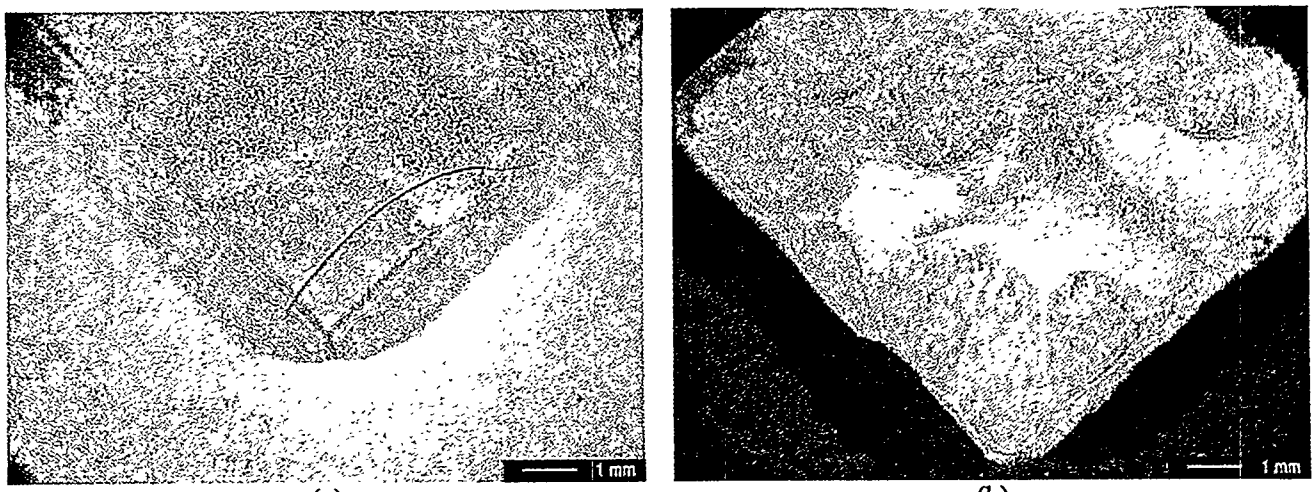


Figure 4-9. The m_d of HLP-51 as a Function of Volume of Water in the Vessel



(a) (b)

Figure 4-10. HLP-51 Glass after 1.5 Days at 300°C with (a) 0.9 mL and (b) 1.4 mL of Water

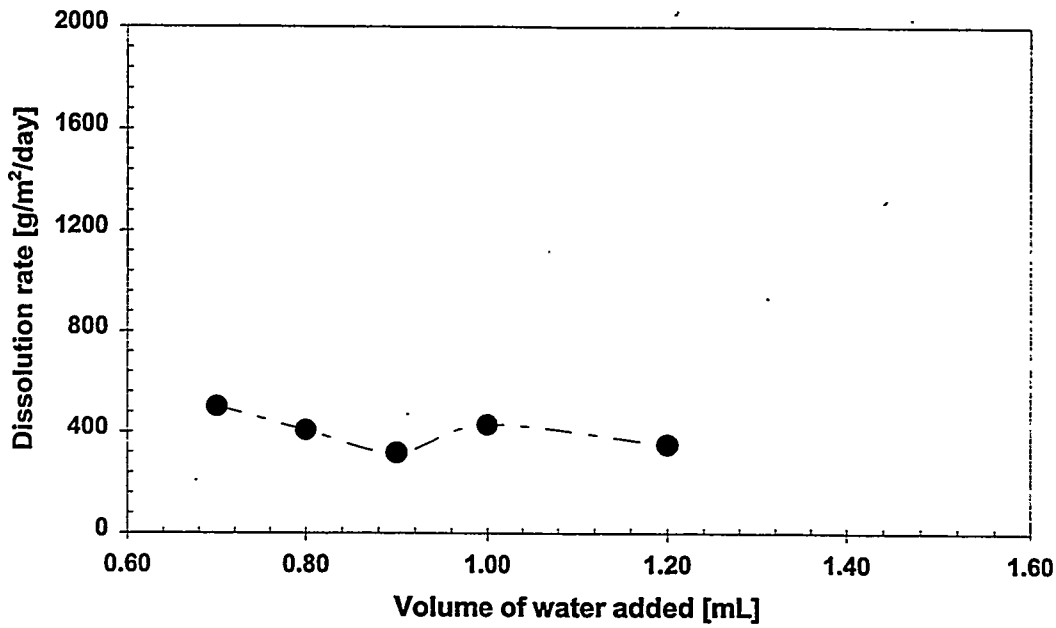


Figure 4-11. The rate of HLP-51 as a Function of Volume of Water in the Vessel

Unlike in tests at 250°C, the intercept of m_d-t increased with decreasing amount of water used in the test (except 0.7 mL, which showed a different rate), as shown in Figure 4-12.

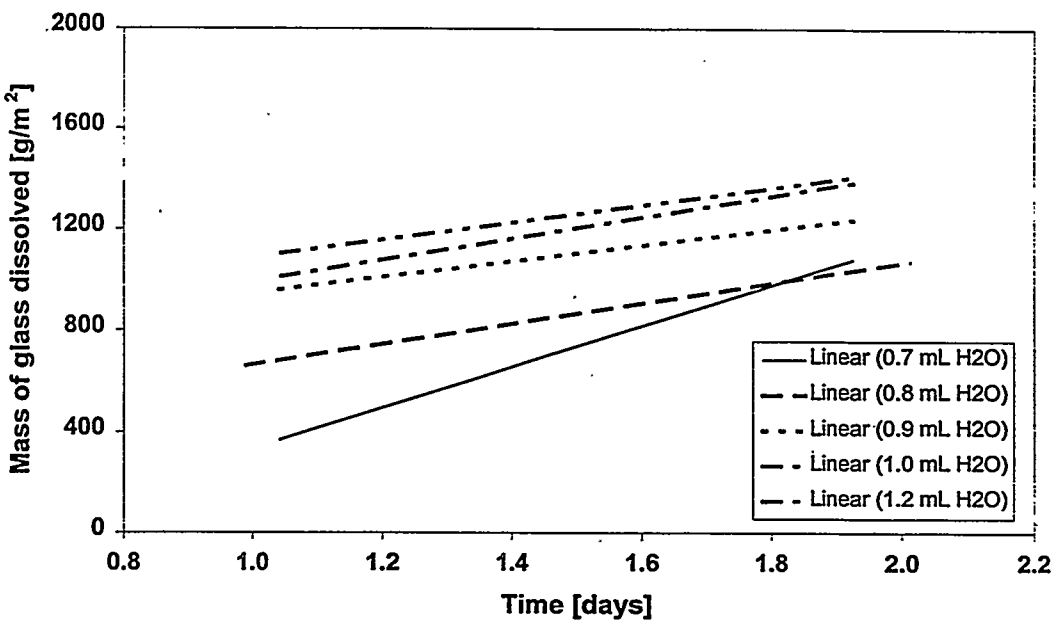


Figure 4-12. The m_d of HLP-51 as a Function of t for Different Volumes of Water

It was shown that the amount of water used to conduct VHT affects the intercept of the m_d vs. t line and results in a difference in measured m_d values. This observation plays an important role when combining results from different test, as will be shown later. However, because the amount of water showed the opposite effect on the intercept at 250°C and 300°C, further research is required to identify the phenomenon(a) responsible for the difference. These tests are currently in progress.

HLP-46 was tested at 175°C in May 1999 and then again in January 2000 to ensure reproducibility. In both series of tests, one sample was loaded in each 22-mL reaction vessel with 0.14-mL of water. Figure 4-13 compares the m_d of the samples as a function of time. Qualitatively, the results compare very well. As only two samples were measured in January, we do not make a quantitative comparison of the rate.

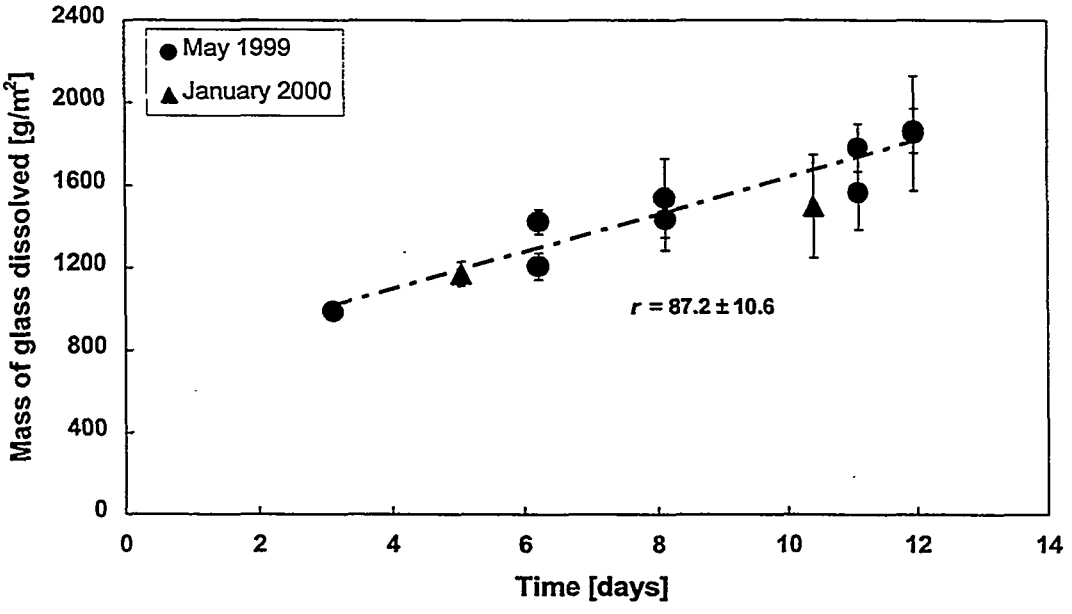


Figure 4-13. The m_d as a Function of t for HLP-46 at 175°C Tested at PNNL in May 1999 and January 2000

The VHT response of HLP-47 at 200°C was measured in September 1999 and again in December 1999. In September, one sample of HLP-47 and one sample of HLP-53 were tested together in each vessel along with 0.25 mL of water. The resistance of HLP-53 to the VHT is low, and the samples were completely corroded after 3 days at 200°C. As HLP-47 is still within its incubation period at 3 days, the amount of water available to HLP-47 during this testing was reduced by absorption and alteration-product formation in the fully corroded HLP-53 sample. The tests performed in December 1999 contained only one sample per vessel with 0.20 mL of water. Figure 4-14 compares the m_d for these different tests. The m_d of those samples tested in September 1999 are clearly lower than those tested in December 1999. However, the rate is nearly identical (4.7% difference). The difference in m_d may be due to the difference in available water to corrode the HLP-47 samples.

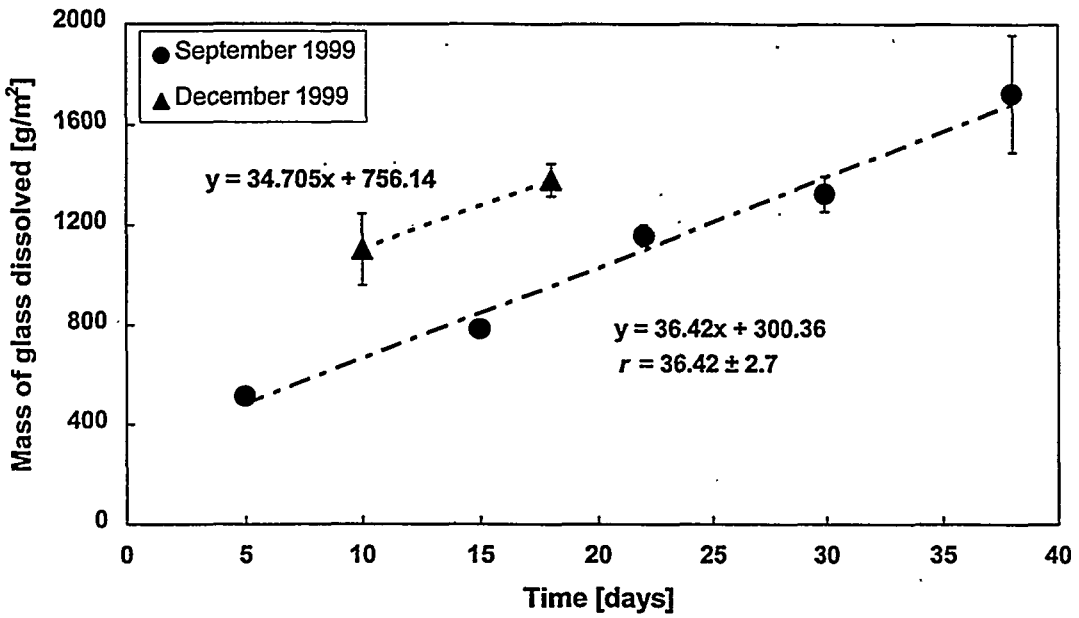


Figure 4-14. The m_d as a Function of t for HLP-47 at 200°C

The VHT response of HLP-48 at 200°C was measured in May 1999 and again in December 1999. In May, one sample of HLP-48 and one sample of HLP-51 were tested together in each vessel along with 0.25 mL of water. The rate of HLP-51 is roughly 10× lower that of HLP-48. After roughly 25 days, HLP-48 is completely corroded while HLP-51 is still within its incubation period. The amount of water available for corrosion of HLP-48 was much larger due to the low rate of HLP-51. The tests performed in December 1999 contained only one sample per vessel with 0.20 mL of water. Figure 4-15 compares the m_d for these different tests. The m_d of those samples tested in May 1999 are clearly higher than those tested in December 1999. However, the rate is nearly identical (1.2% difference). The difference in m_d is attributed to the difference in available water to corrode the HLP-48 samples.

Before comparing the VHT data generated by ANL (HLP-46, -48, -54, and -55), we have to evaluate the differences between experimental methods used. Table 4-4 summarizes the differences in test procedures. Two major differences between the two procedures are the manner in which alteration extent is measured and the sample size.

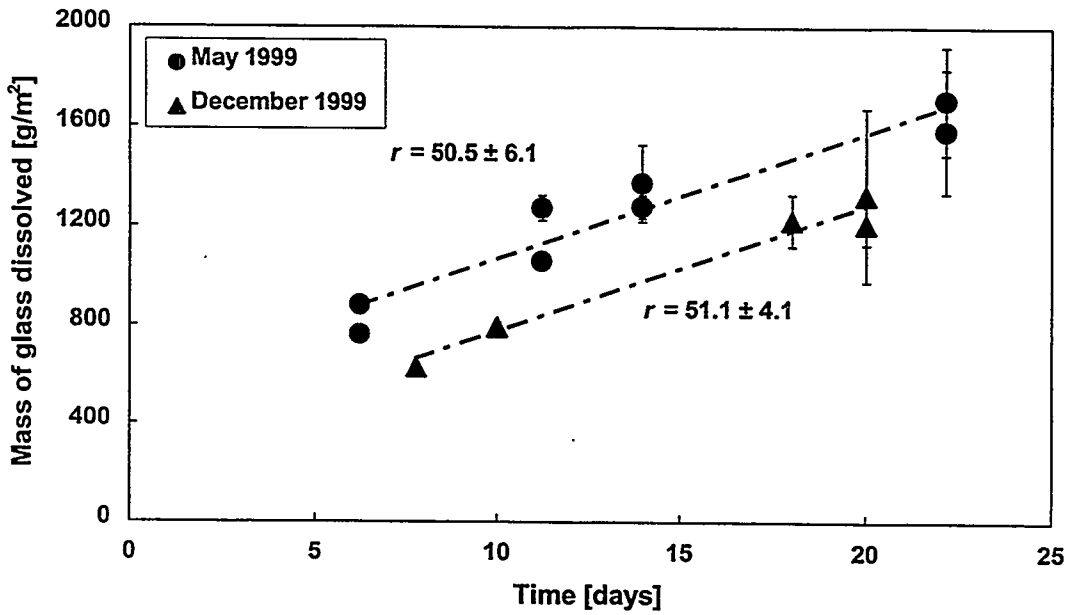


Figure 4-15. The m_d as a Function of t for HLP-48 at 200°C Tested at PNNL in May 1999 and December 1999

Table 4-4. Comparison of Test Parameters

	ANL	PNNL
Sample dimensions	Core drilled sample diameter = 10 mm thickness = 1 mm	Square sample width = 10 mm length = 10 mm thickness = 1.5 mm
Surface finish	One side polished to 600 grit	All sides polished to 600 grit
Mass of glass present during the test [g]	0.20	0.39
m_d- mass of glass per unit surface area [g/m^2]	1300	1950
Mass of water added to 22 mL vessel with 2 samples at		
T=150°C	0.15	0.15
T=175°C	0.20	0.19
T=200°C	0.25	0.25
Evaluation method	Thickness of alteration layer	Thickness of remaining glass layer

The results measured according to the ANL procedure were recalculated to yield the amount of glass dissolved in g/m^2 to be directly compared to PNNL results. Because the thickness of the sample before the test is 1000 μm, and the maximum amount of glass to be dissolved is 1300 g/m^2, we can assume that 0 μm corresponds to 0 g/m^2 of dissolved glass and 1000 μm thick alteration layer corresponds to 1300 g/m^2 of dissolved glass. This approximation enables direct comparison of the results.

Figure 4-16 compares the ANL and PNNL results for HLP-46 subjected to the VHT at 175°C. The ANL tests were performed with two samples per vessel and 0.20 mL of water, and the PNNL tests were performed with one sample per vessel and 0.14 mL of water. Qualitatively, there is good agreement between the m_d values. However, the calculated rate for the ANL data, 35.8 g/m^2/d,[a] is significantly lower than that for the PNNL data.

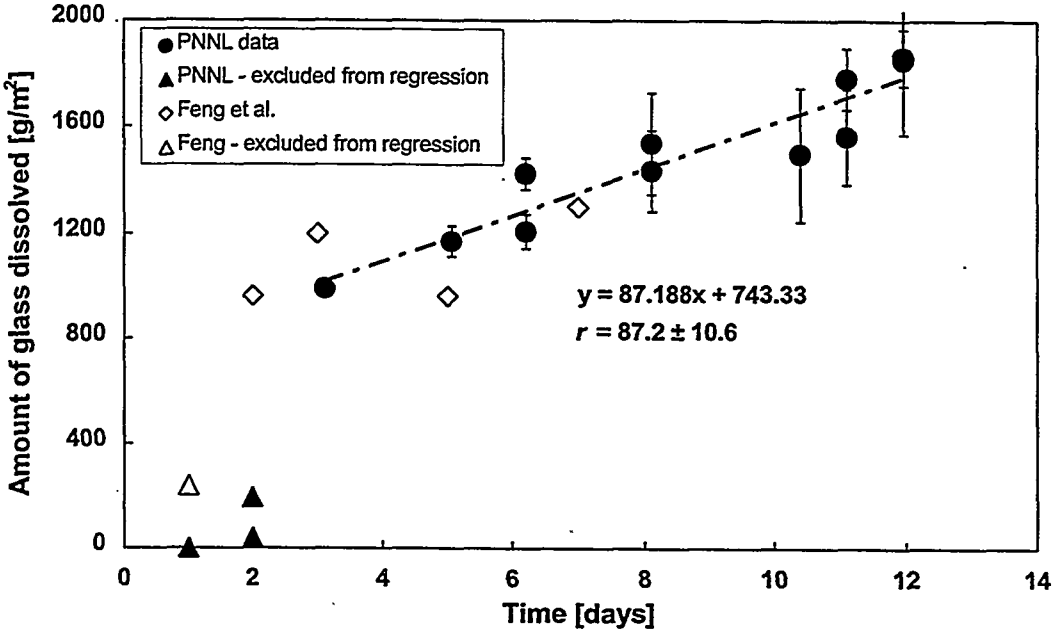


Figure 4-16. Comparison of VHT Results on HLP-46 at 175°C

Figure 4-17 compares the ANL and PNNL results for HLP-48 subjected to the VHT at 150°C. The ANL tests were performed with two samples per vessel and 0.15 mL of water, and the PNNL tests were performed with one sample per vessel and 0.10 mL of water. The m_d values are in very good agreement and confirm the existence of the incubation time ending at roughly 70 days. Insufficient data were generated at ANL to estimate a rate.

[a] The rate value for ANL data was calculated by linear regression of the calculated m_d vs. t for the data taken at times of 2 days and longer.

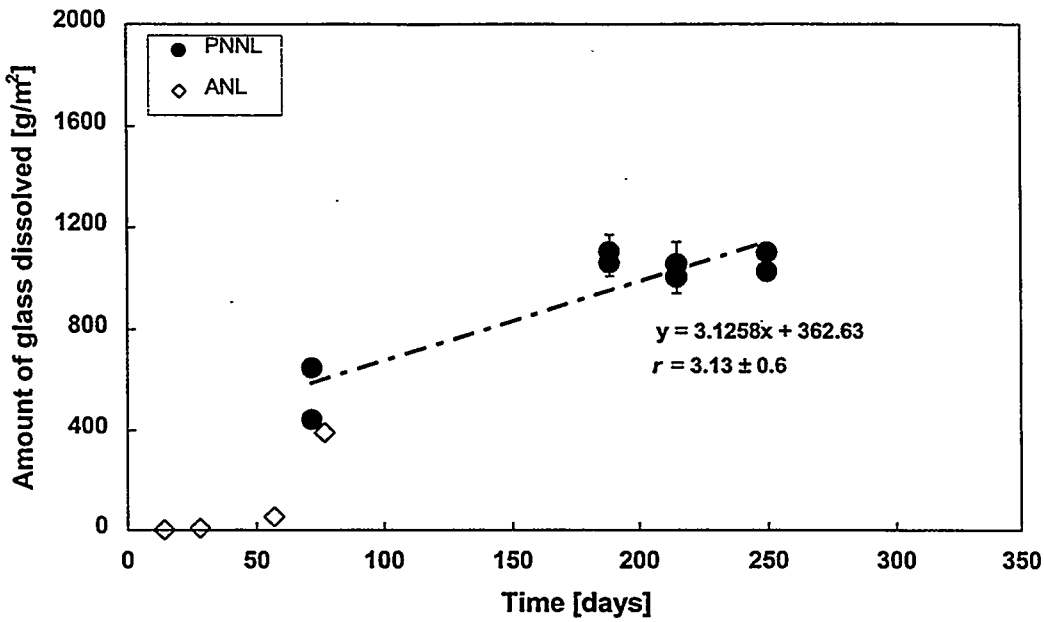


Figure 4-17. Comparison of VHT Results on HLP-48 Glass at 150°C

Comparison of PNNL and ANL results on HLP-48 tested at 175°C is displayed in Figure 4-18. These results do not show very good agreement. The ANL tests were performed with two samples per vessel and 0.20 mL of water, and the PNNL tests were performed with one sample per vessel and 0.14 mL of water. The m_d values determined from the ANL samples are significantly lower than those determined from the PNNL tests. The samples tested for less than 15 days are likely in the incubation stage of alteration (see Section 3.6.1 for discussion of the stages). There is no explanation for the differences in the results from the sample tested for 28 and 15 days. Insufficient data were generated at ANL to estimate a rate.

The alteration rates measured at multiple times within the same laboratory are similar (e.g., within 6.5%). The measured m_d values are dependent upon test conditions (such as the amount of water in the vessel and the presence and alteration rate of additional samples in the same vessel). Qualitative comparison between VHT results from ANL and PNNL show that the results are similar. Insufficient data exist to quantitate the similarity between the measurements at the two sites.

4.3 Repeated Glasses

Four glasses, HLP-01, -25, -26, and -43, with the same target compositions were included in the test matrix to give an indication of the reproducibility of the test methods involved. The variation in the property measurements of these glasses results from many sources, including batching, melting, and heat treating (at different sites) as well as property measurement. The PNNL replicate glasses were fabricated in the following order: HLP-26, HLP-43, and HLP-25. HLP-01 was the only glass fabricated at SRTC. The timing of the tests on these glasses is discussed below along with their properties.

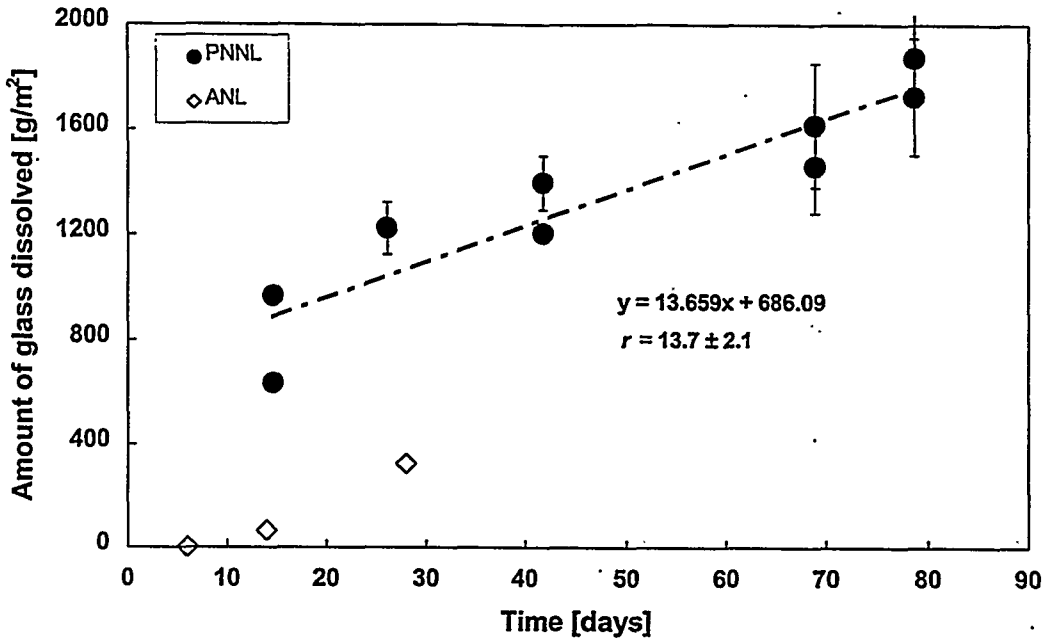


Figure 4-18. Comparison of VHT Results on HLP-48 Glass at 175°C

4.3.1 Composition

The chemical compositions of the four repeated or "center" glasses (HLP-01, HLP-25, HLP-26 and HLP-43) were measured and are provided in Table 4-5. Analysis of the variance or standard deviation in the measured compositional values provides insight into reproducibility of the batching and analytical measurements. Comparisons among the mean measured compositional values to the targeted values provide an indication of how well the targeted composition was reproduced. Examination of the differences among component measurements and targeted concentrations (on a glass-by-glass basis) can provide some insight into the possibility of either gross batching or measurement errors.

The relative differences for the major oxide components presented in Table 4-5 indicate that reasonably good agreement between batching and chemical analysis was achieved. For the majority of the oxide components, the mean concentration was consistent with the targeted value (i.e., the relative difference was 5.33% or less). This was not the case with Fe_2O_3 and Cr_2O_3 where contamination from the grinding vessel was indicated, and the measured values were significantly higher than targeted. This was also not the case for Na_2O where the relative difference between the mean measured and targeted concentrations was approximately 8%. Further examination of this and the compositional data for the other glasses, however, indicates that the Na_2O measurement values may be biased low since in almost all cases measured Na_2O values were lower than targeted. The measured SiO_2 concentrations were also consistently lower than the target values, although the difference (in means) was only approximately 2.6%. A more detailed analysis of variance is planned for these "replicate" glasses.

An examination of the relative standard deviations for the major constituents of the four glasses represented in Table 4-5 indicates that there was good precision in the measured glass concentrations relative to the results from the LRM round-robin study (Ebert and Wolf 1999). That is, despite the fact that these batches were fabricated in separate batches in different laboratories, the relative standard deviations in the measured glass concentrations for these four glasses are generally lower than those from

the LRM study. Considering the likely errors in the concentration measurements, it would be difficult to distinguish amongst these glasses based upon their measured compositions.

Table 4-5. Target Compositions (in mass% of oxides) and Measured Compositions (in mass% of oxides) for the Replicate Hanford LAW Product-Acceptance (HLP) "Center" Glasses (Li_2O, Cl, SO_3, P_2O_5, F, ReO_2, and MoO_3, not included here, can be found in Table A-1)

Glass ID	Description	SiO_2	Al_2O_3	B_2O_3	Fe_2O_3	TiO_2	ZnO	ZrO_2	MgO	Na_2O	K_2O	CaO	Cr_2O_3	La_2O_3
HLP-01	Measured	48.8	7.04	8.92	6.52	3.00	1.4	1.54	1.41	18.4	0.4	0.0	0.25	0.02
HLP-25	Measured	47.2	6.76	10.1	6.27	2.66	1.4	1.48	1.54	18.5	0.4	0.0	0.21	0.02
HLP-26	Measured	46.8	6.68	9.43	5.97	2.86	1.4	1.50	1.45	18.2	0.4	BD	0.21	BD
HLP-43	Measured	48.4	6.69	9.85	6.23	2.86	1.4	1.50	1.33	18.5	0.4	0.0	0.23	BD
Mean	Measured(M)	47.8	6.79	9.58	6.25	2.84	1.4	1.50	1.43	18.4	0.4		0.22	
Target	Center (C)	49.07	7.00	10.00	5.50	3.00	1.5	1.50	1.50	20.00	0.4	0.0	0.08	0.00
Diff	$\Delta = C - M$	1.27	0.21	0.42	-0.75	0.16	0.0	0	0.07	1.6	-0.0	0.0	-0.14	
Diff (%)	100%(Δ/C)	2.59	3.00	4.20	-13.64	5.33	4.0	0	4.67	8.00	-4.8		-175	
Std Dev	Measured	0.82	0.15	0.45	0.20	0.12	0.0	0.02	0.08	0.12	0.0		0.02	
Rel Std Dev (%)	Mean Measured LRM	1.7	2.2	4.7	3.2	4.2	2.8	1.3	5.3	0.65	6.3		7.7	
Rel Std Dev (%)	(Ebert and Wolf 1999)	2.62	3.75	4.37	13.48	13.00	n/a	6.99	9.00	6.07	33.0	15.9	11.58	

BD – below detection limits

4.3.2 Density

Glass densities were measured in numerical order. The densities of repeated glasses are compared in Table 4-6. Figure 4-19 gives a comparison of the densities of repeated glasses with a two-standard-deviation range. The density of HLP-01 appears to be significantly above those of HLP-26 and HLP-43. The range of all other repeated glasses overlap.

Table 4-6. Density and Standard Deviation of Repeated Glasses in g/cm^3

Glass	Density	St.Dev.
HLP-01	2.6493	0.0020
HLP-25	2.6409	0.0018
HLP-26	2.6418	0.0018
HLP-43	2.6354	0.0026
Min	2.6354	0.0018
max	2.6493	0.0026
St. Dev.	0.0057	

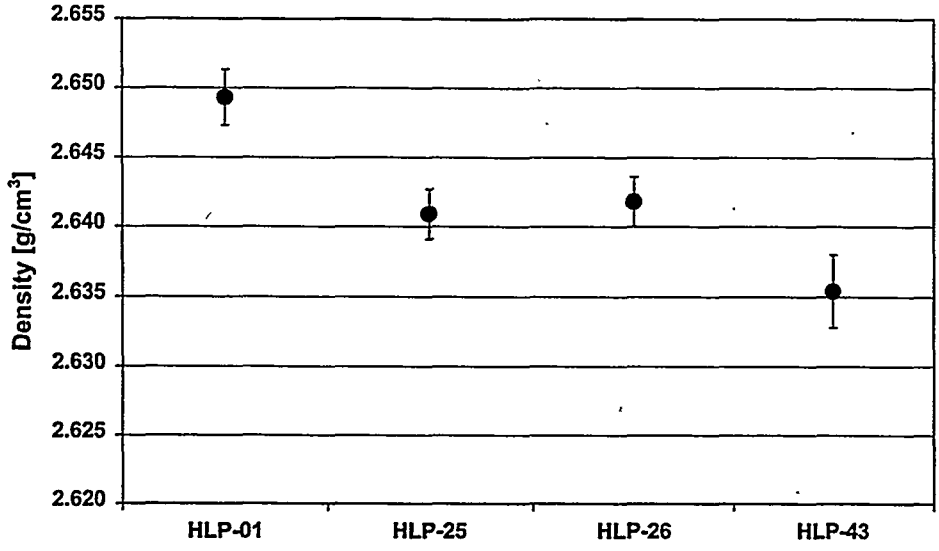


Figure 4-19. Density Range (2 standard deviations) for Repeated Glasses

4.3.3 PCT

Four of the HLP glasses (namely, HLP-01, -25, -26, and -43) were batched at either PNNL or SRTC to the same target composition. In each case, these glasses were only repeated in a very broad sense. HLP-25 was batched at SRTC, and the remaining three glasses (i.e., HLP-01, -26, and -43) were batched at PNNL. Both PCT-A (i.e., in triplicate for 165 h in stainless steel vessels) and PCT-B series (i.e., one per each glass at 10, 100, and 1000 h in Teflon® vessels) were conducted at SRTC for these glasses. Thus there were numerous effects (e.g., glass to glass, vessel type, etc.) that might have impacted the measured responses.

To simplify the analysis of such an unbalanced set of data (i.e., unbalanced in the sense of experimental design), the PCT-A results were initially examined as there is a wealth of information on the uncertainties involved with these tests. Furthermore, the possible impacts due to either vessel type (i.e., whether the system is "open" or "closed") or S/V can be assumed negligible for solely PCT-A. Because the differences among the boron and sodium concentrations for these four glasses are likely indistinguishable based upon Table 4-5, the PCT-A results for the four "replicate" glasses are illustrated in Figure 4-20. These results indicate significant differences in PCT responses from glass to glass (as evidenced by lack of overlap, differences in means, and Tukey-Kramer statistical comparisons[a]) when the concentrations of boron and sodium expected in the test solutions are assumed to be the same. From a cursory examination of Figure 4-20, this effect appears to not be the result of laboratory-to-laboratory variations as the PCT responses for the single glass (i.e., HLP-25) batched at SRTC is well within the range of the responses for the three glasses (i.e., HLP-01, -26, and -43) batched at PNNL. (Note that the relative positions for the log-transformed boron and sodium concentrations from the four repeat glasses would be the same as those shown in Figure 4-20.) More data will be necessary to perform a more complete statistical examination of the components of variance for these glasses.

[a] JMP® Reference Guide: Statistics and Graphics Guide, Version 3.1. SAS Institute Inc., Cary, NC, USA.

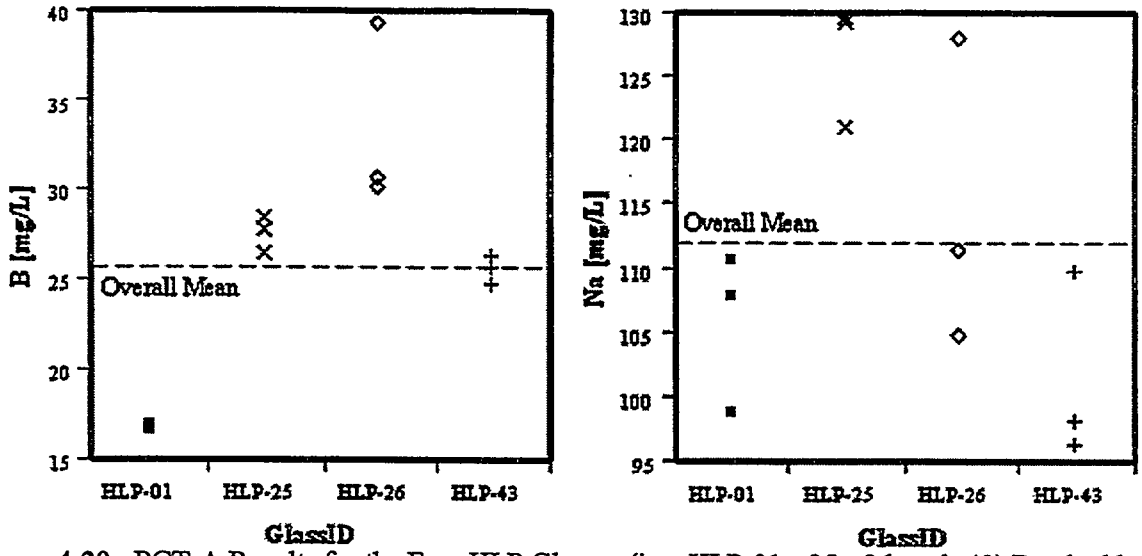


Figure 4-20. PCT-A Results for the Four HLP Glasses (i.e., HLP-01, -25, -26, and -43) Batched by PNNL and SRTC to the Same Target Composition. HLP-25 was fabricated at SRTC and the remaining three were prepared at PNNL. The dotted lines represent the overall means of the data.

However, even though the measured concentrations for B and Na for the four replicate glasses appear to be statistically indistinguishable; they do vary both from their corresponding targets and mean concentrations. However, as illustrated in Figure 4-21, accounting for these composition differences (by using normalizing releases) does not fully explain the differences noted previously. That is, there appear to be other differences between the PCT-A responses for these "replicate" glasses (indicated by lack of overlap, differences in means, and Tukey-Kramer comparisons) that cannot be explained by solely compositional differences. As expected, these same differences manifest themselves in the PCT-B data. Additional designed experiments can be performed to determine the probable sources of these differences.

The PCT-A data for the three glasses (i.e., HLP-01, -26, and -43) fabricated at PNNL can be examined to estimate glass-to-glass and within-glass (or residual) variance components. These are provided in Table 4-7. These results indicate that the variance structures for the boron and sodium data appear to be different for this very limited sample set. Also the residual errors for both the boron and sodium PCT-A data (i.e., 12.0 and 8.2%, respectively)[a] are somewhat larger than would be expected, based upon historical information for glasses measured by the same laboratory. (Note that the relative positions for the log-transformed NL_B and NL_{Na} values from the four repeat glasses would be the same as those shown in Figure 4-20.) Additional designed experiments can be performed to examine the cause of these larger than expected variance components.

[a] Note that these residual errors compare favorably to those (i.e., 17.5 and 8.7% for boron and sodium, respectively) presented in Section 3.5.3, which were necessary to describe the likely errors in corrosion-rate estimates.

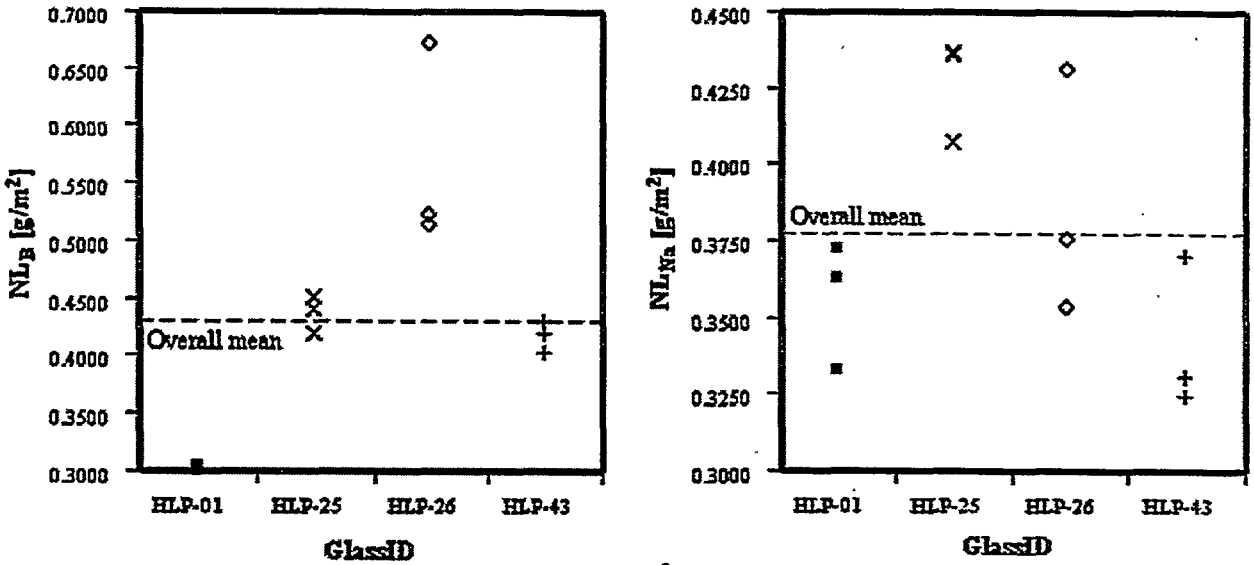


Figure 4-21. Normalized PCT-A Results, NL_i in g/m^2, for the Four HLP Glasses (i.e., HLP-01, -25, -26, and -43) Batched by PNNL and SRTC to the Same Target Composition. HLP-25 was fabricated by SRTC, and the remaining three were prepared by PNNL. The dotted line represents the overall mean of the data.

Table 4-7. PCT-A Variance Components Estimates for the PNNL "Replicate" Glasses

			Variance			% Rel. Standard Deviation		
	N	Mean	Glass	Residual	Total	Glass	Residual	Total
B	9	25.17	63.69	9.09	72.78	31.71	11.98	33.89
Na	9	107.15	19.73	77.72	97.45	4.15	8.23	9.21

4.3.4 VHT

The rate measured by VHT is obtained from several samples tested at different times; therefore, measurements were not performed in a specific glass number order. However, an effort was made to stagger the testing of the repeated glasses. Table 4-8 lists the current VHT duration for repeated glasses, which ranges from 14 days for HLP-43 to 144 days for HLP-26. The measured rates for repeated glasses at 200°C and 300°C are compared in Table 4-8. Both sets of values are preliminary. As discussed in Section 3.6.2, the glasses with rates below 12 take very long to accurately measure and are currently uncertain. Figure 4-22 compares the m_d of these glasses measured at 200°C as a function of time. Once the test enters the linear $m_d - t$, it is difficult to distinguish between the alteration of these glasses, despite the large difference in rates reported in Table 4-8. In addition, the time to fully corrode the repeated glass at 300°C is less than 2 days. For such short-term tests, the amount of time required for samples to heat up to test temperature and cool to room temperature after testing is thought to become a significant fraction of the total test time and introduces error in the measurement. Figure 4-23 compares the m_d of these glasses measured at 300°C as a function of time. These glasses do not appear to have significant differences in their measured rates.

Table 4-8. Comparison of Rates (in $g/m^2/d$) and Test Durations for Repeated Glasses

Glass ID	*r* at 300°C	*r* at 200°C	200°C Test Duration (days)
HLP-01	505±80	4.26±0.75	117
HLP-25	655±166	5.7±0 (2 points)	70
HLP-26	686±94	2.56±0.84	144
HLP-43	id	id	14

id = insufficient data

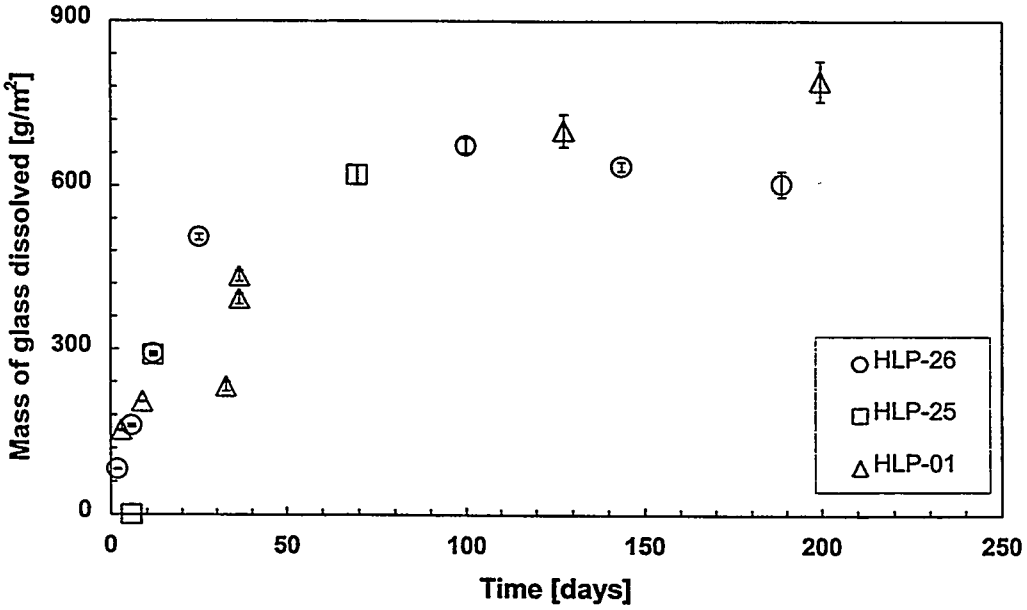


Figure 4-22. The m_d as a Function of Time for Repeated Glasses at 200°C

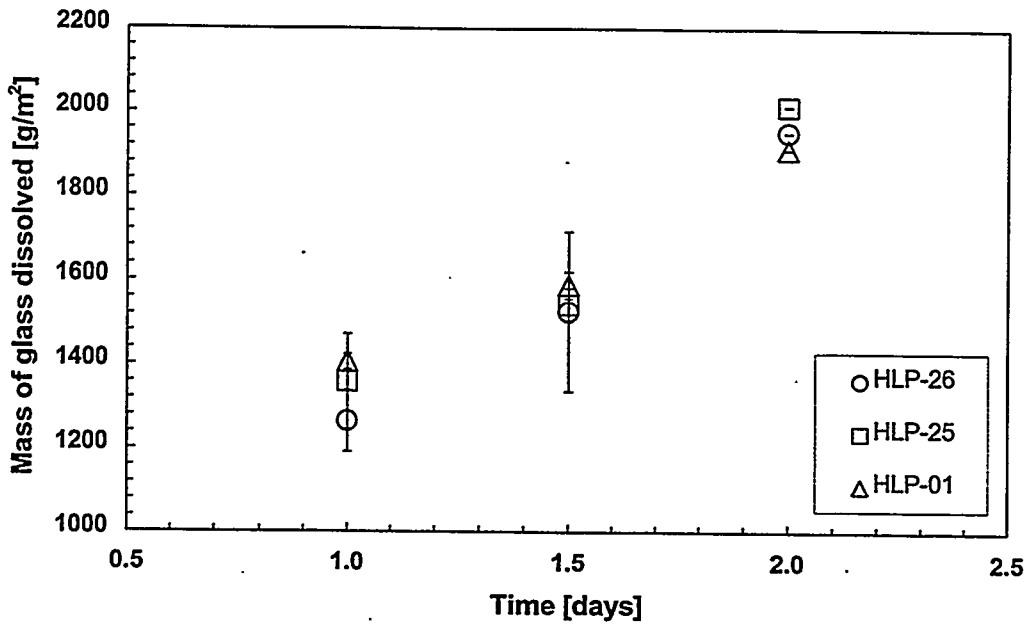


Figure 4-23. The m_d as a Function of Time for Repeated Glasses at 300°C

5.0 Comparison Between Test Methods

One of the goals of this task is to correlate the likely long-term durability of potential waste glasses, as measured with PCTs and VHTs, with the glass composition. Evaluation of the test results is in progress to identify correlations between the results of either PCTs or VHTs and the glass compositions. At this time, we can compare the PCT and VHT results directly to determine if the two data sets are correlated. The values of NL(B) and NL(Na) calculated from the results of PCT-B tests conducted at 20,000 m-1 for 10, 100, and 1000 hours and PCT-A tests conducted at 2000 m-1 for 7 days with the suite of 56 glasses and the alteration rates determined from VHTs conducted at 200°C are summarized in Table 5-1. The logarithms of the values of NL(B) and NL(Na) for PCT-B tests conducted at 20,000 m-1 for and 1000 hours are plotted against the logarithms of the alteration rates that were determined from the VHTs in Figure 5-1. (Note that an average dissolution rate could be calculated for the PCTs by dividing NL(i) by 41.7 days (which is equivalent to 1000 hours) to directly compare rates. This would shift all the data equally and not affect the correlation.) No correlation is seen between the test results. This is probably because the alteration progress is much greater in the VHTs than in the PCTs. In the VHTs, alteration phases have formed that are believed to control the solution chemistry and the glass dissolution rate. Alteration phases have not yet formed in the PCTs conducted for 1000 hours. If PCTs are conducted for sufficiently long durations or at higher temperatures so that alteration phases form, we expect that those test results would be correlated with the VHT results. This is because the solution chemistry would be influenced by the same phases, although differences in test temperatures may result in differences in the phase assemblages.

Table 5-1. Summary of Results from PCT (NL_i in g/m^2) and VHT of Heat-Treated Glasses

SampleID	Description	PCT-A		10-h PCT-B		100-h PCT-B		1000-h PCT-B		200°C VHT
		NL_B	NL_{Na}	NL_B	NL_{Na}	NL_B	NL_{Na}	NL_B	NL_{Na}	r ($g/m^2/d$)
HLP-01	Center	0.27	0.36	0.04	0.05	0.16	0.14	0.37	0.28	4.3
HLP-02	L Si	2.89	2.30	0.38	0.27	1.14	0.78	2.15	1.27	264.7
HLP-03	H Si	0.29	0.32	0.03	0.05	0.14	0.13	0.31	0.22	1.0
HLP-04	I Si	1.95	1.18	0.14	0.01	0.77	0.49	1.56	0.90	18.3
HLP-05	L Al	1.28	0.85	0.09	0.09	1.36	0.85	3.09	1.74	2.5
HLP-06	H Al	0.31	0.30	0.02	0.04	0.10	0.09	0.14	0.13	1.6
HLP-07	I Al	0.31	0.32	0.03	0.05	0.12	0.11	0.25	0.20	13.8
HLP-08	L B	0.33	0.44	0.02	0.06	0.12	0.15	0.17	0.26	7.2
HLP-09	H B	0.51	0.47	0.04	0.05	0.24	0.16	0.81	0.45	0.9
HLP-10	I B	0.35	0.38	0.02	0.05	0.13	0.14	0.33	0.21	3.6
HLP-11	L Fe	0.47	0.43	0.06	0.07	0.47	0.31	0.83	0.52	5.4
HLP-12	H Fe	0.41	0.34	0.03	0.05	0.14	0.12	0.27	0.22	14.4
HLP-13	I Fe	0.46	0.44	0.03	0.06	0.23	0.18	0.50	0.33	1.3
HLP-14	L Ti	0.72	0.56	0.05	0.07	0.39	0.27	0.72	0.41	13.2
HLP-15	H Ti	0.35	0.36	0.02	0.05	0.13	0.14	0.27	0.21	1.1
HLP-16	L Zn	0.37	0.37	0.04	0.06	0.20	0.16	0.39	0.28	1.4
HLP-17	H Zn	0.45	0.42	0.03	0.05	0.18	0.16	0.39	0.25	9.6
HLP-18	L Zr	0.52	0.47	0.04	0.06	0.24	0.19	0.53	0.33	16.1
HLP-19	H Zr	0.28	0.30	0.02	0.04	0.11	0.11	0.20	0.17	0

SampleID	Description	PCT-A		10-h PCT-B		100-h PCT-B		1000-h PCT-B		200°C VHT
		NL_B	NL_{Na}	NL_B	NL_{Na}	NL_B	NL_{Na}	NL_B	NL_{Na}	r (g/m^2/d)
HLP-20	L Mg	0.38	0.34	0.03	0.05	0.15	0.14	0.28	0.21	8.7
HLP-21	H Mg	0.60	0.48	0.05	0.06	0.30	0.21	0.58	0.37	4
HLP-22	L Na	0.25	0.24	0.01	0.03	0.10	0.08	0.20	0.13	1.5
HLP-23	H Na	0.98	0.78	0.08	0.11	0.42	0.35	0.70	0.50	15.9
HLP-24	I Na	0.34	0.36	0.02	0.04	0.14	0.12	0.30	0.20	3.1
HLP-25	Center	0.44	0.43	0.04	0.06	0.22	0.17	0.46	0.29	5.7
HLP-26	Center	0.53	0.38	0.04	0.06	0.21	0.16	0.41	0.29	0.6
HLP-27	HHHH	2.33	1.63	0.17	0.13	0.86	0.54	2.00	1.05	84.2
HLP-28	HHHL	0.27	0.21	0.02	0.03	0.10	0.07	0.21	0.11	1.7
HLP-29	HHLH	0.40	0.56	0.02	0.07	0.12	0.17	0.24	0.30	55.4
HLP-30	HHLL	0.16	0.24	0.00	0.03	0.05	0.06	0.11	0.10	11.5
HLP-31	HLHH	6.71	4.79	0.44	0.30	1.60	1.07	2.84	1.81	78.3
HLP-32	HLHL	0.48	0.35	0.04	0.04	0.23	0.14	0.61	0.28	4.5
HLP-33	HLLH	1.96	1.65	0.07	0.12	1.68	1.12	6.31	3.53	18.2
HLP-34	HLLL	0.38	0.36	0.01	0.04	0.14	0.11	0.29	0.17	id
HLP-35	LHHH	1.35	1.02	0.08	0.08	0.60	0.36	1.19	0.74	17.8
HLP-36	LHHL	0.43	0.34	0.03	0.04	0.19	0.12	0.73	0.39	13.5
HLP-37	LHLH	1.29	1.15	0.02	0.08	0.40	0.28	-	-	10.7
HLP-38	LHLL	0.40	0.36	0.02	0.05	0.12	0.10	0.19	0.18	6.7
HLP-39	LLHH	2.28	1.47	0.27	0.21	2.08	1.20	2.53	1.56	id
HLP-40	LLHL	0.90	0.69	0.06	0.07	0.81	0.46	1.58	0.93	1
HLP-41	LLLH	6.63	4.46	0.21	0.21	3.10	1.59	4.16	2.28	14.1
HLP-42	LLLL	0.68	0.54	0.03	0.06	0.56	0.33	3.73	2.11	0.2
HLP-43	Center	0.41	0.34	0.04	0.05	0.27	0.20	0.47	0.28	id
HLP-44	reduced	0.46	0.41	0.04	0.05	0.02	0.12	0.38	0.31	id
HLP-45	reduced	0.42	0.38	0.04	0.05	0.02	0.13	0.32	0.32	id
HLP-46	LD6-5412	0.05	0.50	0.02	0.00	0.10	0.26	0.30	0.43	254.6
HLP-47	LRM-1	0.53	0.53	0.06	0.08	0.32	0.26	0.92	0.61	36.4
HLP-48	LAW-A33	0.61	0.52	0.06	0.06	0.30	0.20	0.65	0.45	50.5
HLP-49	LAW-B	0.30	0.28	0.03	0.04	0.11	0.09	0.15	0.15	0.6
HLP-51	LAW-ABP1	0.34	0.38	0.04	0.06	0.04	0.13	0.33	0.32	4.4
HLP-52	HAN-28	-	5.65	-	0.02	-	2.24	-	7.21	1219.4
HLP-53	LAW-A23	-	-	-	-	-	-	-	-	552.6
HLP-54	L4-912	0.46	0.48	0.02	0.08	0.12	0.12	0.25	0.20	57
HLP-55	L4-99	0.16	0.28	0.07	0.09	0.30	0.21	0.70	0.48	24.7

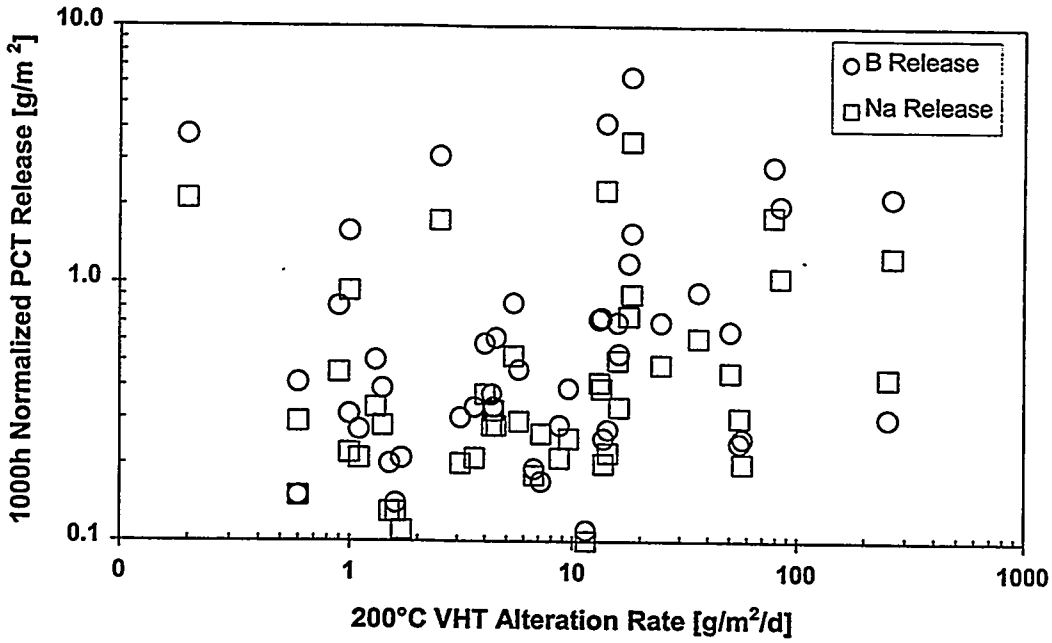


Figure 5-1. Comparison of 1000-h PCT Release to 200°C VHT Alteration Rate

6.0 Conclusions and Recommendations

A voluminous database of corrosion characteristics is being developed on a systematically designed matrix of simulated LAW glasses. The data are being generated with two types of corrosion tests: the PCT and the VHT. Data from triplicate PCT-A performed in stainless steel at a temperature of 90°C and an S/V of 2000 m^{-1} have been completed. Data from the PCT-B were generated for times of 10, 100, and 1000 h performed in Teflon® at a temperature of 90°C and an S/V of 20 000 m^{-1}. The short-term PCT-B releases for many of the test matrix glasses appear to follow a power-law function. That is to say that no significant rate increase was detected in any of the matrix glasses for times up to 1000 h. The ordering of glasses by PCT-B release data appears to be similar for times up to 1000 h.

The normalized PCT releases for the 1000-h tests range from 0.1 to 6.3 g/m^2 for boron and from 0.1 to 7.2 g/m^2 for sodium. Based upon the boron releases, the estimated release rates for these glasses range up to 1.0 and 0.1 $g/m^2/d$ for periods of 1 and 1000 h, respectively. The glasses with the highest boron release rates were HLP-31, -02, -39, -41, and -27 at 10 h and HLP-51, -41, -33, and -39, and -31 at 1000 h. For the sodium data, the release rates range up to 0.7 and 0.2 $g/m^2/d$ for periods of 1 and 1000 h, respectively. The glasses with the highest sodium release rates were HLP-31, -02, -41, -39,and -27 at 1 h and HLP-52, -33, -41, -42, and -31 at 1000 h. Insufficient information concerning the alteration products formed during PCT was available to make a comparison to the VHT or other data.

The VHT are still in progress. Preliminary rates have been determined for most glasses at 200°C. These rates range from 0.0 to 1219 $g/m^2/d$ and cover at least three orders of magnitude. The glasses are grouped into three categories based on their VHT rates at 200°C.

1. Glasses with low resistance to VHT – rates between 14 and 1219 $g/m^2/d$. For these glasses, we have good estimates of rate since the samples in this group are completely dissolved in roughly 100 days or less. This group contains 18 glasses, listed in Table 3-12.
2. Glasses with medium resistance to VHT – rates between 6 and 14 $g/m^2/d$. For these glasses, we have poor estimates of rate. The ranking of glasses within this category is likely to change; however, these glasses are clearly more resistant to VHT than glasses in Group 1 and less resistant to VHT than glasses in Group 3. This group has 9 glasses.
3. Glasses with high resistance to VHT – rates between 0 and 6 $g/m^2/d$. For these glasses, we have poor estimates of rate. The ranking of glasses within this category is likely to change; however, these glasses are clearly more resistant to VHT than glasses in Groups 1 and 2. This group contains 22 glasses.

Many alteration products were found to form on the matrix glasses during VHT. Analcime, sodium aluminum silicate hydrate, and sodium aluminum silicate boron hydroxide hydrate were the three most common major phases identified.

The effect of temperature on VHT response was investigated for selected glasses. The rate of alteration for HLP-46, -48, and -51 was found to follow the Arrhenius model with E_a values ranging from 87 kJ/mol to 98 kJ/mol. The assemblage of alteration phases was the same; however, the relative amount varied with temperature.

Little correlation was found between the release rates as measured by PCT and the alteration rates measured by VHT. This was expected since the stage of dissolution probed by VHT is much later than could be achieved with PCT at 90°C in 1000 h. The results from the two tests are expected to become more comparable once the corrosion extent in PCT is sufficiently advanced.

These data have led to three recommendations for future studies:

1. Data collection should continue on this program. The VHT rate should be determined for all matrix glasses at 200°C. The VHT rate should be determined at a number of temperatures ranging from 90°C to 300°C for selected glasses. The major alteration products formed on VHT samples should be identified. The PCT should be completed for matrix glasses with times up to 10,000 h. The alteration products formed on selected PCT samples should be identified and compared with those formed during VHT.
2. The PCT should be further accelerated by increasing test temperature. This will allow the similar reaction extents observed in VHT during similar time frames and potentially provide a link to lower temperature PCT data.
3. Further studies should be performed to determine the corrosion mechanisms that determine alteration rates by VHT and how they are impacted by temperature. The procedure for VHT should be further optimized and standardized.
4. The effect of composition on corrosion rate should be determined and modeled. It has been speculated that the glass stability with respect to conversion into key alteration products determines its long-term performance (McGrail et al. 1999). This data set, when sufficiently complete, can be used to test this theory. The impact of composition on the shorter-term PCT (up to 1000 h) can be assessed immediately. The impact of composition on the VHT and longer-term PCT (> 1000 h) can only be assessed once sufficient data are available.

7.0 References

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APPENDIX A

Target and Measured Composition Information for the HLP Glasses

Table A-1. Target Compositions (in mass% of oxides) and Measured Compositions (in mass% of oxides) for the HLP Glasses

Glass ID	Description[a]	SiO_2	Al_2O_3	B_2O	Fe_2O_3	TiO_2	ZnO	ZrO_2	MgO	Li_2O	Na_2	K_2O	CaO	Cl	SO_3	P_2O_5	Cr_2O_3	F	ReO_2	MoO_3	La_2O	Total
HLP-01	Center	49.07	7.00	10.00	5.50	3.00	1.50	1.50	1.50	0.00	20.00	0.41	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	48.80	7.04	8.92	6.52	3.00	1.46	1.54	1.41	BD	18.40	0.40	0.01				0.25				0.02	97.77
HLP-02	L Si	36.00	8.79	12.57	6.92	3.77	1.88	1.88	1.88	0.00	25.14	0.52	0.02	0.35	0.09	0.07	0.09	0.01	0.01	0.00	0.00	99.99
	Measured	35.20	8.95	11.40	7.63	3.86	1.88	1.88	1.81	BD	25.80	0.59	BD				0.22				BD	99.22
HLP-03	H Si	52.00	6.60	9.43	5.19	2.82	1.41	1.41	1.41	0.00	18.85	0.39	0.01	0.26	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.99
	Measured	51.50	7.08	9.09	6.06	2.89	1.43	1.36	1.36	BD	17.90	0.41	BD				0.19				BD	99.27
HLP-04	I Si	40.00	8.24	11.78	6.48	3.53	1.77	1.77	1.77	0.00	23.57	0.49	0.01	0.33	0.09	0.07	0.09	0.01	0.01	0.00	0.00	100.01
	Measured	40.40	8.74	12.40	7.72	3.56	1.74	1.74	1.68	BD	22.20	0.52	BD				0.24				BD	100.94
HLP-05	L Al	50.65	4.00	10.32	5.68	3.09	1.55	1.55	1.55	0.00	20.65	0.43	0.01	0.29	0.08	0.06	0.08	0.01	0.01	0.00	0.00	100.01
	Measured	47.30	4.24	10.30	6.80	3.17	1.56	1.45	1.45	BD	20.30	0.50	BD				0.27				BD	97.34
HLP-06	H Al	46.46	11.94	9.47	5.21	2.84	1.42	1.42	1.42	0.00	18.94	0.39	0.01	0.26	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.99
	Measured	44.60	12.30	8.89	5.96	2.94	1.42	1.35	1.34	BD	19.10	0.42	BD				0.14				BD	98.46
HLP-07	I Al	48.01	9.00	9.79	5.38	2.93	1.47	1.47	1.47	0.00	19.57	0.40	0.01	0.27	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.98
	Measured	50.30	9.79	9.45	6.32	3.15	1.56	1.55	1.46	BD	19.30	0.43	BD				0.20				BD	103.51
HLP-08	L B	51.25	7.31	6.00	5.75	3.13	1.57	1.57	1.57	0.00	20.89	0.43	0.01	0.29	0.08	0.06	0.08	0.01	0.01	0.00	0.00	100.01
	Measured	48.90	7.06	5.94	5.84	3.04	1.46	1.44	1.31	BD	19.50	0.56	BD				0.19				BD	95.24
HLP-09	H B	47.98	6.84	12.00	5.38	2.93	1.47	1.47	1.47	0.00	19.56	0.40	0.01	0.27	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.99
	Measured	43.30	7.12	11.80	6.40	2.87	1.51	1.22	1.29	BD	18.60	0.41	BD				0.21				BD	94.73
HLP-10	I B	50.16	7.15	8.00	5.63	3.06	1.53	1.53	1.53	0.00	20.45	0.42	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	99.98
	Measured	47.90	7.04	8.92	6.33	3.09	1.49	1.55	1.36	BD	18.40	0.48	BD				0.22				0.01	96.79
HLP-11	L Fe	51.93	7.41	10.58	0.00	3.17	1.59	1.59	1.59	0.00	21.17	0.44	0.01	0.29	0.08	0.06	0.08	0.01	0.01	0.00	0.00	100.01
	Measured	50.80	6.91	10.60	0.55	2.83	1.48	1.38	1.23	BD	18.20	0.40	BD				0.21				BD	94.59
HLP-12	H Fe	47.25	6.74	9.63	9.00	2.89	1.44	1.44	1.44	0.00	19.26	0.40	0.01	0.27	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.98
	Measured	44.80	6.44	10.20	9.20	2.75	1.45	1.34	1.23	BD	18.00	0.46	0.05				0.23				BD	96.15
HLP-13	I Fe	50.37	7.18	10.27	3.00	3.08	1.54	1.54	1.54	0.00	20.53	0.42	0.01	0.28	0.08	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	49.90	6.44	10.20	3.80	2.95	1.53	1.34	1.51	BD	18.50	0.41	0.06				0.24				BD	96.88
HLP-14	L Ti	50.59	7.21	10.31	5.67	0.00	1.55	1.55	1.55	0.00	20.62	0.43	0.01	0.29	0.08	0.06	0.08	0.01	0.01	0.00	0.00	100.02
	Measured	47.30	7.23	10.10	6.31	BD	1.55	1.43	1.53	BD	19.40	0.45	0.06				0.24				BD	95.60
HLP-15	H Ti	47.55	6.78	9.69	5.33	6.00	1.45	1.45	1.45	0.00	19.39	0.40	0.01	0.27	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.98
	Measured	47.80	6.52	9.72	6.69	5.91	1.51	1.06	1.54	BD	18.60	0.38	0.07				0.26				BD	100.06
HLP-16	L Zn	49.82	7.10	10.15	5.59	3.04	0.00	1.52	1.52	0.00	20.31	0.42	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	99.99
	Measured	53.40	6.79	10.00	6.84	3.18	BD	1.30	1.61	BD	19.00	0.41	0.08				0.26				BD	102.87
HLP-17	H Zn	47.82	6.82	9.75	5.36	2.92	4.00	1.46	1.46	0.00	19.50	0.40	0.01	0.27	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.98
	Measured	48.30	6.84	9.86	6.36	3.00	3.96	1.30	1.53	BD	18.40	0.36	BD				0.23				0.05	100.19
HLP-18	L Zr	49.82	7.10	10.15	5.59	3.04	1.52	0.00	1.52	0.00	20.31	0.42	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	99.99

Table A-1 Continued

Glass ID	Description[a]	SiO_2	Al_2O_3	B_2O	Fe_2O_3	TiO_2	ZnO	ZrO_2	MgO	Li_2O	Na_2	K_2O	CaO	Cl	SO_3	P_2O_5	Cr_2O_3	F	ReO_2	MoO_3	La_2O	Total
	Measured	46.20	7.45	10.20	6.22	3.18	1.54	BD	1.54	BD	19.20	0.43	BD				0.26				BD	96.22
HLP-19	H Zr	46.83	6.68	9.55	5.25	2.86	1.43	6.00	1.43	0.00	19.09	0.39	0.01	0.26	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.99
	Measured	48.20	6.94	9.63	6.40	2.98	1.50	5.64	1.47	BD	17.80	0.43	BD				0.25				BD	101.24
HLP-20	L Mg	49.82	7.10	10.15	5.59	3.04	1.52	1.52	0.00	0.00	20.31	0.42	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	99.99
	Measured	49.30	7.19	10.10	6.26	3.20	1.60	1.51	BD	BD	19.30	0.40	BD				0.26				BD	99.12
HLP-21	H Mg	47.82	6.82	9.75	5.36	2.92	1.46	1.46	4.00	0.00	19.50	0.40	0.01	0.27	0.07	0.05	0.07	0.01	0.01	0.00	0.00	99.98
	Measured	45.90	6.89	10.20	6.71	3.03	1.68	1.34	3.93	BD	18.30	0.37	BD				0.25				BD	98.60
HLP-22	L Na	51.67	7.37	10.53	5.79	3.16	1.58	1.58	1.58	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	100.00
	Measured	53.30	7.67	11.00	7.02	3.27	1.65	1.26	1.66	BD	15.40	0.30	BD				0.27				BD	102.80
HLP-23	H Na	47.13	6.72	9.61	5.29	2.88	1.44	1.44	1.44	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	100.00
	Measured	44.10	6.92	9.65	5.91	2.90	1.47	1.38	1.47	BD	21.50	0.42	BD				0.27				BD	95.99
HLP-24	I Na	50.37	7.18	10.27	5.65	3.08	1.54	1.54	1.54	0.00	18.00	0.37	0.01	0.25	0.07	0.05	0.07	0.01	0.01	0.00	0.00	100.01
	Measured	48.90	7.44	10.00	6.59	3.24	1.60	1.51	1.63	BD	17.20	0.40	BD				0.24				BD	98.75
HLP-25	Center	49.07	7.00	10.00	5.50	3.00	1.50	1.50	1.50	0.00	20.00	0.41	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	47.20	6.76	10.10	6.27	2.66	1.49	1.48	1.54	BD	18.50	0.41	0.01				0.21				0.02	96.65
HLP-26	Center	49.07	7.00	10.00	5.50	3.00	1.50	1.50	1.50	0.00	20.00	0.41	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	46.80	6.68	9.43	5.97	2.86	1.40	1.50	1.45	BD	18.20	0.43	BD				0.21				BD	94.93
HLP-27	HHHH	52.00	11.94	12.00	0.00	0.00	0.00	0.00	0.00	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	99.99
	Measured	50.40	12.00	12.30	0.60	BD	BD	BD	BD	BD	21.70	0.44	BD				0.26				BD	97.70
HLP-28	HHHL	52.00	11.94	12.00	3.10	1.69	0.84	0.84	0.84	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	99.99
	Measured	51.80	12.10	13.00	3.82	1.74	0.92	0.75	0.80	BD	15.10		BD				0.22				BD	100.25
HLP-29	HHLH	52.00	11.94	6.00	2.54	1.38	0.69	0.69	0.69	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	99.98
	Measured	49.50	11.80	6.51	3.12	1.41	0.73	0.64	0.69	BD	21.50	0.42	BD				0.25				BD	96.57
HLP-30	HHLL	52.00	11.94	6.00	5.64	3.07	1.54	1.54	1.54	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	100.01
	Measured	47.30	12.20	6.56	6.38	3.20	1.55	1.43	1.50	BD	15.40	0.29	BD				0.23				BD	96.04
HLP-31	HLHH	52.00	4.00	12.00	3.36	1.83	0.92	0.92	0.92	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	100.00
	Measured	48.90	4.20	12.30	4.30	1.78	0.94	0.70	0.84	BD	22.00	0.40	BD				0.24				BD	96.60
HLP-32	HLHL	52.00	4.00	12.00	6.46	3.52	1.76	1.76	1.76	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	100.00
	Measured	46.00	4.21	12.90	7.05	3.57	1.86	1.60	1.66	BD	15.70	0.31	BD				0.25				BD	95.11
HLP-33	HLLH	52.00	4.00	6.00	5.90	3.21	1.61	1.61	1.61	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	99.99
	Measured	52.30	4.16	6.44	6.92	3.23	1.67	1.31	1.57	BD	22.00	0.45	BD				0.30				BD	100.35
HLP-34	HLLL	52.00	4.00	6.00	9.00	4.90	2.45	2.45	2.45	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	99.99
	Measured	51.00	3.97	6.24	10.20	4.70	2.32	2.00	2.10	BD	14.30	0.30	BD				0.20				BD	97.33
HLP-35	LHHH	36.00	11.94	12.00	6.77	3.69	1.85	1.85	1.85	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	100.00
	Measured	36.00	11.50	12.10	7.47	3.61	1.83	1.73	1.68	BD	21.60	0.50	BD				0.22				BD	98.24
HLP-36	LHHL	36.00	11.94	12.00	9.87	5.38	2.69	2.69	2.69	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	100.00

Table A-1 Continued

Glass ID	Description[a]	SiO_2	Al_2O_3	B_2O	Fe_2O_3	TiO_2	ZnO	ZrO_2	MgO	Li_2O	Na_2	K_2O	CaO	Cl	SO_3	P_2O_5	Cr_2O_3	F	ReO_2	MoO_3	La_2O	Total
	Measured	35.60	12.00	12.60	10.30	5.49	2.69	2.44	2.41	BD	15.50	0.27	BD				0.17				BD	99.47
HLP-37	LHLH	36.00	11.94	6.00	9.31	5.07	2.54	2.54	2.54	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	99.99
	Measured	35.60	11.60	6.78	9.71	5.04	2.46	2.28	2.19	BD	21.80	0.40	BD				0.19				BD	98.05
HLP-38	LHLL	36.00	11.94	6.00	12.41	6.76	3.38	3.38	3.38	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	99.99
	Measured	35.40	12.00	6.09	12.60	6.88	3.33	3.38	3.15	BD	15.30	0.30	BD				0.17				BD	98.60
HLP-39	LLHH	36.00	4.00	12.00	10.13	5.52	2.76	2.76	2.76	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	99.98
	Measured	34.40	3.99	12.60	10.40	5.50	2.72	2.62	2.59	BD	21.50	0.45	BD				0.23				BD	97.00
HLP-40	LLHL	36.00	4.00	12.00	13.23	7.21	3.61	3.61	3.61	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	100.01
	Measured Q	34.10	4.01	12.70	13.40	7.28	3.62	3.16	3.46	BD	15.40	0.31	BD				0.20				BD	97.64
	Measured HT	35.10	4.26	12.40	13.40	7.65	3.73	3.44	3.65	BD	16.30	0.31	BD				0.18				BD	100.42
HLP-41	LLLH	36.00	4.00	6.00	12.67	6.90	3.45	3.45	3.45	0.00	23.00	0.47	0.01	0.32	0.08	0.06	0.09	0.01	0.01	0.00	0.00	99.97
	Measured	35.00	3.91	6.47	13.00	6.78	3.48	3.19	3.20	BD	21.60	0.43	BD				0.22				BD	97.28
HLP-42	LLLL	36.00	4.00	6.00	15.77	8.59	4.30	4.30	4.30	0.00	16.00	0.33	0.01	0.22	0.06	0.04	0.06	0.01	0.01	0.00	0.00	100.00
	Measured Q	35.10	4.09	6.32	16.80	8.31	4.29	3.27	4.05	BD	15.50	0.37	BD				0.19				0.10	98.39
	Measured HT	34.20	4.13	6.46	15.80	8.66	4.17	3.78	4.09	BD	15.60	0.42	BD				0.17				BD	97.48
HLP-43	Center	49.07	7.00	10.00	5.50	3.00	1.50	1.50	1.50	0.00	20.00	0.41	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	48.40	6.69	9.85	6.23	2.86	1.40	1.50	1.33	BD	18.50	0.47	0.01				0.23				BD	97.47
HLP-44	Reduced	49.07	7.00	10.00	5.50	3.00	1.50	1.50	1.50	0.00	20.00	0.41	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	48.30	6.93	9.97	6.07	3.12	1.51	1.22	1.46	BD	18.60	0.35	BD				0.21				BD	97.74
HLP-45	Reduced	49.07	7.00	10.00	5.50	3.00	1.50	1.50	1.50	0.00	20.00	0.41	0.01	0.28	0.07	0.06	0.08	0.01	0.01	0.00	0.00	100.00
	Measured	48.60	7.10	10.10	6.06	2.93	1.46	1.34	1.55	BD	18.50	0.34	BD				0.22				BD	98.20
HLP-46	LD6-5412	55.91	12.17	5.05	0.11	0.02	0.14	0.08	0.00	0.00	20.41	1.66	4.12	0.00	0.18	0.22	0.05	0.00	0.00	0.00	0.00	100.12
	Measured	57.70	11.70	5.50	0.49	BD	BD	BD	BD	BD	18.00	0.28	3.92				0.16				BD	97.75
HLP-47	LRM-1	54.37	10.00	8.00	1.00	0.10	0.00	1.00	0.10	0.10	20.00	1.50	0.50	0.80	0.20	0.50	0.20	1.00	0.00	0.00	0.01	99.38
	Measured	55.10	9.42	7.64	2.04	0.09	BD	0.94	0.11	0.12	18.90	1.40	0.52				0.32				BD	96.60
HLP-48	LAW-A33[b]	38.25	11.97	8.85	5.77	2.49	4.27	2.49	1.99	0.00	20.00	3.10	0.00	0.58	0.10	0.08	0.02	0.04	0.00	0.00	0.00	100.00
	Measured	36.40	11.50	8.93	6.37	2.45	4.10	2.04	1.83	BD	18.50	2.75	BD				0.14				BD	95.01
HLP-49	LAW-B29[b]	43.93	8.03	8.07	8.03	0.00	3.99	3.04	3.00	4.08	10.00	0.36	7.03	0.29	0.02	0.01	0.10	0.00	0.00	0.00	0.00	99.98
	Measured	41.10	7.76	8.74	8.71	BD	3.93	2.73	2.81	4.11	9.65	0.36	6.96				0.24				BD	97.10
HLP-51	LAW-ABP1	41.89	10.00	9.25	2.50	2.49	2.60	5.25	1.00	0.00	20.00	2.20	0.00	0.58	0.10	0.08	0.02	0.04	0.00	0.00	2.00	100.00
	Measured	41.20	9.68	9.26	2.94	2.37	2.51	3.90	0.92	BD	18.80	2.07	BD				0.14				1.94	95.73
HLP-52	HAN-28[b]	44.46	10.15	0.00	2.53	0.38	0.00	5.00	1.18	0.00	28.62	1.96	2.59	0.13	0.30	1.90	0.08	0.31	0.00	0.00	0.00	99.59
	Measured	45.80	9.63	0.10	3.00	0.37	BD	2.54	1.08	BD	27.50	1.80	2.51				0.21				BD	94.54
HLP-53	LAW-A23[b]	40.15	9.86	4.23	7.30	0.00	3.28	2.99	2.04	2.04	20.00	3.10	4.38	0.36	0.04	0.08	0.01	0.12	0.00	0.00	0.00	99.98
	Measured Q	40.80	9.79	4.54	7.52	BD	3.24	2.82	1.84	2.13	20.40	3.08	4.33				BD				BD	100.49
	Measured HT	39.50	9.31	5.46	7.67	BD	3.09	2.76	1.93	2.29	18.60	2.75	4.21				0.14				BD	97.71

Table A-1 Continued

Glass ID	Description[a]	SiO_2	Al_2O_3	B_2O	Fe_2O_3	TiO_2	ZnO	ZrO_2	MgO	Li_2O	Na_2	K_2O	CaO	Cl	SO_3	P_2O_5	Cr_2O_3	F	ReO_2	MoO_3	La_2O	Total
	Measured In	42.20	9.59	4.34	7.99	BD	3.07	2.79	1.85	2.11	18.70	2.98	4.27				BD				0.30	100.19
	Measured Out	43.50	9.49	4.26	8.12	BD	3.26	2.67	1.89	2.09	19.30	2.93	4.32				BD				BD	101.83
HLP-54	L4-912	56.78	12.00	9.00	0.00	0.00	0.00	0.00	0.00	0.00	20.00	0.33	0.00	0.09	0.32	1.19	0.04	0.21	0.00	0.00	0.01	99.97
	Measured	56.40	11.70	8.76	0.56	BD	BD	0.07	BD	BD	17.80	0.28	BD				0.16				BD	95.73
HLP-55	L4-99	59.78	9.00	9.00	0.00	0.00	0.00	0.00	0.00	0.00	20.00	0.33	0.00	0.09	0.32	1.19	0.04	0.21	0.00	0.00	0.01	99.97
	Measured	60.60	8.87	8.92	0.58	BD	BD	BD	BD	BD	17.70	0.32	BD				0.17				BD	97.16
HLP-56	LAW-A44b,[c]																					

(a) Levels of glass components are given as L – low, I – intermediate, and H – high for the components following the level; for four consecutive levels the components are SiO_2, Al_2O_3, B_2O_3, and Na_2O, respectively.
(b) Preliminary Hanford LAW glasses developed by Catholic University of America for BNFL Inc. HT – heat treated glass, Q – quenched glass, In – inside area of HT glass, Out – outside area of HT glass.
BD – below detection limits.
(c) Composition of LAW-A44 is proprietary.

APPENDIX B

PCT-A, PCT-B, and Corrosion Information for the HLP Glasses

APPENDIX B
Measured Concentrations in PCT-A Solutions

Table B-1. SRTC Mobile Laboratory Results for the Measured pH and Concentrations for the Hanford PCT-A Series. Results Reported on 9/18/1999, Test Temperature = 90°C, Test Duration = 165 h, (S/V) ≈ 2000/m, and Dilution Factor = 5/3.

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	Zn	Fe	B	Si	Mg	Ti	Zr	Al	Na
Blank	6.67	<0.040	0.025	<0.180	<0.180	<0.010	<0.010	<0.010	<0.200	<0.530
HLP-01	10.31	0.920	4.09	10.1	47.6	0.500	1.68	0.600	6.62	64.8
HLP-01	10.31	0.830	3.73	10.2	47.6	0.440	1.63	0.550	7.24	66.4
HLP-01	10.32	0.780	4.17	10.1	47.0	0.440	1.62	0.430	6.91	59.4
HLP-02	11.69	0.370	2.14	144	69.1	0.300	0.280	<0.100	16.1	499
HLP-02	11.68	0.260	1.53	130	64.0	0.260	0.320	<0.100	15.8	520
HLP-02	11.67	0.250	1.95	132	69.0	0.240	0.320	<0.100	16.4	525
HLP-03	10.23	1.04	4.49	11.2	54.0	0.550	1.88	0.760	6.73	60.4
HLP-03	10.21	0.830	4.20	9.39	50.4	0.510	1.77	0.620	5.98	53.5
HLP-03	10.22	1.09	4.70	9.96	53.3	0.590	1.92	0.720	6.65	49.4
HLP-04	11.3	1.08	3.94	87.9	69.6	0.860	1.46	0.600	13.3	244
HLP-04	11.29	1.30	4.41	82.3	67.1	0.850	1.67	0.790	12.2	252
HLP-04	11.29	1.26	4.39	86.5	70.2	0.910	1.53	0.610	12.9	245
HLP-05	10.31	0.580	2.82	47.9	117	0.390	0.890	0.380	<2.00	144
HLP-05	10.36	0.750	2.78	51.3	121	0.500	0.650	<0.100	<2.00	163
HLP-05	10.38	0.740	2.69	48.9	120	0.490	0.650	<0.100	<2.00	162
Blank	6.81	<0.040	0.022	<0.180	<0.180	<0.010	<0.010	<0.010	<0.200	<0.530
STD	n/a	<0.040	4.08	20.7	52.4	<0.010	<0.010	<0.010	3.98	87.3
HLP-06	10.21	0.860	3.88	11.8	47.9	0.470	1.55	0.590	13.2	53.8
HLP-06	10.31	0.820	3.92	10.6	47.2	0.420	1.49	0.490	13.0	49.0
HLP-06	10.3	0.900	4.27	10.7	51.5	0.510	1.65	0.710	13.7	47.9
HLP-07	10.28	0.850	3.84	11.6	47.8	0.490	1.52	0.600	8.87	54.9
HLP-07	10.29	0.930	4.08	11.4	49.8	0.510	1.64	0.620	9.60	57.1
HLP-07	10.3	1.00	4.43	11.4	49.7	0.520	1.78	0.660	9.98	54.1
HLP-08	10.85	1.10	4.79	7.43	61.8	0.690	1.93	0.800	8.44	81.5
HLP-08				Results are missing for this sample						
HLP-08	10.83	1.17	5.02	7.14	62.4	0.730	1.96	0.690	8.78	80.6
HLP-09	10.24	0.990	4.00	23.1	46.1	0.480	1.43	0.450	9.24	82.9
HLP-09	10.31	0.770	3.70	23.2	43.6	0.430	0.122	0.430	8.58	81.8
HLP-09	10.33	0.870	3.90	22.6	45.8	0.430	1.39	0.550	8.79	80.4
HLP-10	10.61	1.12	4.41	10.7	57.1	0.600	1.80	0.790	8.23	68.8
HLP-10	10.59	0.990	4.41	10.1	54.8	0.570	1.75	0.740	7.76	69.3
HLP-10	10.61	1.08	4.78	10.6	58.6	0.630	1.82	0.710	8.42	70.3
HLP-11	10.6	0.780	0.220	16.7	57.4	0.590	3.69	2.53	7.22	81.4
HLP-11	10.56	0.800	0.100	17.5	56.5	0.630	1.44	0.800	6.73	80.2
HLP-11	10.54	1.12	0.220	21.3	66.5	0.820	1.99	1.04	7.80	82.2
HLP-12	10.31	0.630	4.75	13.9	59.7	0.380	0.970	0.300	8.25	55.4
HLP-12	10.33	0.490	4.39	14.1	56.1	0.340	0.910	0.350	7.83	57.1
HLP-12	10.32	0.440	4.55	15.9	61.4	0.340	0.940	0.250	8.00	62.4
Blank	6.48	<0.040	<0.020	<0.180	<0.180	<0.010	<0.010	<0.010	<0.200	<0.530
STD	n/a	<0.040	4.13	20.9	50.7	<0.010	<0.010	<0.010	4.04	84.9
HLP-13	10.5	1.20	2.75	18.4	59.3	0.870	1.87	0.580	7.14	86.2
HLP-13	10.56	1.18	2.53	17.4	56.1	0.830	1.87	0.850	7.17	77.0
HLP-13	10.5	1.13	2.43	17.4	57.5	0.830	1.69	0.620	7.52	80.7
HLP-14	10.61	0.460	2.30	25.2	53.2	0.350	<0.100	0.190	6.43	100
HLP-14	10.65	0.460	2.29	26.8	54.1	0.300	<0.100	0.240	6.25	108

Table B-1 Continued

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	Zn	Fe	B	Si	Mg	Ti	Zr	Al	Na
HLP-14	10.65	0.650	2.55	31.1	62.8	0.470	<0.100	0.280	7.34	100
HLP-15	10.47	1.40	5.45	13.8	65.1	0.940	4.42	0.920	9.04	60.2
HLP-15	10.43	1.04	4.46	13.2	59.6	0.750	3.73	0.680	8.24	61.2
HLP-15	10.42	0.890	4.01	11.0	55.1	0.720	3.58	0.710	7.49	62.9
HLP-16	10.57	<0.400	6.04	14.5	58.6	1.03	2.31	0.700	8.25	67.1
HLP-16	10.54	<0.400	5.84	13.5	57.8	0.980	2.31	0.850	8.08	68.8
HLP-16	10.54	<0.400	6.11	14.2	57.7	1.01	2.30	0.460	8.35	66.4
HLP-17	10.45	0.830	1.20	17.4	55.7	<0.100	0.400	<0.100	5.94	75.2
HLP-17	10.47	0.560	0.970	16.0	50.7	<0.100	0.320	<0.100	5.47	73.9
HLP-17	10.45	0.690	1.09	15.3	52.8	<0.100	0.360	<0.100	6.34	72.2
HLP-18	10.63	2.71	8.21	19.6	71.1	1.83	3.53	<0.100	9.48	87.0
HLP-18	10.61	2.57	8.80	19.7	70.3	1.72	3.63	<0.100	8.88	82.1
HLP-18	10.6	2.65	8.58	20.2	68.6	1.79	3.45	<0.100	9.52	84.8
HLP-19	10.6	<0.400	0.580	8.90	42.5	<0.100	<0.100	<0.100	6.18	54.3
HLP-19	10.54	<0.400	0.450	11.6	44.0	<0.100	<0.100	<0.100	6.03	48.9
HLP-19	10.52	<0.400	0.480	9.21	43.3	<0.100	<0.100	<0.100	6.23	50.2
Blank	6.79	<0.040	<0.020	0.214	<0.180	<0.010	<0.010	<0.010	<0.200	<0.530
STD	n/a	<0.040	4.65	22.2	55.0	<0.010	<0.010	<0.010	4.34	82.6
HLP-20	10.57	1.72	7.69	15.8	61.7	<0.100	3.20	1.14	9.33	59.1
HLP-20	10.52	1.22	6.13	12.2	50.6	<0.100	2.70	1.24	7.14	63.8
HLP-20	10.52	1.58	7.18	14.9	60.2	<0.100	2.98	1.05	8.18	62.4
HLP-21	10.59	<0.400	0.820	20.8	58.9	0.240	0.220	<0.100	5.10	83.6
HLP-21	10.55	<0.400	1.55	22.8	67.0	0.470	0.340	<0.100	6.22	80.0
HLP-21	10.55	<0.400	0.840	22.0	63.2	0.260	0.240	<0.100	5.10	85.6
HLP-22	9.8	0.110	2.11	9.76	50.7	0.160	0.610	<0.100	6.02	36.4
HLP-22	9.82	0.280	2.18	10.4	57.1	0.240	0.790	0.250	7.18	31.8
HLP-22	9.79	<0.400	1.68	9.02	45.6	0.160	0.620	0.150	5.90	32.9
HLP-23	11.15	2.26	7.85	30.5	77.3	1.76	3.03	1.01	9.70	145
HLP-23	11.17	1.91	7.17	34.5	77.0	1.55	2.60	0.660	9.09	167
HLP-23	11.18	2.14	7.63	41.0	88.2	1.80	2.82	0.550	10.2	169
HLP-24	10.11	0.410	2.78	13.0	53.5	0.360	1.00	0.350	7.12	59.2
HLP-24	10.17	0.470	2.94	12.7	55.4	0.360	1.14	0.370	7.30	55.0
HLP-24	10.13	0.460	2.89	13.2	55.8	0.350	1.12	0.210	7.42	58.7
HLP-25	10.54	0.580	3.55	17.0	56.6	0.430	1.07	0.150	9.92	77.7
HLP-25	10.51	0.590	3.66	16.6	58.2	0.400	1.06	0.110	7.14	72.5
HLP-25	10.46	0.570	2.99	15.8	55.6	0.430	1.03	0.370	7.37	77.5
Blank	6.34	<0.040	<0.020	<0.180	<0.180	<0.010	<0.010	<0.010	<0.200	<0.530
STD	n/a	<0.040	4.49	23.9	55.8	<0.010	<0.010	<0.010	4.29	86.9
HLP-26	10.47	1.51	6.21	23.5	76.4	0.870	2.08	0.380	9.85	62.7
HLP-26	10.44	1.04	4.19	18.3	57.2	0.630	1.59	0.440	7.43	66.7
HLP-26	10.45	1.14	4.32	18.0	56.7	0.650	1.79	0.710	8.09	76.6
HLP-27	11.36	<0.400	<0.200	99.7	70.7	<0.100	<0.100	<0.100	16.5	325
HLP-27	11.36	<0.400	0.220	106	70.9	<0.100	<0.100	<0.100	16.6	329
HLP-27	11.35	<0.400	0.480	107	73.2	<0.100	<0.100	<0.100	17.0	347
HLP-28	9.65	<0.400	2.63	11.8	73.1	<0.100	0.950	0.100	10.5	33.7
HLP-28	9.57	0.400	3.15	12.1	49.0	<0.100	1.11	0.160	12.3	28.7
HLP-28	9.54	0.350	2.83	11.9	48.8	<0.100	1.09	0.190	12.1	26.6
HLP-29	11.05	0.860	3.77	8.03	62.2	0.550	1.57	0.280	15.4	90.9
HLP-29	11.07	1.02	4.69	8.74	67.1	0.680	1.74	0.440	17.8	104
HLP-29	11.08	2.37	5.08	10.2	114	1.03	2.55	1.51	27.1	159
HLP-30	10.14	1.04	1.73	3.76	46.2	0.210	0.890	<0.100	12.0	35.4
HLP-30	10.19	0.960	1.55	3.36	46.2	0.180	0.870	<0.100	11.8	36.8
HLP-30	10.19	0.890	1.30	3.42	45.2	0.170	0.850	0.140	11.1	32.5
Blank	5.61	0.109	0.077	<0.180	<0.180	<0.010	<0.010	<0.010	0.234	<0.530

Table B-1 Continued

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	Zn	Fe	B	Si	Mg	Ti	Zr	Al	Na
HLP-31	11.4	0.940	<0.200	297	457	0.290	0.140	<0.100	<2.00	985
HLP-31	11.4	0.190	<0.200	307	456	<0.100	<0.100	<0.100	<2.00	1000
HLP-31	11.4	0.920	<0.200	296	418	0.280	0.140	<0.100	<2.00	958
HLP-32	9.88	0.540	<0.200	21.0	49.1	<0.100	<0.100	<0.100	3.35	49.7
HLP-32	9.81	0.660	<0.200	23.3	60.0	<0.100	<0.100	<0.100	3.83	48.9
HLP-32	9.83	0.600	<0.200	19.7	53.0	<0.100	<0.100	<0.100	3.21	50.0
HLP-33	11.36	3.39	7.94	38.7	211	1.63	2.07	0.900	2.04	223
HLP-33	11.35	5.09	11.7	59.2	332	2.65	3.79	1.98	2.94	422
HLP-33	11.34	3.41	6.53	36.9	197	1.74	2.78	0.710	2.19	408
HLP-34	10.22	0.450	<0.200	8.95	53.8	<0.100	<0.100	<0.100	3.59	57.8
HLP-34	10.2	0.470	<0.200	8.47	57.9	<0.100	<0.100	<0.100	4.09	50.2
HLP-34	10.19	0.530	<0.200	8.07	56.1	<0.100	<0.100	<0.100	3.85	46.9
HLP-35	11.21	1.03	<0.200	63.6	43.7	0.320	0.260	<0.100	15.5	242
HLP-35	11.14	0.900	0.590	56.4	44.7	0.110	0.170	<0.100	15.3	211
HLP-35	11.12	0.940	<0.200	61.0	43.6	0.130	0.240	<0.100	16.0	178
HLP-36	9.92	0.530	<0.200	20.0	32.4	<0.100	<0.100	<0.100	12.2	47.8
HLP-36	9.86	0.580	<0.200	18.5	<0.100	<0.100	<0.100	<0.100	12.7	47.6
HLP-36	9.83	0.580	<0.200	18.6	31.0	<0.100	<0.100	<0.100	11.6	51.2
HLP-37	11.61	7.99	14.0	28.7	77.5	4.34	<0.100	<0.100	50.5	222
HLP-37	11.6	8.14	14.2	29.1	80.3	4.71	<0.100	<0.100	49.8	235
HLP-37	11.58	8.67	14.9	28.9	85.7	4.84	<0.100	<0.100	49.5	248
Blank	5.39	0.106	<0.020	0.343	<0.180	<0.010	<0.010	<0.100	<0.200	<0.530
STD	n/a	<0.040	4.04	20.8	53.3	<0.010	<0.010	<0.010	3.78	83.3
HLP-37Q	11.47	0.610	<0.200	14.3	61.6	<0.100	<0.100	<0.100	22.1	158
HLP-37Q	11.43	0.510	<0.200	14.1	61.0	<0.100	<0.100	<0.100	23.0	150
HLP-37Q	11.44	0.670	<0.200	13.9	57.9	<0.100	<0.100	<0.100	21.7	148
HLP-38	10.55	0.350	<0.200	9.00	36.8	<0.100	<0.100	<0.100	14.4	62.4
HLP-38	10.54	0.320	<0.200	9.00	36.2	<0.100	<0.100	<0.100	14.6	43.1
HLP-38	10.54	0.330	<0.200	8.65	38.4	<0.100	<0.100	<0.100	14.1	49.3
HLP-38Q	10.61	0.310	<0.200	8.64	34.6	<0.100	<0.100	<0.100	13.6	49.0
HLP-38Q	10.57	0.260	<0.200	8.26	34.5	<0.100	<0.100	<0.100	13.6	49.6
HLP-38Q	10.57	0.350	<0.200	8.77	35.2	<0.100	<0.100	<0.100	13.9	54.1
HLP-39	11.48	0.460	<0.200	106	83.2	<0.100	<0.100	<0.100	4.53	306
HLP-39	11.45	0.450	<0.200	102	78.2	<0.100	<0.100	<0.100	4.04	283
HLP-39	11.44	0.380	<0.200	97.8	74.9	<0.100	<0.100	<0.100	3.71	312
HLP-40	10.05	0.370	<0.200	39.8	38.6	<0.100	<0.100	<0.100	2.06	100
HLP-40	10.05	0.320	<0.200	38.9	40.0	<0.100	<0.100	<0.100	2.03	96.2
HLP-40	10.06	0.350	<0.200	42.0	40.7	<0.100	<0.100	<0.100	2.48	100
HLP-40Q	10.02	0.270	<0.200	34.7	40.0	<0.100	<0.100	<0.100	2.53	85.8
HLP-40Q	10.03	0.310	<0.200	34.8	40.3	<0.100	<0.100	<0.100	2.53	84.8
HLP-40Q	10.04	0.210	<0.200	33.7	38.8	<0.100	<0.100	<0.100	2.16	88.2
Blank	5.62	0.083	<0.020	0.263	<0.180	<0.010	<0.010	<0.010	<0.200	<0.530
HLP-41	12.17	2.93	3.31	152	223	2.58	<0.100	<0.100	4.15	915
HLP-41	12.22	1.33	0.710	148	210	0.780	<0.100	<0.100	3.51	876
HLP-41	12.22	1.51	0.960	145	211	0.970	<0.100	<0.100	3.18	950
HLP-42	10.85	0.200	<0.200	16.6	50.1	<0.100	<0.100	<0.100	4.20	81.6
HLP-42	10.86	0.200	<0.200	14.7	47.4	<0.100	<0.100	<0.100	4.01	73.1
HLP-42	10.89	0.290	<0.200	14.3	46.4	<0.100	<0.100	<0.100	4.03	76.6
HLP-42Q	11.01	0.250	<0.200	20.4	50.7	<0.100	<0.100	<0.100	2.93	93.8
HLP-42Q	10.98	0.210	<0.200	19.1	47.7	<0.100	<0.100	<0.100	2.68	91.2
HLP-42Q	10.98	0.250	<0.200	19.8	48.5	<0.100	<0.100	<0.100	2.69	92.7
HLP-43	10.54	1.87	4.12	14.7	50.0	0.630	1.89	0.570	7.54	65.7
HLP-43	10.47	2.05	4.77	15.3	51.7	0.550	1.90	0.560	7.54	58.7
HLP-43	10.47	1.82	3.70	15.7	52.2	0.480	1.84	0.590	7.65	57.6

Table B-1 Continued

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	Zn	Fe	B	Si	Mg	Ti	Zr	Al	Na
STD	n/a	<0.040	3.78	20.9	49.4	<0.010	<0.010	<0.010	3.95	84.0
HLP-44	10.49	1.11	1.41	18.5	50.7	0.220	0.800	0.220	6.64	81.5
HLP-44	10.47	1.15	1.45	17.1	49.4	0.280	0.890	0.250	6.81	68.3
HLP-44	10.48	1.03	1.72	16.1	45.2	0.260	0.870	0.100	7.08	68.9
HLP-45	10.47	1.12	1.99	15.4	48.2	0.390	1.08	0.280	7.29	69.8
HLP-45	10.46	1.19	2.31	16.5	49.4	0.380	1.02	0.370	7.16	68.8
HLP-45	10.46	1.13	1.78	15.6	47.4	0.360	0.990	0.390	6.99	65.5
HLP-47	10.94	0.100	<0.200	17.0	48.8	<0.100	<0.100	0.490	8.66	95.9
HLP-47	10.88	0.310	0.130	14.8	45.6	<0.100	<0.100	0.540	8.34	89.5
HLP-47	10.89	0.150	<0.200	15.3	44.5	<0.100	<0.100	0.540	7.90	95.5
HLP-48	10.93	1.11	<0.200	19.4	36.0	<0.100	<0.100	<0.100	11.1	89.7
HLP-48	10.93	1.20	<0.200	20.5	36.7	<0.100	<0.100	<0.200	11.4	91.7
HLP-48	10.93	1.11	<0.200	20.8	37.3	<0.100	<0.100	<0.100	11.4	95.5
Blank	5.46	0.090	<0.020	0.431	<0.180	<0.010	<0.010	<0.100	<0.200	<0.530
STD	n/a	<0.040	4.08	21.0	51.6	<0.100	<0.100	<0.010	4.08	84.1
HLP-49	10.57	<0.400	<0.200	9.08	21.4	<0.100	<0.100	<0.100	3.88	26.3
HLP-49	10.59	<0.400	<0.200	9.03	22.5	<0.100	<0.100	<0.100	4.21	24.5
HLP-49	10.54	<0.400	<0.200	8.75	22.0	<0.100	<0.100	<0.100	4.04	23.6
HLP-51	10.86	0.460	<0.200	11.0	33.5	<0.100	<0.100	<0.100	8.82	64.2
HLP-51	10.89	0.490	<0.200	12.1	35.7	<0.100	<0.100	<0.100	9.24	66.2
HLP-51	10.86	0.430	<0.200	11.6	34.5	<0.100	<0.100	<0.100	9.08	71.0
HLP-52	12.66	0.450	1.30	<1.80	153	<0.100	<0.100	<0.100	40.6	1490
HLP-52	12.68	0.700	1.09	<1.80	177	<0.100	<0.100	<0.100	43.9	1420
HLP-52	12.7	0.460	1.38	<1.80	165	<0.100	<0.100	<0.100	42.2	1410
HLP-54	10.41	0.390	<0.200	15.8	64.5	<0.100	<0.100	<0.100	5.46	92.2
HLP-54	10.31	0.510	<0.200	16.6	66.5	<0.100	<0.100	<0.100	5.69	80.2
HLP-54	10.27	0.410	<0.200	14.4	63.4	<0.100	<0.100	<0.100	5.85	85.8
HLP-55	10.36	0.400	<0.200	5.43	42.1	<0.100	<0.100	<0.100	11.2	53.4
HLP-55	10.31	0.350	<0.200	5.17	42.0	<0.100	<0.100	<0.100	10.1	47.3
HLP-55	10.3	0.420	<0.200	5.07	42.1	<0.100	<0.100	<0.100	10.5	47.5
HLP-46	11.39	0.410	<0.200	<1.80	37.8	<0.100	<0.100	<0.100	9.41	91.3
HLP-46	11.37	0.400	<0.200	<1.80	37.9	<0.100	<0.100	<0.100	8.36	91.6
HLP-46	11.33	0.390	<0.200	<1.80	37.0	<0.100	<0.100	<0.100	8.31	89.7
Blank	5.35	0.088	<0.020	0.318	0.070	<0.100	<0.100	<0.010	<0.200	<0.530
STD	n/a	<0.040	4.03	21.0	50.1	0.021	<0.010	<0.010	3.84	82.9

Measured Concentrations in 10-h PCT-B Solutions

Table B-2. SRTC Mobile Laboratory Results for the Measured Concentrations for the 10-h Hanford PCT-B Series. Results Reported on 9/10/1999 and 9/13/1999, Test Temperature = 90°C, Test Duration = 10 h, (S/V) ≈ 20,000/m, and Dilution Factor = 5/3.

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	B	Si	Al	Zn	Fe	Mg	Ti	Zr	Na
STD	n/a	20.1	55.3	4.18	<0.200	4.50	<0.200	<0.200	<0.100	82.7
HLP-01	10.19	13.3	46.7	5.27	0.583	1.51	0.367	0.608	0.317	93.6
HLP-02	11.41	178	70.6	15.1	2.39	2.18	1.85	1.13	<0.100	615
HLP-03	10.27	10.1	48.5	4.23	0.667	1.74	0.383	0.703	0.348	75.9
HLP-04	11.07	60.0	57.8	9.85	2.48	2.56	1.97	1.29	<0.100	26.9
HLP-05	10.57	34.1	90.0	1.55	0.249	0.234	<0.200	<0.200	<0.100	160
HLP-06	10.35	6.00	37.9	9.95	0.743	1.72	0.387	0.750	0.390	62.1
HLP-07	10.44	9.15	51.3	9.09	1.15	3.16	0.667	1.38	0.491	79.3
HLP-08	10.92	4.12	63.5	7.71	1.23	3.39	0.857	1.36	0.642	115
HLP-09	10.38	17.3	44.7	5.11	0.653	1.67	0.351	0.672	0.351	90.6
HLP-10	10.74	5.99	54.1	7.13	0.850	2.29	0.531	0.967	0.466	94.1
Blank	7.03	<1.80	<1.80	<2.00	0.252	0.235	<0.200	<0.200	0.101	<0.530
HLP-11	10.63	23.2	70.0	4.54	0.973	0.224	0.897	1.24	0.535	134
HLP-12	10.5	9.57	50.0	5.78	0.648	2.39	0.349	0.629	0.331	80.9
HLP-13	10.66	11.7	57.7	5.37	0.920	1.63	0.695	1.10	0.503	102
HLP-14	10.71	19.5	60.4	4.89	0.913	2.19	0.887	<0.200	0.315	125
HLP-15	10.59	8.79	52.5	5.46	0.923	2.44	0.609	2.08	0.548	88.4
HLP-16	10.67	13.5	58.2	6.05	0.278	2.06	0.520	0.819	0.423	107
HLP-17	10.68	9.35	55.1	5.64	1.14	1.29	0.486	0.468	0.244	91.5
HLP-18	10.67	13.3	66.3	6.69	1.92	5.86	1.42	2.51	<0.100	107
HLP-19	10.7	6.07	37.8	4.72	0.330	0.438	0.222	<0.200	0.224	74.2
HLP-20	10.65	12.6	56.8	5.39	1.28	3.88	<0.200	1.69	0.711	96.8
Blank	7.04	<1.80	<1.80	<2.00	0.247	0.183	<0.200	<0.200	<0.100	<0.530
STD	n/a	20.2	55.0	4.10	<0.200	4.60	<0.200	<0.200	<0.100	85.0
HLP-21	10.63	17.1	58.7	3.88	0.668	1.26	1.20	0.436	0.179	107
HLP-22	10.15	3.66	36.7	4.02	0.417	0.759	0.259	0.320	0.193	37.6
HLP-23	11.24	29.2	88.8	7.06	1.36	4.02	1.54	1.39	0.517	226
HLP-24	10.4	8.49	47.6	4.97	0.606	1.35	0.395	0.587	0.290	67.3
HLP-25	10.68	13.2	58.3	5.06	0.809	2.09	0.647	0.764	0.386	112
HLP-26	10.7	14.8	56.9	5.51	0.820	2.23	0.545	0.912	0.437	106
HLP-27	11.05	74.1	67.8	8.28	2.15	1.52	1.72	1.04	<1.00	265
HLP-28	9.71	9.18	28.5	6.15	0.483	0.982	0.219	0.389	0.204	39.4
HLP-29	11.21	3.74	60.7	13.3	0.938	2.42	0.638	1.06	0.434	150
HLP-30	10.28	<1.80	33.3	7.75	0.449	1.00	0.279	0.362	0.207	41.6
Blank	6.74	<1.80	<1.80	<2.00	0.245	0.144	<0.200	<0.200	<0.100	<0.530
STD	n/a	19.9	54.9	4.16	0.208	4.62	<0.200	<0.200	<0.100	84.1
HLP-31	10.94	195	296	<2.00	2.31	1.79	2.01	1.26	<1.00	604
HLP-32	9.88	18.3	51.8	<2.00	0.422	0.667	0.270	0.311	0.184	62.7
HLP-33	11.34	16.4	138	3.72	1.14	3.38	1.26	1.14	0.380	243
HLP-34	10.43	2.67	46.7	2.23	0.373	0.533	0.279	0.227	0.149	57.1
HLP-35	10.91	37.2	44.0	17.7	0.502	0.956	0.322	0.351	0.228	169
HLP-36	10.19	12.9	26.2	9.86	0.333	0.321	0.253	<0.200	0.140	58.4
HLP-37	11.32	4.44	47.7	30.5	2.59	5.17	1.82	<0.200	0.101	160
HLP-37Q	11.41	7.16	44.8	19.4	0.468	0.815	0.277	0.217	0.117	181
HLP-38	10.67	4.14	29.6	13.6	0.335	0.410	0.316	<0.200	0.176	66.1
HLP-38Q	10.73	<1.80	26.0	11.1	0.327	0.321	0.226	<0.200	0.134	52.9
Blank	6.75	<1.80	<1.80	<2.00	0.247	0.144	<0.200	<0.200	<0.100	47.2

Table B-2 Continued

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	B	Si	Al	Zn	Fe	Mg	Ti	Zr	Na
HLP-39	11.49	120	72.9	3.21	2.40	2.94	2.03	1.14	<1.00	433
HLP-40	10.38	26.3	39.1	2.15	0.391	0.419	0.331	<0.200	0.112	92.7
HLP-40Q	10.36	19.6	34.4	2.68	0.292	0.309	0.251	<0.200	<0.100	80.4
HLP-41	11.77	47.82	94.4	4.59	2.45	2.42	1.84	1.14	<1.00	435
HLP-42	11.03	6.75	40.9	3.61	0.394	0.469	0.344	<0.200	0.100	91.6
HLP-42Q	10.95	7.96	32.7	3.88	0.376	0.436	0.301	<0.200	0.103	81.3
HLP-43	10.74	13.3	45.8	4.80	0.710	2.04	0.393	0.823	0.389	88.6
HLP-47	11.04	16.7	57.8	5.50	0.292	0.941	<0.200	<0.200	0.355	144
HLP-48	11.07	19.8	42.5	14.8	0.824	0.686	0.383	<0.200	0.143	112
HLP-49	10.68	9.13	26.8	4.32	0.365	0.310	0.223	<0.200	<0.100	34.4
STD	n/a	20.9	54.5	4.01	0.210	4.78	<0.200	<0.200	<0.100	80.4
HLP-52	12.49	<1.80	116	24.7	2.84	2.00	1.78	1.06	<1.00	59.0
HLP-54	11.01	7.39	34.2	6.24	0.301	0.199	<0.200	<0.200	<0.100	134
HLP-55	10.49	25.1	74.3	2.38	0.303	0.198	<0.200	<0.200	<0.100	163
HLP-46	11.42	3.32	54.2	8.86	0.246	0.141	<0.200	<0.200	<0.100	<0.530
HLP-44	10.5	15.5	49.5	5.58	0.522	5.70	0.252	0.651	0.150	87.8
HLP-45	10.59	16.1	50.4	5.33	0.523	1.80	0.309	0.613	0.213	95.6
HLP-51	10.8	13.2	34.1	8.80	0.361	1.13	<0.100	<0.100	<0.100	99.9
Blank	6.21	<1.80	<1.80	<2.00	0.223	0.274	<0.200	<0.200	<0.100	<0.530
Blank	6.30	<1.80	<1.80	<2.00	0.241	0.148	<0.200	<0.200	<0.100	<0.530
Blank	6.25	<1.80	<1.80	<2.00	0.250	0.187	<0.200	<0.200	<0.100	<0.530
Blank	6.08	<1.80	<1.80	<2.00	0.238	0.143	<0.200	<0.200	<0.100	<0.530
Blank	6.01	<1.80	<1.80	<2.00	0.263	0.141	<0.200	<0.200	<0.100	<0.530
Blank	6.02	<1.80	<1.80	<2.00	0.243	0.141	<0.200	<0.200	<0.100	<0.530

Measured Concentrations in 100-h PCT-B Solutions

Table B-3. SRTC Mobile Laboratory Results for the Measured Concentrations for the 100-h Hanford PCT-B Series. Results Reported on 9/13/1999, Test Temperature = 90°C, Test Duration = 100 h, (S/V) ≈ 20 000/m, and Dilution Factor = 5/3.

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	**pH**	**B**	**Si**	**Al**	**Zn**	**Fe**	**Mg**	**Ti**	**Zr**	**Na**
STD	n/a	21.7	53.5	4.10	<0.040	4.24	<0.100	<0.100	<0.100	87.0
HLP-01	10.95	60.8	92.8	6.39	2.79	4.86	2.79	2.69	1.27	258
HLP-02	12.09	532	114	18.6	0.530	<0.200	0.680	<1.00	<1.00	1740
HLP-03	10.92	49.3	99.2	4.63	2.58	5.29	2.41	2.80	1.28	221
HLP-04	11.84	338	110	11.8	0.710	0.740	0.950	1.08	<1.00	1020
HLP-05	11.56	524	528	<2.00	0.420	<0.200	0.670	1.00	<1.00	1560
HLP-06	10.98	33.7	54.7	15.8	2.53	4.65	2.11	2.79	1.21	148
HLP-07	11.09	45.5	78.8	11.6	3.32	5.83	2.93	3.13	1.32	188
HLP-08	11.63	26.4	125	12.5	3.83	8.10	3.22	3.66	1.19	275
HLP-09	10.92	106	73.6	6.45	3.58	5.05	4.03	2.20	1.08	286
HLP-10	11.44	38.7	109	9.44	2.96	6.27	2.57	3.22	1.26	250
Blank	6.76	0.369	<0.180	0.202	0.109	<0.020	<0.100	<0.100	<0.100	<0.530
HLP-11	11.3	185	226	1.82	4.34	<0.200	4.49	1.85	1.10	589
HLP-12	11.17	50.7	88.0	7.41	2.38	6.51	2.23	2.18	1.04	214
HLP-13	11.33	89.7	130	4.58	3.66	3.92	4.11	3.09	1.45	336
HLP-14	11.47	149	151	4.41	4.76	7.41	4.94	<1.00	1.28	487
HLP-15	11.28	48.3	103	8.31	2.75	5.74	2.67	5.03	1.27	236
HLP-16	11.36	75.3	111	6.85	<0.400	7.11	4.15	3.14	1.41	291
HLP-17	11.29	66.7	109	6.23	8.30	5.57	3.18	2.72	1.15	282
HLP-18	11.34	92.1	147	8.62	7.36	13.1	7.14	5.74	<1.00	335
HLP-19	11.29	38.9	72.3	5.83	1.22	1.81	1.53	1.40	1.24	185
HLP-20	11.33	56.4	96.0	6.70	2.20	7.22	0.670	3.84	1.53	250
Blank	7.11	0.370	<0.180	<0.200	0.090	<0.200	<0.100	<0.100	0.112	<0.530
STD	n/a	21.6	51.4	4.00	<0.040	4.38	<0.100	<0.100	<0.100	83.6
HLP-21	11.33	110	121	7.82	2.55	3.27	4.94	1.82	1.18	373
HLP-22	10.34	37.9	66.2	4.79	2.02	3.50	2.09	2.16	1.08	119
HLP-23	11.92	152	187	6.72	2.31	4.65	2.79	2.06	1.09	726
HLP-24	10.89	54.0	86.3	5.40	2.63	4.74	2.67	2.75	1.32	186
HLP-25	11.36	80.5	113	6.29	3.64	5.90	3.74	2.71	1.22	309
HLP-26	11.33	78.0	111	6.67	3.35	5.90	3.43	2.87	1.40	282
HLP-27	12.01	384	138	16.6	<0.400	0.300	<1.00	<1.00	<1.00	1110
HLP-28	10.04	42.5	46.8	10.0	0.990	2.01	<1.00	1.62	<1.00	94.3
HLP-29	11.87	27.0	126	25.8	2.02	4.44	1.91	2.53	1.16	340
HLP-30	10.95	12.0	60.8	14.0	1.42	3.28	1.39	2.18	1.09	88.4
Blank	5.17	0.409	<0.180	<0.200	0.103	<0.200	<0.100	<0.100	<0.100	<0.530
STD	n/a	21.7	52.2	3.99	<0.040	4.42	<0.100	<0.100	<0.100	85.4
HLP-31	11.71	714	804	<2.00	0.500	<0.200	<1.00	<1.00	<1.00	2200
HLP-32	9.96	101	95.9	<2.00	1.49	2.18	1.73	1.72	<1.00	206
HLP-33	12.34	376	1270	<2.00	0.790	0.470	<1.00	1.00	<1.00	2300
HLP-34	11	31.9	122	2.31	1.79	3.56	1.82	2.18	1.12	163
HLP-35	11.76	270	65.5	20.0	0.950	1.09	1.06	1.17	<1.00	739
HLP-36	10.22	82.8	35.2	12.0	2.05	1.16	1.86	1.22	1.07	174
HLP-37	12.06	89.0	97.2	62.2	4.74	7.68	2.69	1.07	<1.00	580
HLP-37Q	12.08	38.9	106	40.9	0.780	1.06	<1.00	1.08	<1.00	502
HLP-38	11.3	26.3	52.2	22.2	0.990	1.18	1.51	1.35	<1.00	143
HLP-38Q	11.35	19.9	54.9	21.2	1.10	1.45	1.28	1.49	1.15	144
Blank	5.15	0.523	<0.180	<0.200	<0.040	<0.200	<0.100	<0.100	<0.100	<0.530

Table B-3 Continued

		Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	B	Si	Al	Zn	Fe	Mg	Ti	Zr	Na
HLP-39	12.2	931	312	<2.00	0.540	<0.200	<1.00	<1.00	<1.00	2460
HLP-40	10.18	361	66.0	<2.00	1.51	1.41	1.82	1.11	<1.00	655
HLP-40Q	10.1	378	46.2	<2.00	0.410	0.260	<1.00	<1.00	<1.00	660
HLP-41	12.72	694	55.1	6.21	2.24	1.16	<1.00	<1.00	<1.00	3260
HLP-42	11.75	125	176	2.35	2.28	3.17	2.25	1.36	<1.00	463
HLP-42Q	11.67	120	127	2.93	2.43	4.66	2.40	1.62	<1.00	395
HLP-43	11.32	99.5	124	36.4	15.3	42.4	9.87	17.9	1.18	350
HLP-47	10.67	96.8	147	8.60	<0.040	1.54	<1.00	<1.00	1.34	459
HLP-48	11.74	97.6	70.6	20.1	4.46	2.46	1.59	1.51	1.16	361
HLP-49	11.32	33.8	56.1	9.19	0.560	0.220	<1.00	<1.00	<1.00	80.3
STD	n/a	23.2	53.6	4.14	<0.040	4.54	<0.100	<0.100	<0.100	83.6
HLP-52	13.19	15.2	367	36.7	0.400	1.42	<1.00	<1.00	<1.00	5700
HLP-54	11.29	40.7	78.2	11.2	0.320	<0.200	<1.00	<1.00	<1.00	214
HLP-55	11.26	102	196	<2.00	0.330	<0.200	<1.00	<1.00	<1.00	368
HLP-46	12.1	18.6	142	26.1	0.310	<0.200	<1.00	<1.00	<1.00	470
Blank	5.43	0.805	<0.180	<0.200	0.105	0.028	<0.100	<0.100	<0.100	<0.530
Blank	5.52	0.773	<0.180	<0.200	0.127	0.035	<0.100	0.101	<0.100	<0.530
Blank	5.29	0.713	<0.180	<0.200	0.107	0.026	<0.100	<0.100	<0.100	<0.530
Blank	5.22	0.632	<0.180	<0.200	0.095	<0.020	<0.100	<0.100	<0.100	<0.530
Blank	5.10	<0.180	<0.180	<0.200	0.179	0.084	<0.100	<0.100	<0.100	<0.530
Blank	5.10	<0.180	<0.180	<0.200	0.164	0.174	<0.100	<0.100	<0.100	<0.530
Blank	6.68	0.595	<0.180	<0.200	0.168	0.059	<0.100	<0.100	<0.100	<0.530
HLP-44	10.97	53.7	86.0	5.80	2.14	3.72	2.25	2.21	1.13	205
HLP-45	11.13	57.0	99.0	6.57	2.37	4.94	2.38	2.48	1.14	238
HLP-51	11.48	45.9	65.7	13.8	1.68	0.650	1.06	1.05	<1.00	232
STD	n/a	21.8	55.2	4.01	<0.040	4.62	<0.100	<0.100	<0.100	82.2

Measured Concentrations in 1000-h PCT-B Solutions

Table B-4. SRTC Mobile Laboratory Results for the Measured pH and Concentrations for the 1000-h Hanford PCT-B Series. Results Reported on 9/19/1999, 9/29/1999, and 10/20/19999, Test Temperature = 90°C, Test Duration = 1000 h, and (S/V) ≈ 20 000/m. Dilution factors are also provided.

		Dilution	Diluted Concentration, p_i, in Test Solution (mg/L)								
SampleID	pH	Factor	Zn	Fe	B	Si	Mg	Ti	Zr	Al	Na
Blank	6.72	5/3	0.115	0.020	<0.180	0.308	<0.010	<0.060	<0.060	<0.200	<0.530
HLP-47	12.13	5/3	<0.400	0.340	273	215	<0.100	<0.600	<0.600	11.4	1080
HLP-02	12.51	5/3	0.410	0.250	1007	162	<0.100	<0.600	<0.600	21.9	2850
HLP-03	11.11	5/3	3.95	5.27	110	133	2.83	2.36	1.14	3.53	371
HLP-04	12.22	9/5	<0.400	<0.200	634	139	<0.100	<0.600	<0.600	11.2	1740
HLP-05	11.86	9/5	0.300	<0.200	1102	875	<0.100	<0.600	<0.600	<2.00	2960
HLP-09	11.05	5/3	1.25	1.67	361	80.5	<0.100	0.900	<0.600	<2.00	781
HLP-11	11.73	5/3	1.50	<0.200	329	247	1.18	0.880	<0.600	1.57	986
HLP-13	11.51	5/3	3.41	2.45	190	160	3.69	1.82	0.840	3.56	611
HLP-14	11.74	5/3	0.620	0.740	275	182	0.210	<0.600	<0.600	2.55	755
HLP-15	11.33	5/3	2.37	3.64	96.7	116	1.82	2.98	1.03	6.39	367
HLP-16	11.58	5/3	<0.400	3.51	147	125	2.45	1.64	0.890	5.29	513
HLP-17	11.45	5/3	7.64	4.08	140	130	2.09	1.93	0.880	4.82	438
HLP-18	11.61	5/3	0.440	0.630	200	165	<0.100	0.750	<0.600	3.85	602
HLP-19	11.35	5/3	1.91	3.05	71.3	83.9	1.44	1.30	1.22	5.77	282
HLP-20	11.38	5/3	2.85	7.57	107	116	<0.100	3.46	1.51	6.44	377
HLP-21	11.64	5/3	2.04	2.79	211	157	3.78	1.21	0.860	4.47	638
HLP-22	10.16	5/3	2.97	4.29	77.0	71.2	1.96	2.34	1.16	3.87	183
HLP-23	12.18	5/3	<0.400	0.520	252	223	<0.100	0.650	0.640	7.01	1030
HLP-24	10.83	5/3	3.81	4.87	116	9.89	3.07	2.43	1.30	4.35	318
HLP-25	11.57	5/3	3.88	5.29	172	146	3.61	1.87	1.01	5.64	515
STD	n/a	5/3	<0.040	3.96	21.4	49.3	<0.010	<0.060	<0.060	3.87	78.8
Blank	6.46	5/3	0.099	<0.020	1.41	<0.180	<0.060	<0.060	<0.200	<0.530	0.745
HLP-26	11.49	5/3	4.21	5.46	152	142	4.05	2.31	2.07	5.31	518
HLP-27	12.34	5/3	<0.400	<0.200	893	181	<0.100	<0.600	<0.600	22.1	2140
HLP-28	9.57	5/3	1.61	1.52	92.6	38.7	0.570	1.09	0.660	6.25	151
HLP-29	12.18	9/5	<0.400	0.670	50.2	152	<0.100	0.700	<0.600	30.4	572
HLP-30	10.94	9/5	1.56	3.48	21.9	64.3	0.740	1.97	0.870	13.6	134
HLP-31	11.99	5/3	<0.400	<0.200	1270	1150	<0.100	<0.600	<0.600	<2.00	3700
HLP-32	9.85	5/3	8.33	9.54	275	123	6.67	3.11	1.11	<2.00	405
HLP-33	12.65	5/3	<0.400	<0.200	1410	485	<0.100	<0.600	<0.600	<2.00	7230
HLP-34	11.28	5/3	5.60	11.2	64.9	188	3.87	3.29	1.29	2.86	244
HLP-35	12.09	5/3	<0.400	<0.200	530	68.8	<0.100	<0.600	<0.600	20.6	1520
HLP-36	9.72	5/3	7.13	3.09	328	29.8	5.03	1.35	0.980	8.79	551
HLP-37	12.42	5/3					Lost sample				
HLP-37Q	11.66	5/3	<0.400	0.400	76.0	134	<0.100	<0.600	<0.600	49.4	854
HLP-38Q	11.67	5/3	2.48	3.77	43.4	72.7	1.59	1.54	1.07	25.0	248
HLP-39	12.39	5/3	<0.400	<0.200	1130	421	<0.100	<0.600	<0.600	1.27	3190
HLP-40Q	10.1	5/3	<0.400	<0.200	706	54.1	<0.100	<0.600	<0.600	<2.00	1320
HLP-40	10.04	9/5	<0.400	<0.200	675	53.2	<0.100	<0.600	<0.600	<2.00	1300
HLP-41	12.99	5/3	2.44	1.00	930	867	<0.100	<0.600	<0.600	4.82	4660
HLP-42Q	12.34	5/3	<0.400	<0.200	880	270	<0.100	<0.600	<0.600	1.38	2440
HLP-43	11.6	5/3	5.26	7.22	174	148	4.59	2.54	1.58	5.44	498
HLP-46	12.37	5/3	<0.400	<0.200	55.7	252	<0.100	<0.600	<0.600	16.3	778
STD	n/a	5/3	<0.040	4.28	20.7	49.6	0.035	<0.010	<0.080	3.93	<0.530
HLP-01	11.47	5/3	4.73	5.54	139	126	4.44	0.730	<0.800	6.02	505

Table B-4 Continued

SampleID	pH	Dilution Factor	Diluted Concentration, p_i, in Test Solution (mg/L)								
			Zn	Fe	B	Si	Mg	Ti	Zr	Al	Na
HLP-06	11.29	5/3	4.11	4.82	50.7	67.2	2.73	0.870	<0.800	15.8	227
HLP-07	11.5	5/3	5.00	5.93	89.6	92.8	3.79	1.22	<0.800	11.7	353
HLP-08	12.05	5/3	2.22	3.49	37.1	168	1.63	<0.100	<0.800	14.3	485
HLP-10	11.85	5/3	4.40	6.47	63.8	153	3.58	1.00	<0.800	11.2	419
HLP-12	11.59	5/3	4.74	10.7	98.0	114	3.70	1.04	<0.800	7.47	377
STD	n/a	5/3	<0.040	4.40	21.0	51.4	0.032	<0.010	<0.080	3.96	81.0
HLP-38	11.66	5/3	3.86	3.29	41.6	70.0	4.05	<0.100	<0.800	28.8	252
HLP-42	12.42	5/3	0.680	<0.200	835	509	0.310	<0.100	<0.800	<2.00	3000
HLP-48	11.87	9/5	1.68	<0.200	200	86.5	0.570	<0.100	<0.800	22.6	744
HLP-49	11.41	5/3	0.630	<0.200	45.8	78.8	0.380	<0.100	<0.800	13.4	137
HLP-52	13.57	9/5	<0.400	4.80	12.4	4900	0.300	<0.100	1.91	64.7	17000
HLP-54	11.52	5/3	<0.400	<0.200	82.4	92.6	0.330	<0.100	<0.800	9.97	360
HLP-55	11.73	5/3	<0.400	<0.200	235	265	0.300	<0.100	<0.800	2.85	851
STD	n/a	5/3	21.4	50.3	3.98	0.114	4.28	0.051	0.129	<0.080	85.0
Blank	5.61	5/3	0.279	0.308	0.629	0.279	<0.020	0.077	<0.100	<0.080	0.902
HLP-44	11.34	5/3	142	132	6.53	4.65	3.08	3.95	1.87	0.690	543
HLP-45	11.45	5/3	119	136	7.50	3.82	2.76	3.04	1.77	0.790	567
HLP-51	11.48	5/3	114	80.6	15.6	2.81	<0.200	1.04	<0.100	0.510	577
STD	n/a	5/3	22.2	49.8	3.99	0.114	3.99	0.050	<0.100	<0.080	78.8
Blank	5.90	5/3	0.317	0.285	0.208	0.186	<0.020	0.060	<0.100	<0.080	0.927
Blank	7.0	5/3	0.243	0.243	<0.200	0.166	<0.020	0.056	<0.100	<0.080	0.774

PCT-A Normalized Release Information

Table B-5. Dilution Adjusted Release Values for the PCT-A Boron, Sodium, and Silicon Results for the Hanford Glasses. Test Temperature = 90°C, Test Duration = 165 h, (S/V) ≈ 2000/m, and Dilution Factor = 5/3. For these glasses, (S/V)t is approximately 330 000 h/m.

	Mean ln[p_i (mg/L)]			NC_i (g/L)			NL_i (g/m^2)		
SampleID	B	Na	Si	B	Na	Si	B	Na	Si
HLP-01	2.83	4.66	4.37	0.54	0.71	0.34	0.27	0.36	0.17
HLP-02	5.42	6.75	4.72	5.77	4.60	0.67	2.89	2.30	0.33
HLP-03	2.83	4.50	4.47	0.58	0.65	0.36	0.29	0.32	0.18
HLP-04	4.96	6.02	4.74	3.90	2.35	0.61	1.95	1.18	0.31
HLP-05	4.41	5.56	5.29	2.57	1.70	0.84	1.28	0.85	0.42
HLP-06	2.91	4.43	4.40	0.62	0.60	0.37	0.31	0.30	0.19
HLP-07	2.95	4.52	4.40	0.63	0.64	0.36	0.31	0.32	0.18
HLP-08	2.50	4.91	4.64	0.65	0.87	0.43	0.33	0.44	0.22
HLP-09	3.64	4.91	4.32	1.03	0.94	0.34	0.51	0.47	0.17
HLP-10	2.86	4.75	4.55	0.70	0.76	0.40	0.35	0.38	0.20
HLP-11	3.42	4.91	4.60	0.93	0.86	0.41	0.47	0.43	0.21
HLP-12	3.19	4.58	4.59	0.81	0.68	0.45	0.41	0.34	0.22
HLP-13	3.39	4.91	4.56	0.93	0.89	0.41	0.46	0.44	0.20
HLP-14	3.83	5.14	4.55	1.44	1.12	0.40	0.72	0.56	0.20
HLP-15	3.05	4.63	4.60	0.70	0.71	0.45	0.35	0.36	0.22
HLP-16	3.15	4.72	4.57	0.74	0.75	0.42	0.37	0.37	0.21
HLP-17	3.30	4.81	4.48	0.89	0.85	0.40	0.45	0.42	0.20
HLP-18	3.50	4.95	4.76	1.05	0.94	0.50	0.52	0.47	0.25
HLP-19	2.80	4.44	4.28	0.55	0.60	0.33	0.28	0.30	0.16
HLP-20	3.17	4.63	4.56	0.75	0.68	0.41	0.38	0.34	0.20
HLP-21	3.60	4.93	4.65	1.20	0.96	0.47	0.60	0.48	0.23
HLP-22	2.78	4.03	4.44	0.49	0.47	0.35	0.25	0.24	0.18
HLP-23	4.07	5.59	4.90	1.96	1.56	0.61	0.98	0.78	0.31
HLP-24	3.07	4.56	4.52	0.68	0.72	0.39	0.34	0.36	0.19
HLP-25	3.31	4.84	4.55	0.88	0.85	0.41	0.44	0.43	0.21
HLP-26	3.50	4.74	4.65	1.06	0.77	0.46	0.53	0.38	0.23
HLP-27	5.16	6.32	4.78	4.66	3.26	0.49	2.33	1.63	0.25
HLP-28	2.99	3.90	4.53	0.53	0.41	0.38	0.27	0.21	0.19
HLP-29	2.70	5.25	4.87	0.80	1.12	0.54	0.40	0.56	0.27
HLP-30	1.77	4.06	4.34	0.31	0.49	0.31	0.16	0.24	0.16
HLP-31	6.21	7.40	6.61	13.42	9.58	3.04	6.71	4.79	1.52
HLP-32	3.57	4.41	4.50	0.95	0.70	0.37	0.48	0.35	0.18
HLP-33	4.29	6.33	5.99	3.93	3.30	1.64	1.96	1.65	0.82
HLP-34	2.65	4.45	4.53	0.76	0.72	0.38	0.38	0.36	0.19
HLP-35	4.61	5.85	4.29	2.70	2.04	0.44	1.35	1.02	0.22
HLP-36	3.46	4.40	3.97	0.85	0.69	0.31	0.43	0.34	0.16
HLP-37	3.87	5.97	4.91	2.59	2.29	0.80	1.29	1.15	0.40
HLP-37Q[a]	3.16	5.53	4.61	1.26	1.48	0.60	0.63	0.74	0.30
HLP-38	2.69	4.44	4.13	0.79	0.72	0.37	0.40	0.36	0.18
HLP-38Q[a]	2.66	4.44	4.06	0.77	0.71	0.34	0.38	0.36	0.17
HLP-39	5.13	6.21	4.88	4.56	2.93	0.78	2.28	1.47	0.39
HLP-40	4.21	5.10	4.19	1.80	1.39	0.39	0.90	0.69	0.20
HLP-40Q[a]	4.05	4.97	4.19	1.54	1.21	0.39	0.77	0.61	0.20
HLP-41	5.51	7.33	5.88	13.27	8.92	2.13	6.63	4.46	1.06
HLP-42	3.23	4.85	4.38	1.36	1.08	0.47	0.68	0.54	0.24
HLP-42Q[a]	3.49	5.04	4.40	1.77	1.30	0.48	0.88	0.65	0.24
HLP-43	3.23	4.61	4.45	0.82	0.68	0.37	0.41	0.34	0.19

Table B-5 Continued

SampleID	Mean ln[p_i (mg/L)] B	Na	Si	NC_i (g/L) B	Na	Si	NL_i (g/m^2) B	Na	Si
HLP-44	3.36	4.80	5.16	0.92	0.82	0.35	0.46	0.41	0.18
HLP-45	3.27	4.73	4.39	0.85	0.76	0.35	0.42	0.38	0.18
HLP-46	0.41[b]	5.02	4.14	0.096	1.00	0.24	0.048	0.50	0.12
HLP-47	3.26	5.05	4.35	1.05	1.05	0.30	0.53	0.53	0.15
HLP-48	3.52	5.04	4.11	1.23	1.04	0.34	0.61	0.52	0.17
HLP-49	2.70	3.72	3.60	0.60	0.56	0.18	0.30	0.28	0.09
HLP-50				No results for this glass					
HLP-51	2.96	4.72	4.05	0.67	0.75	0.29	0.34	0.38	0.15
HLP-52	--[c]	7.78	5.62	--[c]	11.3	1.32	--[c]	5.65	0.66
HLP-53				No results for this glass					
HLP-54	3.26	4.96	4.68	0.93	0.97	0.41	0.46	0.48	0.20
HLP-55	2.16	4.41	4.25	0.31	0.55	0.25	0.16	0.28	0.13

(a) This indicates that this glass was quenched because the heat-treated glass exhibited crystalline material.
(b) The measured boron release for HLP-46 was less than 1.80 mg/L. A value of one-half this concentration was used for the B concentration for this glass.
(c) As indicated in Table 2-1, Glass HLP-52 contained no boron so the test solution concentration cannot be normalized using the concentration in the glass.

PCT-B Normalized Release Information

Table B-6. Normalized Release Values for the PCT-B Boron, Sodium, and Silicon Results for the Hanford Glasses. Test Temperature = 90°C; Test Duration = 10, 100, and 1000 h; and (S/V) ≈ 20,000/m.

SampleID	Time, t (hours)	(S/V)t (h/m)	NC_i (g/L) B	Na	Si	NL_i (g/m^2) B	Na	Si
HLP-01	10	2×10^5	0.71	1.05	1.25	0.036	0.053	0.062
HLP-01	100	2×10^6	3.26	2.90	2.48	0.16	0.14	0.12
HLP-01	1000	2×10^7	7.46	5.67	3.37	0.37	0.28	0.17
HLP-02	10	2×10^5	7.60	5.50	2.57	0.38	0.27	0.13
HLP-02	100	2×10^6	22.71	15.55	4.15	1.14	0.78	0.21
HLP-02	1000	2×10^7	42.99	25.47	5.90	2.15	1.27	0.30
HLP-03	10	2×10^5	0.57	0.90	1.22	0.029	0.045	0.061
HLP-03	100	2×10^6	2.81	2.63	2.50	0.14	0.13	0.12
HLP-03	1000	2×10^7	6.26	4.42	3.35	0.31	0.22	0.17
HLP-04	10	2×10^5	2.73	0.26	1.90	0.14	0.01	0.095
HLP-04	100	2×10^6	15.40	9.72	3.61	0.77	0.49	0.18
HLP-04	1000	2×10^7	31.20	17.91	4.92	1.56	0.90	0.25
HLP-05	10	2×10^5	1.77	1.74	2.33	0.09	0.09	0.12
HLP-05	100	2×10^6	27.25	16.97	13.7	1.36	0.85	0.68
HLP-05	1000	2×10^7	61.89	34.78	24.5	3.09	1.74	1.22
HLP-06	10	2×10^5	0.34	0.74	1.07	0.017	0.037	0.054
HLP-06	100	2×10^6	1.91	1.76	1.54	0.10	0.09	0.077
HLP-06	1000	2×10^7	2.87	2.69	1.90	0.14	0.13	0.095
HLP-07	10	2×10^5	0.50	0.91	1.40	0.03	0.05	0.070
HLP-07	100	2×10^6	2.49	2.16	2.15	0.12	0.11	0.11
HLP-07	1000	2×10^7	4.91	4.05	2.54	0.25	0.20	0.13
HLP-08	10	2×10^5	0.37	1.24	1.63	0.018	0.062	0.081
HLP-08	100	2×10^6	2.36	2.96	3.20	0.12	0.15	0.16
HLP-08	1000	2×10^7	3.32	5.22	4.30	0.17	0.26	0.22
HLP-09	10	2×10^5	0.77	1.04	1.22	0.039	0.052	0.061
HLP-09	100	2×10^6	4.74	3.29	2.01	0.24	0.16	0.10
HLP-09	1000	2×10^7	16.15	8.97	2.20	0.81	0.45	0.11
HLP-10	10	2×10^5	0.40	1.03	1.41	0.020	0.052	0.071
HLP-10	100	2×10^6	2.60	2.75	2.85	0.13	0.14	0.14
HLP-10	1000	2×10^7	6.57	4.14	2.98	0.33	0.21	0.15
HLP-11	10	2×10^5	1.18	1.42	1.77	0.06	0.07	0.088
HLP-11	100	2×10^6	9.38	6.25	5.71	0.47	0.31	0.28
HLP-11	1000	2×10^7	16.69	10.46	6.24	0.83	0.52	0.31
HLP-12	10	2×10^5	0.53	0.94	1.39	0.027	0.047	0.069
HLP-12	100	2×10^6	2.83	2.50	2.44	0.14	0.12	0.12
HLP-12	1000	2×10^7	5.46	4.40	3.16	0.27	0.22	0.16
HLP-13	10	2×10^5	0.61	1.12	1.50	0.031	0.056	0.075
HLP-13	100	2×10^6	4.69	3.68	3.39	0.23	0.18	0.17
HLP-13	1000	2×10^7	9.93	6.69	4.17	0.50	0.33	0.21
HLP-14	10	2×10^5	1.02	1.36	1.57	0.051	0.068	0.078
HLP-14	100	2×10^6	7.76	5.31	3.92	0.39	0.27	0.20
HLP-14	1000	2×10^7	14.32	8.23	4.72	0.72	0.41	0.24
HLP-15	10	2×10^5	0.49	1.02	1.45	0.024	0.051	0.072
HLP-15	100	2×10^6	2.68	2.73	2.84	0.13	0.14	0.14

Table B-6 Continued

SampleID	Time, t (hours)	(S/V)t (h/m)	NC_i (g/L) B	Na	Si	NL_i (g/m^2) B	Na	Si
HLP-15	1000	2×10^7	5.36	4.25	3.20	0.27	0.21	0.16
HLP-16	10	2×10^5	0.71	1.18	1.53	0.036	0.059	0.077
HLP-16	100	2×10^6	3.98	3.22	2.92	0.20	0.16	0.15
HLP-16	1000	2×10^7	7.77	5.67	3.29	0.39	0.28	0.16
HLP-17	10	2×10^5	0.51	1.05	1.51	0.026	0.053	0.076
HLP-17	100	2×10^6	3.67	3.25	2.99	0.18	0.16	0.15
HLP-17	1000	2×10^7	7.71	5.05	3.57	0.39	0.25	0.18
HLP-18	10	2×10^5	0.70	1.18	1.75	0.035	0.059	0.087
HLP-18	100	2×10^6	4.87	3.71	3.87	0.24	0.19	0.19
HLP-18	1000	2×10^7	10.58	6.66	4.34	0.53	0.33	0.22
HLP-19	10	2×10^5	0.34	0.87	1.06	0.017	0.044	0.053
HLP-19	100	2×10^6	2.19	2.18	2.03	0.11	0.11	0.10
HLP-19	1000	2×10^7	4.01	3.32	2.35	0.20	0.17	0.12
HLP-20	10	2×10^5	0.67	1.07	1.50	0.033	0.054	0.075
HLP-20	100	2×10^6	2.98	2.77	2.53	0.15	0.14	0.13
HLP-20	1000	2×10^7	5.66	4.17	3.05	0.28	0.21	0.15
HLP-21	10	2×10^5	0.94	1.23	1.61	0.047	0.062	0.081
HLP-21	100	2×10^6	6.05	4.30	3.32	0.30	0.21	0.17
HLP-21	1000	2×10^7	11.61	7.35	4.31	0.58	0.37	0.22
HLP-22	10	2×10^5	0.19	0.53	0.93	0.009	0.026	0.047
HLP-22	100	2×10^6	1.93	1.67	1.68	0.10	0.084	0.084
HLP-22	1000	2×10^7	3.92	2.57	1.81	0.20	0.13	0.090
HLP-23	10	2×10^5	1.63	2.21	2.47	0.082	0.11	0.12
HLP-23	100	2×10^6	8.49	7.09	5.20	0.42	0.35	0.26
HLP-23	1000	2×10^7	14.07	10.06	6.21	0.70	0.50	0.31
HLP-24	10	2×10^5	0.44	0.84	1.24	0.022	0.042	0.062
HLP-24	100	2×10^6	2.82	2.32	2.25	0.14	0.12	0.11
HLP-24	1000	2×10^7	6.06	3.97	0.26	0.30	0.20	0.013
HLP-25	10	2×10^5	0.71	1.26	1.56	0.035	0.063	0.078
HLP-25	100	2×10^6	4.32	3.47	3.02	0.22	0.17	0.15
HLP-25	1000	2×10^7	9.23	5.79	3.90	0.46	0.29	0.20
HLP-26	10	2×10^5	0.79	1.19	1.52	0.040	0.060	0.076
HLP-26	100	2×10^6	4.19	3.17	2.97	0.21	0.16	0.15
HLP-26	1000	2×10^7	8.16	5.82	3.80	0.41	0.29	0.19
HLP-27	10	2×10^5	3.31	2.59	1.71	0.166	0.129	0.086
HLP-27	100	2×10^6	17.17	10.84	3.48	0.86	0.54	0.17
HLP-27	1000	2×10^7	39.94	20.90	4.57	2.00	1.05	0.23
HLP-28	10	2×10^5	0.41	0.55	0.72	0.021	0.028	0.036
HLP-28	100	2×10^6	1.90	1.32	1.18	0.10	0.07	0.059
HLP-28	1000	2×10^7	4.14	2.12	0.98	0.21	0.11	0.049
HLP-29	10	2×10^5	0.33	1.47	1.53	0.017	0.073	0.077
HLP-29	100	2×10^6	2.42	3.32	3.18	0.12	0.17	0.16
HLP-29	1000	2×10^7	4.85	6.03	4.14	0.24	0.30	0.21
HLP-30	10	2×10^5	0.08	0.58	0.84	0.004	0.029	0.042
HLP-30	100	2×10^6	1.07	1.24	1.53	0.054	0.062	0.077
HLP-30	1000	2×10^7	2.12	2.03	1.75	0.11	0.10	0.088
HLP-31	10	2×10^5	8.72	5.90	7.47	0.436	0.295	0.37
HLP-31	100	2×10^6	31.93	21.49	20.3	1.60	1.07	1.01
HLP-31	1000	2×10^7	56.80	36.14	29.0	2.84	1.81	1.45
HLP-32	10	2×10^5	0.82	0.88	1.31	0.041	0.044	0.065

Table B-6 Continued

SampleID	Time, t (hours)	(S/V)t (h/m)	NC_i (g/L) B	Na	Si	NL_i (g/m^2) B	Na	Si
HLP-32	100	2×10^6	4.52	2.89	2.42	0.23	0.14	0.12
HLP-32	1000	2×10^7	12.30	5.69	3.10	0.61	0.28	0.16
HLP-33	10	2×10^5	1.47	2.37	3.48	0.073	0.119	0.17
HLP-33	100	2×10^6	33.63	22.47	32.0	1.68	1.12	1.60
HLP-33	1000	2×10^7	126.12	70.62	12.2	6.31	3.53	0.61
HLP-34	10	2×10^5	0.24	0.80	1.18	0.012	0.040	0.059
HLP-34	100	2×10^6	2.85	2.29	3.08	0.14	0.11	0.15
HLP-34	1000	2×10^7	5.81	3.43	4.74	0.29	0.17	0.24
HLP-35	10	2×10^5	1.66	1.65	1.60	0.083	0.083	0.080
HLP-35	100	2×10^6	12.08	7.22	2.39	0.60	0.36	0.12
HLP-35	1000	2×10^7	23.70	14.85	2.51	1.19	0.74	0.13
HLP-36	10	2×10^5	0.58	0.82	0.95	0.029	0.041	0.048
HLP-36	100	2×10^6	3.70	2.44	1.28	0.19	0.12	0.064
HLP-36	1000	2×10^7	14.67	7.74	1.09	0.73	0.39	0.054
HLP-37	10	2×10^5	0.40	1.56	1.74	0.020	0.078	0.087
HLP-37	100	2×10^6	7.96	5.67	3.54	0.40	0.28	0.18
HLP-37	1000	2×10^7			Sample was lost			
HLP-37Q	10	2×10^5	0.64	1.77	1.63	0.032	0.088	0.082
HLP-37Q	100	2×10^6	3.48	4.90	3.86	0.17	0.25	0.19
HLP-37Q	1000	2×10^7	6.80	8.34	4.88	0.34	0.42	0.24
HLP-38	10	2×10^5	0.37	0.93	1.08	0.019	0.046	0.054
HLP-38	100	2×10^6	2.35	2.01	1.90	0.12	0.10	0.095
HLP-38	1000	2×10^7	3.72	3.54	2.55	0.19	0.18	0.13
HLP-38Q	10	2×10^5	0.081	0.74	0.95	0.0040	0.037	0.047
HLP-38Q	100	2×10^6	1.78	2.02	2.00	0.089	0.10	0.10
HLP-38Q	1000	2×10^7	3.88	3.48	2.65	0.19	0.17	0.13
HLP-39	10	2×10^5	5.37	4.23	2.66	0.27	0.21	0.13
HLP-39	100	2×10^6	41.64	24.03	11.37	2.08	1.20	0.57
HLP-39	1000	2×10^7	50.54	31.16	15.34	2.53	1.56	0.77
HLP-40	10	2×10^5	1.18	1.30	1.42	0.059	0.065	0.071
HLP-40	100	2×10^6	16.15	9.20	2.40	0.81	0.46	0.12
HLP-40	1000	2×10^7	31.57	18.54	1.97	1.58	0.93	0.099
HLP-40Q	10	2×10^5	0.88	1.13	1.25	0.044	0.056	0.063
HLP-40Q	100	2×10^6	16.91	9.27	1.68	0.85	0.46	0.084
HLP-40Q	1000	2×10^7	32.60	19.71	2.09	1.63	0.986	0.10
HLP-41	10	2×10^5	4.28	4.25	3.44	0.21	0.21	0.17
HLP-41	100	2×10^6	62.08	31.84	2.01	3.104	1.59	0.10
HLP-41	1000	2×10^7	83.19	45.52	31.59	4.16	2.28	1.58
HLP-42	10	2×10^5	0.60	1.29	1.49	0.030	0.064	0.075
HLP-42	100	2×10^6	11.18	6.50	6.41	0.56	0.33	0.32
HLP-42	1000	2×10^7	74.69	42.13	18.55	3.73	2.11	0.93
HLP-42Q	10	2×10^5	0.71	1.14	1.19	0.036	0.057	0.060
HLP-42Q	100	2×10^6	10.73	5.55	4.63	0.54	0.28	0.23
HLP-42Q	1000	2×10^7	78.71	34.26	9.84	3.94	1.71	0.49
HLP-43	10	2×10^5	0.71	1.00	1.22	0.036	0.050	0.061
HLP-43	100	2×10^6	5.34	3.93	3.31	0.27	0.20	0.17
HLP-43	1000	2×10^7	9.34	5.59	3.96	0.47	0.28	0.20
HLP-44	10	2×10^5	0.83	0.99	1.32	0.042	0.049	0.066
HLP-44	100	2×10^6	0.31	2.30	0.06	0.016	0.12	2.9E-3
HLP-44	1000	2×10^7	7.62	6.10	3.53	0.38	0.31	0.18

Table B-6 Continued

SampleID	Time, t (hours)	(S/V)t (h/m)	NC_i (g/L) B	Na	Si	NL_i (g/m^2) B	Na	Si
HLP-45	10	2×10^5	0.86	1.07	1.35	0.043	0.054	0.067
HLP-45	100	2×10^6	0.35	2.67	0.063	0.018	0.13	3.2E-3
HLP-45	1000	2×10^7	6.39	6.37	3.64	0.32	0.32	0.18
HLP-46	10	2×10^5	0.35	2.9E-03	1.27	0.018	1.0E-04	0.064
HLP-46	100	2×10^6	1.98	5.17	3.33	0.10	0.26	0.17
HLP-46	1000	2×10^7	5.92	8.56	5.91	0.30	0.43	0.30
HLP-47	10	2×10^5	1.12	1.62	1.39	0.056	0.081	0.070
HLP-47	100	2×10^6	6.49	5.16	3.55	0.32	0.26	0.18
HLP-47	1000	2×10^7	18.31	12.13	5.19	0.92	0.61	0.26
HLP-48	10	2×10^5	1.20	1.26	1.46	0.060	0.063	0.073
HLP-48	100	2×10^6	5.92	4.06	2.42	0.30	0.20	0.12
HLP-48	1000	2×10^7	13.10	9.03	3.20	0.65	0.45	0.16
HLP-49	10	2×10^5	0.61	0.77	0.80	0.030	0.039	0.040
HLP-49	100	2×10^6	2.25	1.80	1.68	0.11	0.09	0.084
HLP-49	1000	2×10^7	3.05	3.08	2.35	0.15	0.15	0.12
HLP-50	10	2×10^5			No results for this sample			
HLP-50	100	2×10^6			No results for this sample			
HLP-50	1000	2×10^7			No results for this sample			
HLP-51	10	2×10^5	0.77	1.12	1.07	0.038	0.056	0.053
HLP-51	100	2×10^6	0.80	2.61	0.053	0.04	0.13	2.6E-3
HLP-51	1000	2×10^7	6.61	6.48	2.52	0.33	0.32	0.13
HLP-52	10	2×10^5	--[a]	0.46	3.42	--[a]	0.023	0.17
HLP-52	100	2×10^6	--[a]	44.74	10.8	--[a]	2.24	0.54
HLP-52	1000	2×10^7	--[a]	144.1	156	--[a]	7.21	7.81
HLP-53	10	2×10^5			No results for this sample			
HLP-53	100	2×10^6			No results for this sample			
HLP-53	1000	2×10^7			No results for this sample			
HLP-54	10	2×10^5	0.44	1.51	0.79	0.022	0.075	0.040
HLP-54	100	2×10^6	2.43	2.40	1.81	0.12	0.12	0.090
HLP-54	1000	2×10^7	4.91	4.04	2.14	0.25	0.20	0.11
HLP-55	10	2×10^5	1.50	1.83	1.63	0.075	0.092	0.082
HLP-55	100	2×10^6	6.08	4.13	4.30	0.30	0.21	0.22
HLP-55	1000	2×10^7	14.01	9.56	5.82	0.70	0.48	0.29

[a] As indicated in Table 2-1, glass HLP-52 contained no boron, so the test solution concentration cannot be normalized using the concentration in the glass.

Short-term Release Rates Based Upon PCT-B Results

Table B-7. Short-term Boron Release Rates Based Upon Measured NL_B

	Release Rate, r, in g/m^2-Day			Release Rate, r_Δ[(a)]	
Glass	10 hours	100 hours	1000 hours	100 hours	1000 hours
HLP-01	8.57E-02	3.92E-02	8.95E-03	3.40E-02	5.60E-03
HLP-02	9.12E-01	2.73E-01	5.16E-02	2.02E-01	2.70E-02
HLP-03	6.90E-02	3.37E-02	7.51E-03	2.97E-02	4.61E-03
HLP-04	3.28E-01	1.85E-01	3.74E-02	1.69E-01	2.11E-02
HLP-05	2.13E-01	3.27E-01	7.43E-02	3.40E-01	4.62E-02
HLP-06	4.08E-02	2.29E-02	3.45E-03	2.09E-02	1.28E-03
HLP-07	6.02E-02	2.99E-02	5.89E-03	2.66E-02	3.22E-03
HLP-08	4.42E-02	2.83E-02	3.98E-03	2.66E-02	1.28E-03
HLP-09	9.28E-02	5.69E-02	1.94E-02	5.29E-02	1.52E-02
HLP-10	4.82E-02	3.12E-02	7.89E-03	2.93E-02	5.30E-03
HLP-11	1.41E-01	1.13E-01	2.00E-02	1.09E-01	9.74E-03
HLP-12	6.40E-02	3.39E-02	6.55E-03	3.06E-02	3.51E-03
HLP-13	7.34E-02	5.62E-02	1.19E-02	5.43E-02	6.99E-03
HLP-14	1.22E-01	9.31E-02	1.72E-02	8.99E-02	8.75E-03
HLP-15	5.84E-02	3.21E-02	6.43E-03	2.92E-02	3.57E-03
HLP-16	8.57E-02	4.78E-02	9.33E-03	4.36E-02	5.05E-03
HLP-17	6.18E-02	4.41E-02	9.25E-03	4.21E-02	5.38E-03
HLP-18	8.44E-02	5.84E-02	1.27E-02	5.56E-02	7.61E-03
HLP-19	4.09E-02	2.62E-02	4.81E-03	2.46E-02	2.43E-03
HLP-20	7.99E-02	3.58E-02	6.79E-03	3.09E-02	3.57E-03
HLP-21	1.13E-01	7.27E-02	1.39E-02	6.82E-02	7.41E-03
HLP-22	2.24E-02	2.32E-02	4.71E-03	2.33E-02	2.66E-03
HLP-23	1.96E-01	1.02E-01	1.69E-02	9.14E-02	7.45E-03
HLP-24	5.32E-02	3.39E-02	7.27E-03	3.17E-02	4.32E-03
HLP-25	8.50E-02	5.18E-02	1.11E-02	4.82E-02	6.55E-03
HLP-26	9.53E-02	5.02E-02	9.79E-03	4.52E-02	5.30E-03
HLP-27	3.98E-01	2.06E-01	4.79E-02	1.85E-01	3.04E-02
HLP-28	4.93E-02	2.28E-02	4.97E-03	1.99E-02	2.99E-03
HLP-29	4.01E-02	2.90E-02	5.82E-03	2.77E-02	3.25E-03
HLP-30	9.66E-03	1.29E-02	2.54E-03	1.32E-02	1.39E-03
HLP-31	1.05E+00	3.83E-01	6.82E-02	3.09E-01	3.32E-02
HLP-32	9.82E-02	5.42E-02	1.48E-02	4.93E-02	1.04E-02
HLP-33	1.76E-01	4.04E-01	1.51E-01	4.29E-01	1.23E-01
HLP-34	2.87E-02	3.42E-02	6.97E-03	3.49E-02	3.94E-03
HLP-35	2.00E-01	1.45E-01	2.84E-02	1.39E-01	1.55E-02
HLP-36	6.92E-02	4.44E-02	1.76E-02	4.17E-02	1.46E-02
HLP-37	4.77E-02	9.55E-02	n/a	1.01E-01	n/a
HLP-37Q	7.69E-02	4.18E-02	8.16E-03	3.79E-02	4.42E-03
HLP-38	4.44E-02	2.82E-02	4.47E-03	2.64E-02	1.82E-03
HLP-38Q	9.66E-03	2.14E-02	4.66E-03	2.27E-02	2.80E-03
HLP-39	6.44E-01	5.00E-01	6.06E-02	4.84E-01	1.19E-02
HLP-40	1.41E-01	1.94E-01	3.79E-02	2.00E-01	2.06E-02
HLP-40Q	1.05E-01	2.03E-01	3.91E-02	2.14E-01	2.09E-02
HLP-41	5.13E-01	7.45E-01	9.98E-02	7.71E-01	2.81E-02
HLP-42	7.25E-02	1.34E-01	8.96E-02	1.41E-01	8.47E-02

Table B-7 Continued

Glass	Release Rate, r, in g/m^2-Day			Release Rate, r_Δ[a]	
	10 hours	100 hours	1000 hours	100 hours	1000 hours
HLP-42Q	8.54E-02	1.29E-01	9.45E-02	1.34E-01	9.06E-02
HLP-43	8.57E-02	6.41E-02	1.12E-02	6.17E-02	5.33E-03
HLP-44	9.98E-02	3.74E-03	9.15E-03	-6.94E-03	9.75E-03
HLP-45	1.04E-01	4.23E-03	7.66E-03	-6.82E-03	8.05E-03
HLP-46	4.23E-02	2.37E-02	7.10E-03	2.17E-02	5.26E-03
HLP-47	1.34E-01	7.79E-02	2.20E-02	7.16E-02	1.58E-02
HLP-48	1.44E-01	7.10E-02	1.57E-02	6.29E-02	9.57E-03
HLP-49	7.29E-02	2.70E-02	3.66E-03	2.19E-02	1.06E-03
HLP-50	No results for this glass				
HLP-51	9.19E-02	9.61E-03	7.94E-03	4.64E-04	7.75E-03
HLP-52	This glass contains no boron				
HLP-53	No results for this glass				
HLP-54	5.29E-02	2.91E-02	5.90E-03	2.65E-02	3.32E-03
HLP-55	1.80E-01	7.30E-02	1.68E-02	6.11E-02	1.06E-02

(a) The release rates, r and r_Δ, are the same at 10 hours.

Table B-8. Short-term Sodium Release Rates Based Upon Measured NL_{Na}

	Release Rate, r, in g/m^2-Day			Release Rate, r_Δ[(a)]	
Glass	10 hours	100 hours	1000 hours	100 hours	1000 hours
HLP-01	1.26E-01	3.48E-02	6.81E-03	2.46E-02	3.70E-03
HLP-02	6.60E-01	1.87E-01	3.06E-02	1.34E-01	1.32E-02
HLP-03	1.09E-01	3.16E-02	5.31E-03	2.31E-02	2.38E-03
HLP-04	3.08E-02	1.17E-01	2.15E-02	1.26E-01	1.09E-02
HLP-05	2.09E-01	2.04E-01	4.17E-02	2.03E-01	2.37E-02
HLP-06	8.84E-02	2.11E-02	3.23E-03	1.36E-02	1.25E-03
HLP-07	1.09E-01	2.59E-02	4.86E-03	1.66E-02	2.53E-03
HLP-08	1.48E-01	3.55E-02	6.26E-03	2.29E-02	3.01E-03
HLP-09	1.25E-01	3.94E-02	1.08E-02	2.99E-02	7.58E-03
HLP-10	1.24E-01	3.30E-02	4.97E-03	2.28E-02	1.86E-03
HLP-11	1.71E-01	7.50E-02	1.26E-02	6.44E-02	5.62E-03
HLP-12	1.13E-01	3.00E-02	5.28E-03	2.07E-02	2.54E-03
HLP-13	1.34E-01	4.41E-02	8.02E-03	3.41E-02	4.01E-03
HLP-14	1.63E-01	6.37E-02	9.87E-03	5.26E-02	3.89E-03
HLP-15	1.23E-01	3.28E-02	5.10E-03	2.28E-02	2.02E-03
HLP-16	1.42E-01	3.86E-02	6.81E-03	2.71E-02	3.27E-03
HLP-17	1.27E-01	3.90E-02	6.06E-03	2.93E-02	2.40E-03
HLP-18	1.42E-01	4.45E-02	7.99E-03	3.36E-02	3.94E-03
HLP-19	1.05E-01	2.61E-02	3.98E-03	1.74E-02	1.52E-03
HLP-20	1.28E-01	3.32E-02	5.00E-03	2.26E-02	1.87E-03
HLP-21	1.48E-01	5.16E-02	8.82E-03	4.09E-02	4.07E-03
HLP-22	6.34E-02	2.01E-02	3.08E-03	1.52E-02	1.20E-03
HLP-23	2.65E-01	8.51E-02	1.21E-02	6.51E-02	3.96E-03
HLP-24	1.01E-01	2.79E-02	4.76E-03	1.98E-02	2.20E-03
HLP-25	1.51E-01	4.17E-02	6.94E-03	2.95E-02	3.09E-03
HLP-26	1.43E-01	3.80E-02	6.98E-03	2.64E-02	3.53E-03
HLP-27	3.11E-01	1.30E-01	2.51E-02	1.10E-01	1.34E-02
HLP-28	6.64E-02	1.59E-02	2.54E-03	1.03E-02	1.06E-03
HLP-29	1.76E-01	3.99E-02	7.24E-03	2.47E-02	3.62E-03
HLP-30	7.01E-02	1.49E-02	2.44E-03	8.76E-03	1.05E-03
HLP-31	7.08E-01	2.58E-01	4.34E-02	2.08E-01	1.95E-02
HLP-32	1.06E-01	3.47E-02	6.82E-03	2.68E-02	3.73E-03
HLP-33	2.85E-01	2.70E-01	8.47E-02	2.68E-01	6.42E-02
HLP-34	9.62E-02	2.75E-02	4.11E-03	1.98E-02	1.52E-03
HLP-35	1.98E-01	8.66E-02	1.78E-02	7.42E-02	1.02E-02
HLP-36	9.84E-02	2.93E-02	9.28E-03	2.16E-02	7.06E-03
HLP-37	1.88E-01	6.80E-02	n/a	5.47E-02	n/a
HLP-37Q	2.12E-01	5.88E-02	1.00E-02	4.18E-02	4.58E-03
HLP-38	1.11E-01	2.41E-02	4.25E-03	1.44E-02	2.04E-03
HLP-38Q	8.91E-02	2.43E-02	4.18E-03	1.71E-02	1.95E-03
HLP-39	5.08E-01	2.88E-01	3.74E-02	2.64E-01	9.51E-03
HLP-40	1.56E-01	1.10E-01	2.22E-02	1.05E-01	1.25E-02
HLP-40Q	1.35E-01	1.11E-01	2.37E-02	1.09E-01	1.39E-02
HLP-41	5.10E-01	3.82E-01	5.46E-02	3.68E-01	1.82E-02
HLP-42	1.54E-01	7.80E-02	5.06E-02	6.95E-02	4.75E-02
HLP-42Q	1.37E-01	6.66E-02	4.11E-02	5.87E-02	3.83E-02
HLP-43	1.19E-01	4.72E-02	6.71E-03	3.92E-02	2.22E-03

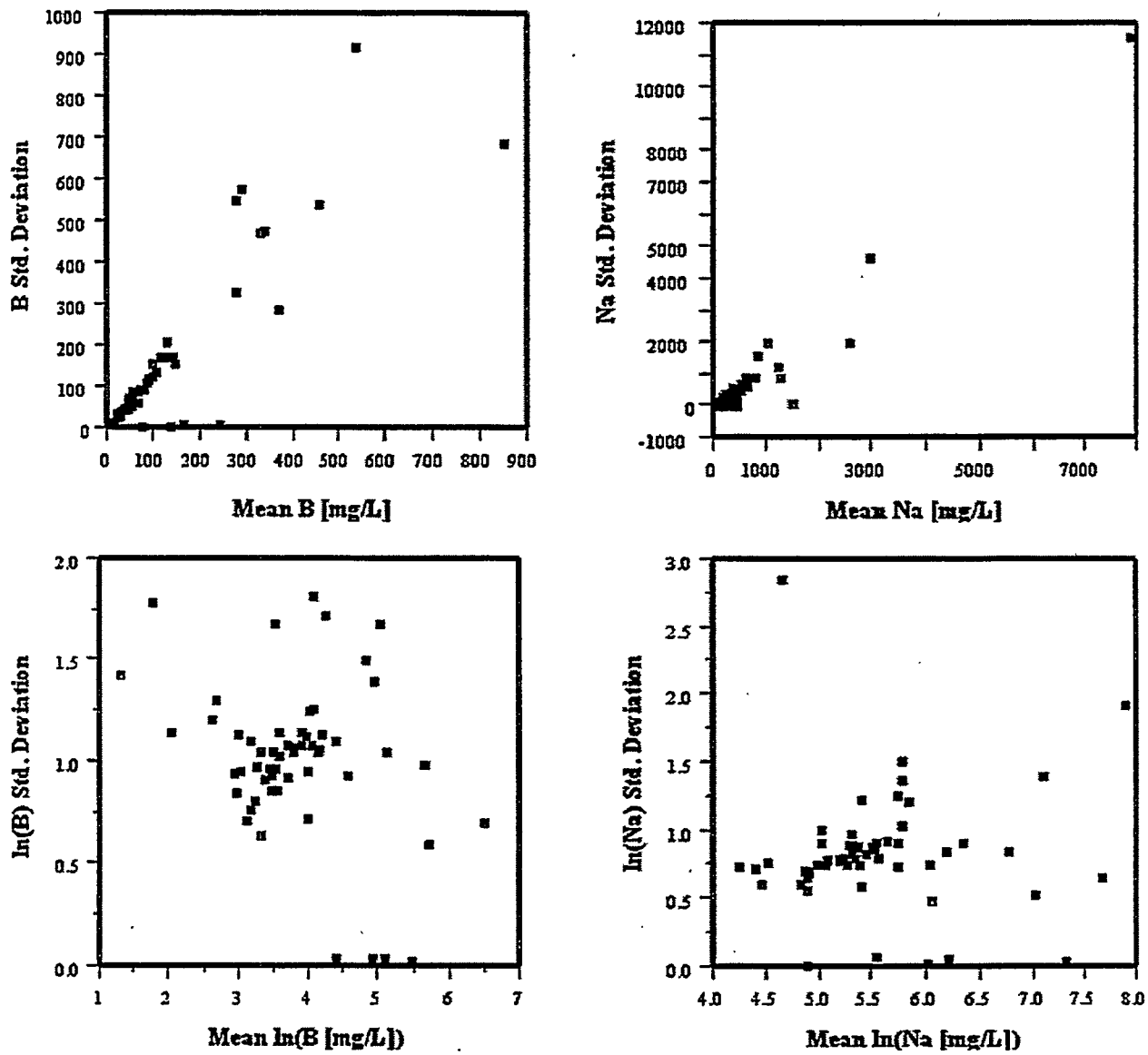
Table B-8 Continued

Glass	Release Rate, r, in g/m^2-Day			Release Rate, r_Δ[a]	
	10 hours	100 hours	1000 hours	100 hours	1000 hours
HLP-44	1.18E-01	2.76E-02	7.32E-03	1.76E-02	5.06E-03
HLP-45	1.29E-01	3.21E-02	7.64E-03	2.13E-02	4.93E-03
HLP-46	3.50E-04	6.21E-02	1.03E-02	6.89E-02	4.52E-03
HLP-47	1.94E-01	6.19E-02	1.46E-02	4.72E-02	9.30E-03
HLP-48	1.51E-01	4.87E-02	1.08E-02	3.73E-02	6.63E-03
HLP-49	9.27E-02	2.16E-02	3.69E-03	1.37E-02	1.70E-03
HLP-50	No results for this glass				
HLP-51	1.35E-01	3.13E-02	7.78E-03	1.98E-02	5.17E-03
HLP-52	5.56E-02	5.37E-01	1.73E-01	5.90E-01	1.33E-01
HLP-53	No results for this glass				
HLP-54	1.81E-01	2.88E-02	4.85E-03	1.20E-02	2.19E-03
HLP-55	2.20E-01	4.96E-02	1.15E-02	3.07E-02	7.23E-03

(a) The release rates, r and r_Δ, are the same at 10 hours.

Relationship Between Standard Deviations and Means from PCT-A Data

Exhibit B-1. Relationship Between Standard Deviations and Means for Boron and Sodium



APPENDIX C

VHT Corrosion Extents

APPENDIX C
VHT Alteration Extents

Table C-1. Results from Terminated VHT Tests

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-01	199.7	0.2	3.0	10.17	9.72	1.5	0.401	-0.03	10	0.00	153	1.5
HLP-01	199.8	0.2	8.8	9.74	10.04	1.5	0.383	-0.04	10	0.00	205	1.1
HLP-01	200.7	0.2	36.6	9.71	10.38	1.5	0.373	-0.06	8	0.03	392	9.5
HLP-01	200.7	0.2	32.8	9.67	10.17	1.6	0.413	-0.07	6	0.01	232	8.1
HLP-01	200.7	0.2	36.5	9.74	10.30	1.6	0.412	-0.06	10	0.02	434	9.8
HLP-02	199.8	0.2	8.8	9.64	10.27	1.4	0.373	-0.04	10	0.07	1884	-
HLP-02	200.5	0.2	3.0	10.30	9.76	1.3	0.363	-0.02	8	0.04	778	122.0
HLP-02	200.5	0.2	5.0	10.17	9.73	1.5	0.399	-0.02	8	0.04	1423	227.7
HLP-02	200.5	0.2	3.0	10.17	9.73	1.5	0.399	-0.02	8	0.04	857	70.1
HLP-02	200.5	0.2	1.6	10.39	9.80	1.4	0.393	-0.01	10	0.03	557	49.2
HLP-02	200.5	0.2	1.0	10.29	9.70	1.5	0.400	-0.02	-	-	351	21.9
HLP-02	200.5	0.2	0.5	10.24	9.72	1.5	0.402	-0.02	10	0.03	207	2.1
HLP-03	199.7	0.2	3.0	10.06	9.92	1.5	0.397	-0.03	10	0.00	153	1.5
HLP-03	199.8	0.2	8.8	9.59	9.90	1.4	0.383	-0.03	10	0.06	235	3.9
HLP-03	200.4	0.2	17.0	10.07	10.13	1.4	0.367	-0.04	10	0.01	343	6.2
HLP-03	200.7	0.2	36.6	10.15	10.12	1.4	0.373	-0.06	8	0.02	254	3.0
HLP-03	200.7	0.2	36.5	10.01	10.04	1.5	0.392	-0.06	10	0.02	306	1.7
HLP-04	199.7	0.2	3.0	9.94	9.96	1.5	0.394	-0.03	10	0.01	377	2.2
HLP-04	199.8	0.2	8.8	9.83	9.98	1.5	0.402	-0.03	10	-0.05	854	47.3
HLP-04	199.9	0.2	41.0	10.05	10.01	1.5	0.388	-0.03	10	0.06	1775	319.5
HLP-04	200.4	0.2	17.0	12.26	9.84	1.5	0.401	-0.04	10	0.04	879	34.7
HLP-04	200.4	0.2	16.0	9.96	9.91	1.4	0.372	-0.03	10	0.05	904	202.9
HLP-04	200.4	0.2	16.0	9.90	9.93	1.5	0.396	-0.02	6	0.04	931	204.9
HLP-04	200.6	0.2	65.0	10.11	9.93	1.5	0.391	-0.05	8.	0.12	1947	-
HLP-04	200.7	0.2	83.1	9.96	10.05	1.5	0.407	-0.08	7	0.06	2033	-
HLP-05	199.7	0.2	3.0	10.14	9.70	1.6	0.411	-0.02	8	0.00	0	-
HLP-05	199.8	0.2	8.8	9.88	10.21	1.4	0.379	-0.03	5.	0.01	444	5.8
HLP-05	200.3	0.2	23.7	10.23	9.89	1.6	0.405	-0.03	6	0.01	188	1.9
HLP-05	200.3	0.2	23.7	9.96	10.18	1.6	0.409	-0.05	6	0.01	237	2.4
HLP-05	200.4	0.2	12.0	9.90	10.16	1.5	0.395	-0.03	5.	0.00	125	1.2
HLP-05	200.4	0.2	13.9	9.89	10.20	1.5	0.408	-0.03	8	0.01	480	14.5
HLP-05	200.6	0.2	12.9	9.88	10.23	1.5	0.405	-0.03	6	0.01	190	1.9
HLP-05	200.7	0.3	8.8	9.96	10.27	1.5	0.404	-0.08	6	0.01	127	0.6
HLP-05	200.8	0.2	41.0	10.46	10.63	1.4	0.420	-0.06	8.	0.02	207	3.4
HLP-06	199.7	0.2	3.0	9.91	10.18	1.6	0.408	-0.02	8	0.00	278	2.9
HLP-06	199.8	0.2	8.8	10.00	10.00	1.5	0.394	-0.03	5.	0.01	811	26.0
HLP-06	200.4	0.2	13.9	10.03	10.00	1.6	0.409	-0.03	8	0.04	1178	62.4

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-06	200.4	0.2	16.0	10.02	10.03	1.5	0.399	-0.03	10	0.01	424	12.2
HLP-06	200.6	0.2	5.1	10.04	10.15	1.6	0.415	-0.02	10	0.00	395	13.2
HLP-06	200.6	0.2	21.7	10.09	10.05	1.5	0.381	-0.04	10	0.02	427	7.7
HLP-06	200.6	0.2	32.8	10.16	10.05	1.5	0.393	-0.04	8	0.01	525	13.5
HLP-06	200.7	0.2	108.7	10.20	10.03	1.5	0.395	-0.09	10	0.02	569	7.5
HLP-07	199.7	0.2	108.7	10.11	10.00	1.5	0.399	-0.08	8.	0.03	1847	398.9
HLP-07	200.2	0.2	12.9	10.09	10.12	1.5	0.405	-0.03	5.	0.01	326	3.6
HLP-07	200.2	0.2	44.9	9.99	10.10	1.5	0.407	-0.02	10	0.02	1118	80.5
HLP-07	200.4	0.2	16.0	10.01	10.03	1.5	0.389	-0.03	6	0.02	329	3.7
HLP-07	200.5	0.2	77.9	10.03	10.06	1.5	0.401	0.00	9	0.02	1350	155.5
HLP-07	200.6	0.2	21.7	10.07	10.03	1.6	0.415	-0.03	10	0.01	552	10.2
HLP-08	199.7	0.2	108.7	10.24	10.07	1.6	0.428	-0.08	8.	0.04	1063	38.8
HLP-08	200.2	0.2	12.9	10.09	10.17	1.5	0.409	-0.03	5.	0.01	267	4.2
HLP-08	200.2	0.2	44.9	10.05	10.07	1.5	0.402	-0.02	10	0.02	532	10.3
HLP-08	200.4	0.2	16.0	10.09	10.10	1.6	0.423	-0.03	6	0.01	168	2.4
HLP-08	200.5	0.2	77.9	10.13	10.16	1.6	0.451	0.00	9	0.01	794	28.0
HLP-08	200.6	0.2	21.7	10.13	10.12	1.5	0.410	-0.03	10	0.01	308	8.4
HLP-09	199.7	0.2	3.0	9.84	10.04	1.4	0.365	-0.03	5.	0.00	103	1.1
HLP-09	199.8	0.2	8.8	9.90	10.09	1.5	0.396	-0.04	6	0.00	343	3.8
HLP-09	200.4	0.2	12.0	9.86	10.22	1.6	0.409	-0.02	6	0.00	88	0.8
HLP-09	200.6	0.2	19.0	9.85	10.30	1.5	0.390	-0.04	6	-0.01	49	0.2
HLP-09	200.6	0.2	19.0	10.10	10.00	1.6	0.401	-0.04	6	0.00	304	3.2
HLP-09	200.7	0.2	26.7	9.93	10.29	1.5	0.392	-0.06	6	0.01	201	4.2
HLP-09	200.7	0.2	32.8	10.22	9.76	1.5	0.394	-0.07	6	0.01	494	6.1
HLP-09	200.7	0.2	26.7	9.95	10.16	1.5	0.402	-0.06	6	0.01	214	1.1
HLP-09	299.6	0.8	2.0	10.15	10.08	1.5	0.408	-0.05	5.	0.03	1248	31.0
HLP-09	299.6	0.7	3.0	10.05	10.15	1.5	0.401	-0.20	6	0.03	1053	42.7
HLP-09	299.7	0.7	1.0	10.10	10.08	1.5	0.405	-0.02	5.	0.03	827	13.2
HLP-09	299.9	0.8	3.0	9.87	9.95	1.4	0.348	-0.04	5	0.04	1645	236.9
HLP-10	199.7	0.2	3.0	10.11	10.10	1.5	0.421	-0.03	5.	0.00	117	0.6
HLP-10	199.8	0.2	8.8	9.09	10.02	1.4	0.372	-0.04	6	0.00	138	1.4
HLP-10	200.7	0.2	32.8	9.98	10.13	1.5	0.425	-0.07	6	0.02	238	2.4
HLP-10	299.9	0.8	1.0	9.91	9.98	1.4	0.352	-0.03	7.	0.04	1416	70.3
HLP-10	300.0	0.8	2.0	9.79	9.86	1.5	0.378	-0.05	8	0.04	1958	-
HLP-11	199.8	0.2	7.3	10.20	10.11	1.5	0.412	-0.03	6	0.00	101	1.9
HLP-11	200.1	0.2	12.9	9.90	10.09	1.5	0.396	0.06	6	0.02	114	1.7
HLP-11	200.6	0.2	88.0	10.08	10.15	1.5	0.403	-0.10	6.	0.04	1267	16.3
HLP-11	200.7	0.2	70.0	10.10	10.13	1.5	0.399	-0.09	8	-	1170	27.2
HLP-12	199.8	0.2	7.3	9.86	10.36	1.5	0.402	-0.03	6	0.00	180	2.8
HLP-12	199.9	0.2	41.0	10.06	10.08	1.5	0.406	-0.03	10	0.03	837	13.5
HLP-12	200.1	0.2	12.9	10.22	9.76	1.5	0.394	-0.01	6	0.01	405	9.4
HLP-12	200.4	0.2	16.0	10.24	10.96	1.7	0.450	-0.03	10	0.03	484	8.1

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-12	200.4	0.2	16.0	10.28	9.94	1.5	0.415	-0.02	6	0.03	553	10.4
HLP-12	200.6	0.2	65.0	9.90	9.96	1.5	0.386	-0.05	8.	0.03	1043	42.3
HLP-12	200.7	0.2	96.7	9.93	10.26	1.6	0.422	-0.08	10	0.04	1677	155.8
HLP-12	200.7	0.2	83.1	9.98	10.16	1.5	0.389	-0.08	7	0.08	1348	82.6
HLP-12	300.0	0.8	1.5	9.93	10.34	1.5	0.408	-0.06	6	0.04	1584	184.0
HLP-12	300.0	0.8	0.5	10.04	10.08	1.5	0.401	-0.03	6	0.03	508	15.8
HLP-12	300.0	0.7	1.0	10.11	10.04	1.4	0.384	-0.05	6	0.03	895	24.8
HLP-13	200.5	0.2	150.0	9.79	10.26	1.5	0.395	-0.11	6	0.01	706	5.1
HLP-13	200.7	0.2	30.6	10.09	9.76	1.5	0.393	-0.09	5	0.02	518	6.5
HLP-13	200.7	0.2	8.7	9.73	10.24	1.4	0.368	-0.03	6	0.01	0	-
HLP-13	200.7	0.2	97.9	9.87	10.33	1.6	0.427	-0.07	8	0.04	782	10.8
HLP-13	200.7	0.2	15.6	10.10	9.81	1.5	0.405	-0.02	6	0.01	279	31.7
HLP-13	200.7	0.2	79.9	9.83	10.20	1.5	0.404	-0.07	5.	0.03	944	40.4
HLP-14	199.9	0.2	20.9	10.03	10.07	1.5	0.403	-0.04	5	0.04	656	9.1
HLP-14	200.5	0.2	150.0	9.94	9.98	1.5	0.380	-0.11	6	0.03	1915	-
HLP-14	200.7	0.2	30.6	9.95	9.80	1.4	0.372	-0.09	5	0.04	1324	21.2
HLP-14	200.7	0.2	8.7	10.09	9.93	1.4	0.376	-0.03	6	0.01	13	0.1
HLP-14	200.7	0.2	97.9	10.02	10.01	1.4	0.374	-0.07	8	0.05	1864	-
HLP-14	200.7	0.2	15.6	9.87	9.97	1.4	0.363	-0.02	6	0.06	392	28.0
HLP-14	200.7	0.2	79.9	9.93	9.88	1.5	0.380	-0.07	5.	0.05	1810	130.3
HLP-14	200.7	0.2	24.9	10.03	10.07	1.5	0.403	-0.04	9.	0.04	1055	52.0
HLP-15	200.7	0.2	30.6	10.06	9.89	1.4	0.382	-0.07	6	0.01	144	1.5
HLP-15	200.7	0.2	8.7	10.08	10.14	1.5	0.409	-0.07	10	0.00	0	-
HLP-15	200.7	0.2	15.6	9.93	10.04	1.5	0.400	-0.04	6	0.02	119	0.6
HLP-15	200.7	0.2	76.9	10.09	9.96	1.5	0.396	-0.11	8	0.00	326	1.9
HLP-16	200.7	0.2	30.6	8.29	11.62	1.4	0.358	-0.07	5	0.01	484	13.3
HLP-16	200.7	0.2	8.7	11.76	8.08	1.5	0.366	-0.07	10	0.00	0	-
HLP-16	200.7	0.2	15.6	8.25	11.42	1.5	0.372	-0.04	6	0.02	310	5.2
HLP-16	200.7	0.2	76.9	8.74	11.30	1.5	0.386	-0.11	8	0.01	792	18.8
HLP-17	200.7	0.2	8.7	9.95	9.90	1.4	0.376	-0.05	6	0.00	0	0.0
HLP-17	200.7	0.2	30.6	9.77	9.99	1.4	0.390	-0.06	5	0.01	416	5.1
HLP-17	200.7	0.2	76.9	10.02	9.89	1.4	0.381	-0.09	10	0.03	903	49.4
HLP-17	200.7	0.2	15.6	9.94	9.85	1.5	0.380	-0.04	6	0.01	334	9.6
HLP-18	200.1	0.2	84.1	9.90	10.09	1.5	0.396	-0.10	10	0.05	1789	257.6
HLP-18	200.2	0.2	73.0	9.97	10.16	1.5	0.400	-0.07	10	0.04	1509	205.6
HLP-18	200.7	0.2	8.7	10.08	10.02	1.4	0.384	-0.06	6	0.01	128	0.7
HLP-18	200.7	0.2	30.6	10.00	10.04	1.3	0.352	-0.06	5	0.05	1022	50.7
HLP-18	200.7	0.2	15.6	9.71	9.76	1.5	0.368	-0.04	6	0.02	527	3.5
HLP-19	200.7	0.3	30.6	9.99	9.72	1.4	0.361	-0.07	5	0.01	0	-
HLP-19	200.7	0.2	15.6	10.35	9.70	1.4	0.389	-0.04	7	0.01	0	-
HLP-20	200.7	0.3	30.6	11.42	8.33	1.5	0.372	-0.07	5	0.02	142	2.2
HLP-20	200.7	0.2	15.6	8.64	11.51	1.5	0.398	-0.04	7	0.00	142	0.7

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-20	200.7	0.2	76.9	8.65	11.54	1.5	0.392	-0.09	10	0.02	646	8.9
HLP-21	199.6	0.2	92.0	10.03	10.02	1.4	0.380	-0.10	5.	0.02	723	17.0
HLP-21	200.3	0.2	85.0	10.06	9.96	1.4	0.382	-0.08	7.	0.02	627	9.0
HLP-21	200.4	0.2	77.0	10.05	10.00	1.5	0.391	-0.10	8	0.01	819	26.8
HLP-21	200.7	0.2	30.6	9.97	9.89	1.5	0.391	-0.05	10	0.01	248	1.3
HLP-21	200.7	0.2	15.6	10.09	10.12	1.5	0.397	-0.04	6	0.00	26	0.3
HLP-21	200.7	0.2	8.7	9.99	10.13	1.5	0.401	-0.02	6	0.00	0	-
HLP-22	200.7	0.2	30.6	10.07	9.89	1.3	0.356	-0.05	10	0.04	90	1.0
HLP-22	200.7	0.2	15.6	9.77	10.25	1.5	0.393	-0.04	6	0.00	0	-
HLP-22	200.7	0.2	8.7	9.78	10.32	1.4	0.361	-0.02	6	0.00	0	-
HLP-23	198.3	0.2	51.8	9.99	10.01	1.4	0.384	-0.05	8.	0.05	1920	-
HLP-23	199.6	0.2	92.0	10.09	9.95	1.5	0.401	-0.10	5.	0.06	1997	-
HLP-23	200.0	0.2	69.6	9.88	9.91	1.5	0.397	-0.10	6	0.04	1911	152.9
HLP-23	200.0	0.2	16.8	9.93	10.04	1.5	0.388	-0.04	9	0.05	1077	92.6
HLP-23	200.3	0.2	85.0	9.95	9.96	1.6	0.416	-0.08	7.	0.06	2099	-
HLP-23	200.5	0.2	34.9	10.00	10.04	1.5	0.408	-0.06	8.	0.05	1229	42.8
HLP-23	200.7	0.2	5.8	10.02	9.82	1.5	0.394	-0.03	10	0.02	92	0.9
HLP-24	200.7	0.2	8.7	10.28	9.72	1.5	0.388	-0.06	6	0.00	51	-
HLP-24	200.7	0.2	30.6	9.42	10.50	1.5	0.390	-0.08	8	0.01	128	1.3
HLP-25	200.0	0.2	69.6	8.58	11.29	1.5	0.394	-0.10	6	0.00	621	16.7
HLP-25	200.7	0.2	5.8	8.30	11.41	1.5	0.375	-0.03	10	0.01	0	-
HLP-25	299.8	0.8	1.5	8.05	11.96	1.4	0.366	-0.04	9	0.03	1541	39.6
HLP-25	299.9	0.8	3.1	9.23	11.84	1.5	0.441	-0.27	10	-	1916	344.9
HLP-25	299.9	0.8	2.5	8.47	11.62	1.5	0.385	-0.04	8.	0.02	1956	-
HLP-25	299.9	0.8	1.0	9.03	11.84	1.4	0.408	-0.03	8	0.04	1357	113.6
HLP-25	300.0	0.8	2.0	8.88	11.22	1.5	0.401	-0.04	9	0.05	2012	-
HLP-26	199.3	0.2	5.8	9.96	9.96	1.6	0.408	-0.01	10	0.03	161	2.3
HLP-26	199.8	0.2	1.9	10.04	9.98	1.5	0.422	-0.02	10	0.00	82	0.8
HLP-26	200.1	0.2	11.9	10.08	10.07	1.5	0.410	-0.02	10	0.02	292	3.1
HLP-26	200.6	0.2	24.9	10.06	10.06	1.6	0.412	-0.05	6	0.02	506	6.0
HLP-26	299.9	0.8	1.0	10.03	10.09	1.4	0.385	-0.03	8	0.03	1264	72.8
HLP-26	299.9	0.8	1.5	10.03	10.06	1.4	0.384	-0.04	9	0.04	1525	189.3
HLP-26	299.9	0.8	2.5	10.02	10.04	1.5	0.396	-0.03	8	0.04	1968	-
HLP-26	300.0	0.8	2.0	10.06	10.07	1.5	0.395	-0.03	9	0.05	1950	-
HLP-27	199.3	0.2	5.8	9.97	10.07	1.6	0.401	-0.01	10	-0.08	1459	193.6
HLP-27	199.8	0.2	1.9	10.04	9.96	1.5	0.401	-0.02	10	0.05	1132	58.9
HLP-27	200.1	0.2	11.9	10.06	10.05	1.6	0.404	-0.02	10	-	1998	-
HLP-27	200.3	0.2	2.3	10.08	10.16	1.5	0.409	-0.03	10	0.10	1557	288.3
HLP-27	200.3	0.2	1.0	10.05	10.09	1.4	0.366	-0.02	-	-0.05	236	1.4
HLP-27	200.4	0.2	16.0	10.10	10.16	1.6	0.405	-0.03	10	-	1973	-
HLP-27	200.4	0.2	8.0	10.06	10.16	1.6	0.413	-0.02	-	-	1154	216.8
HLP-27	200.6	0.2	5.1	10.18	10.08	1.5	0.395	-0.02	10	-	1511	255.9

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-27	200.6	0.2	21.7	10.16	10.05	1.6	0.415	-0.04	10	0.07	2032	-
HLP-28	200.1	0.2	5.8	10.04	9.94	1.5	0.383	-0.02	10	0.02	493	6.2
HLP-28	200.1	0.2	1.8	9.99	9.90	1.5	0.395	-0.02	10	0.01	68	0.7
HLP-28	200.1	0.1	11.9	9.99	10.08	1.5	0.389	-0.03	10	0.01	525	6.7
HLP-28	200.4	0.2	12.0	10.00	9.98	1.5	0.390	-0.02	6	0.02	283	7.5
HLP-28	200.6	0.2	19.0	10.05	10.08	1.6	0.393	-0.04	6	0.01	352	5.8
HLP-28	200.6	0.2	19.0	10.13	10.08	1.5	0.380	-0.04	6	0.01	261	5.6
HLP-28	200.7	0.2	26.7	10.06	10.09	1.5	0.390	-0.06	6	0.02	280	7.5
HLP-28	200.7	0.2	26.7	10.15	10.07	1.5	0.390	-0.06	6	0.00	288	7.7
HLP-29	200.3	0.2	13.2	10.14	10.08	1.6	0.410	-0.01	10	0.05	990	43.5
HLP-29	200.4	0.2	7.1	10.08	10.12	1.6	0.408	-0.02	6	0.03	683	13.9
HLP-29	200.6	0.2	7.8	9.94	10.12	1.5	0.395	-0.04	6	0.05	1395	109.2
HLP-29	200.6	0.2	20.8	10.09	10.02	1.6	0.405	-0.04	5	0.06	1853	333.5
HLP-29	200.6	0.2	3.4	9.85	10.07	1.6	0.403	-0.03	6	0.03	813	12.2
HLP-29	200.6	0.2	5.7	10.08	10.11	1.6	0.407	-0.03	5	0.04	1036	38.7
HLP-30	200.1	0.5	5.8	10.00	10.11	1.6	0.416	-0.02	10	0.01	464	10.8
HLP-30	200.1	0.2	1.8	10.09	10.06	1.5	0.415	-0.02	10	0.00	113	1.1
HLP-30	200.1	0.2	11.9	10.09	10.08	1.4	0.377	-0.02	10	0.00	768	19.5
HLP-30	200.3	0.2	23.7	10.10	10.03	1.6	0.409	-0.03	6	0.02	263	8.1
HLP-30	200.3	0.2	23.7	10.21	10.18	1.6	0.425	-0.05	6	0.01	568	17.5
HLP-30	200.4	0.2	12.0	10.21	10.17	1.5	0.414	-0.03	5.	0.02	404	4.6
HLP-30	200.6	0.2	12.9	10.11	10.11	1.6	0.427	-0.03	6	0.01	617	7.6
HLP-30	200.7	0.2	8.8	10.08	10.08	1.6	0.427	-0.03	6	0.01	315	3.2
HLP-30	200.8	0.2	41.0	9.96	10.00	1.4	0.370	-0.06	8.	0.02	821	86.5
HLP-31	200.1	0.2	5.8	10.10	10.11	1.5	0.418	-0.02	10	0.06	1137	11.7
HLP-31	200.1	0.2	1.8	10.12	10.12	1.6	0.422	-0.02	10	0.04	336	5.4
HLP-31	200.1	0.2	11.9	10.10	10.04	1.5	0.412	-0.03	10	0.08	1899	265.5
HLP-31	200.3	0.2	6.8	10.22	10.16	1.6	0.422	-0.02	6	0.06	1537	198.6
HLP-31	200.6	0.2	3.0	10.14	10.15	1.6	0.420	-0.02	6	0.06	1209	26.4
HLP-31	200.6	0.2	5.1	10.13	10.08	1.6	0.421	-0.02	6	0.06	1502	24.6
HLP-31	200.6	0.2	21.7	10.18	10.16	1.6	0.425	-0.03	6	0.07	1826	146.1
HLP-32	200.3	0.2	13.2	10.10	10.06	1.5	0.391	-0.02	10	0.00	50	0.7
HLP-32	200.4	0.2	7.1	10.20	10.13	1.6	0.423	-0.02	6	0.00	25	0.2
HLP-32	200.6	0.2	24.0	10.05	10.17	1.5	0.413	-0.03	6	0.00	102	1.9
HLP-33	200.1	0.2	1.8	10.02	10.09	1.4	0.351	-0.02	10	0.03	137	2.3
HLP-33	200.1	0.2	5.8	10.09	10.07	1.5	0.419	-0.02	10	0.01	180	1.8
HLP-33	200.1	0.2	11.9	10.10	10.11	1.5	0.424	-0.02	10	0.00	113	2.2
HLP-33	200.2	0.2	30.0	10.05	10.06	1.5	0.420	-0.04	8.	0.06	1656	0.0
HLP-33	200.7	0.2	50.0	10.04	10.08	1.5	0.401	-0.06	7	0.05	1981	-
HLP-33	200.8	0.2	45.0	9.99	10.03	1.5	0.406	-0.06	8.	0.05	2026	-
HLP-34	200.4	0.2	7.1	10.18	10.09	1.4	0.438	-0.02	10	0.00	152	0.8
HLP-34	200.6	0.2	24.0	10.18	10.13	1.2	0.425	-0.03	6	0.00	102	3.2

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-35	198.3	0.2	46.8	10.04	10.09	1.5	0.408	-0.04	8	0.05	1575	133.4
HLP-35	200.1	0.2	5.8	9.94	10.01	1.5	0.390	-0.02	10	-0.01	1166	107.6
HLP-35	200.1	0.2	2.0	10.01	9.93	1.5	0.400	-0.02	10	0.01	460	22.5
HLP-35	200.3	0.2	6.8	10.12	10.07	1.5	0.412	-0.02	6	0.03	966	117.3
HLP-35	200.4	0.2	16.0	9.98	9.91	1.5	0.391	-0.01	6	0.06	1178	175.1
HLP-35	200.5	0.2	29.9	10.05	10.05	1.5	0.400	-0.04	9.	0.07	1376	63.2
HLP-35	200.6	0.2	3.0	10.02	10.05	1.5	0.405	-0.02	6	0.03	653	39.9
HLP-35	200.6	0.2	5.1	10.09	9.89	1.5	0.405	-0.02	6	0.03	976	120.0
HLP-35	200.6	0.2	21.7	10.06	10.12	1.6	0.417	-0.03	6	0.04	1165	85.1
HLP-35	201.0	0.2	60.8	9.18	10.91	1.5	0.405	-0.06	9	0.05	1594	139.1
HLP-36	200.6	0.2	50.0	9.55	10.37	1.5	0.400	-0.06	10	0.00	575	7.7
HLP-36	200.7	0.2	8.7	9.62	10.35	1.4	0.395	-0.06	6	0.01	27	0.1
HLP-36	200.7	0.2	30.6	9.76	10.35	1.5	0.420	-0.08	8	0.02	697	33.5
HLP-37	200.4	0.2	7.1	10.14	10.09	1.2	0.402	-0.02	10	0.00	16	0.2
HLP-37	200.6	0.2	24.0	10.21	10.16	1.5	0.412	-0.03	6	0.01	101	1.9
HLP-37	200.6	0.2	50.0	10.09	10.11	1.5	0.421	-0.06	10	0.02	463	16.5
HLP-38	200.1	0.2	84.1	10.09	10.08	1.5	0.436	-0.09	10	-0.07	1030	55.6
HLP-38	200.2	0.2	73.0	10.04	10.11	1.5	0.438	-0.07	10	0.00	802	41.3
HLP-38	200.3	0.2	13.2	10.10	10.13	1.4	0.410	-0.02	10	0.01	470	18.3
HLP-38	200.4	0.2	7.1	10.16	10.10	1.6	0.456	-0.02	6	0.01	27	0.4
HLP-38	200.6	0.2	24.0	10.18	10.16	1.3	0.394	-0.03	6	0.04	602	55.9
HLP-39	200.1	0.2	5.3	9.95	9.88	1.5	0.416	-0.02	10	0.00	14	0.6
HLP-39	200.1	0.2	2.0	9.96	9.99	1.5	0.428	-0.02	10	0.01	195	8.7
HLP-39	200.6	0.2	3.9	9.98	9.95	1.5	0.396	-0.03	6	0.02	13	0.3
HLP-40	199.5	0.2	51.1	9.94	10.04	1.5	0.415	-0.10	8	0.01	179	6.5
HLP-40	199.7	0.2	88.0	9.96	9.85	1.3	0.363	-0.11	10	0.01	200	8.1
HLP-41	200.1	0.2	5.3	10.00	10.11	1.5	0.448	-0.02	10	0.00	280	13.2
HLP-41	200.1	0.2	11.9	9.95	10.07	1.5	0.435	-0.03	10	0.01	474	17.0
HLP-41	200.1	0.2	2.0	10.07	10.10	1.5	0.448	-0.02	10	0.00	209	5.3
HLP-41	200.4	0.2	29.9	10.15	10.05	1.5	0.420	-0.06	6	0.00	350	15.3
HLP-41	200.4	0.2	29.9	10.10	10.16	1.5	0.434	-0.04	6	0.01	293	6.2
HLP-41	200.6	0.2	35.6	10.01	10.12	1.6	0.449	-0.08	6	0.02	322	8.2
HLP-41	200.6	0.2	50.8	10.05	9.80	1.6	0.434	-0.09	6	0.02	356	11.4
HLP-41	200.6	0.2	35.6	10.10	10.10	1.5	0.439	-0.07	8	0.03	206	4.2
HLP-42	200.3	0.2	13.2	10.07	10.07	1.5	0.462	-0.02	6	0.00	143	2.1
HLP-42	200.4	0.2	7.1	10.03	10.42	1.5	0.471	-0.01	6	0.00	0	-
HLP-42	200.6	0.2	88.0	10.06	10.12	1.5	0.459	-0.10	6.	0.00	102	1.0
HLP-42	200.6	0.2	24.0	10.11	10.08	1.5	0.450	-0.04	6	0.00	142	0.7
HLP-42	200.7	0.2	70.0	10.07	10.07	1.5	0.462	-0.09	8	0.00	131	0.6
HLP-43	200.1	0.2	5.8	10.02	9.90	1.6	0.422	-0.02	10	0.01	283	2.8
HLP-43	200.1	0.2	2.0	9.94	10.00	1.5	0.414	-0.02	10	0.00	134	2.6
HLP-43	200.1	0.2	11.9	10.01	9.98	1.5	0.412	-0.03	10	0.02	425	9.8

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-43	299.8	0.8	1.5	9.94	10.03	1.5	0.390	-0.04	9	0.03	1535	97.5
HLP-43	299.9	0.8	1.0	9.90	10.01	1.5	0.401	-0.03	8	0.03	1302	50.2
HLP-43	300.0	0.8	2.0	9.90	9.99	1.5	0.400	-0.03	9	0.04	2022	-
HLP-44	200.4	0.2	120.0	9.99	10.08	1.5	0.400	-0.05	8.	0.02	1019	29.3
HLP-45	200.4	0.2	120.0	9.93	10.00	1.4	0.371	-0.05	8.	0.04	1310	65.8
HLP-46	149.7	0.1	41.2	10.01	10.06	1.4	0.372	-0.02	5.	0.07	1597	222
HLP-46	149.7	0.1	41.2	10.13	10.12	1.5	0.39	-0.02	5.	0.07	1685	262
HLP-46	149.8	0.1	34.3	10.02	10.08	1.6	0.396	-0.02	-	0.10	1593	201
HLP-46	149.8	0.1	34.3	10.15	10.03	1.5	0.399	-0.02	-	0.09	1592	117
HLP-46	150.1	0.1	23.3	10.08	9.98	1.6	0.406	-0.01	6.	0.07	1403	76
HLP-46	150.1	0.1	23.3	10.09	10.02	1.6	0.406	-0.01	6.	0.06	1585	128
HLP-46	150.2	0.1	15.0	10.02	10.08	1.5	0.408	-0.02	5.	0.07	1138	44
HLP-46	150.2	0.1	15.0	9.99	10.03	1.5	0.392	-0.01	5.	0.06	1089	27
HLP-46	150.4	0.1	7.3	10.07	10.10	1.5	0.407	-0.07	5.	0.00	176	2
HLP-46	150.4	0.1	7.3	10.01	10.01	1.6	0.424	-0.01	5.	0.02	378	5
HLP-46	175.2	0.1	6.2	10.00	10.01	1.4	0.362	-0.02	5.	0.06	1208	64
HLP-46	175.2	0.1	6.2	9.92	9.99	1.5	0.378	-0.02	5.	0.05	1424	59
HLP-46	175.3	0.1	11.1	10.01	10.08	1.6	0.412	-0.03	5	0.06	1779	115
HLP-46	175.3	0.1	11.1	9.99	10.05	1.5	0.388	-0.03	5	0.06	1562	178
HLP-46	175.4	0.1	8.1	9.98	10.11	1.4	0.375	-0.02	10	0.07	1537	190
HLP-46	175.4	0.1	8.1	9.98	10.11	1.6	0.407	-0.03	5	0.07	1435	151
HLP-46	175.4	0.1	3.1	10.05	9.90	1.6	0.399	-0.02	4.	0.05	989	18
HLP-46	175.4	0.1	12.0	10.01	10.09	1.6	0.401	-0.02	5	0.08	1851	278
HLP-46	175.4	0.1	12.0	10.00	10.05	1.5	0.391	-0.01	10	0.08	1862	107
HLP-46	199.9	0.2	4.9	9.95	9.95	1.4	0.365	-0.03	5	0.06	1809	179
HLP-46	199.9	0.2	4.9	10.16	10.08	1.5	0.4	-0.03	5	0.06	1871	156
HLP-46	200.0	0.2	1.1	10.09	10.03	1.6	0.401	-0.03	5	0.05	892	19
HLP-46	200.0	0.2	3.9	10.05	10.08	1.6	0.409	-0.03	5	0.06	1694	103
HLP-46	200.0	0.2	3.9	10.06	10.09	1.5	0.398	-0.03	5	0.06	1748	139
HLP-46	200.0	0.2	1.1	10.20	9.97	1.6	0.403	-0.02	5	0.05	898	22
HLP-46	200.1	0.2	2.1	10.13	10.01	1.5	0.373	-0.02	5	0.05	1053	105
HLP-46	200.1	0.2	2.1	10.03	10.10	1.6	0.403	-0.02	5	0.05	1289	33
HLP-46	200.2	0.2	3.0	10.06	10.01	1.5	0.375	-0.02	5	0.06	1568	161
HLP-46	200.2	0.2	3.0	10.07	9.95	1.5	0.38	-0.02	5.	0.05	1476	50
HLP-47	200.0	0.2	18.0	9.93	10.00	1.5	0.390	-0.03	9	0.04	1381	64.8
HLP-47	200.0	0.2	10.0	10.00	10.06	1.5	0.391	-0.02	8	0.04	1103	142.3
HLP-47	200.0	0.2	29.9	10.04	10.05	1.5	0.406	-0.03	8	0.03	1324	70.6
HLP-47	200.2	0.2	38.0	10.00	10.06	1.4	0.390	-0.05	10	0.05	1724	232.8
HLP-47	200.6	0.2	5.0	9.92	10.01	1.4	0.368	-0.02	10	0.04	513	6.9
HLP-47	200.6	0.2	22.0	10.11	10.05	1.5	0.387	-0.02	6	0.02	1158	41.7
HLP-47	200.6	0.2	15.0	9.91	10.04	1.5	0.389	-0.03	8	0.03	785	18.6
HLP-48	150.6	0.1	214.7	9.91	10.05	1.5	0.375	-0.10	10	0.03	1004	64

Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-48	150.6	0.1	214.7	9.93	10.07	1.4	0.383	-0.04	10	0.03	1054	87
HLP-48	150.7	0.1	188.6	10.09	9.94	1.6	0.417	-0.04	-	0.01	1059	51
HLP-48	150.7	0.1	72.0	9.95	9.96	1.5	0.386	-0.02	6.	0.01	441	6
HLP-48	150.7	0.1	188.6	9.98	10.18	1.5	0.409	-0.05	-	0.04	1103	68
HLP-48	150.7	0.1	72.0	9.99	10.08	1.6	0.401	-0.04	10	0.02	647	10
HLP-48	174.8	0.1	41.9	10.02	9.80	1.6	0.418	-0.03	6.	0.06	1205	28
HLP-48	174.8	0.1	41.9	10.04	10.07	1.6	0.418	-0.03	5.	0.06	1397	103
HLP-48	175.2	0.1	78.6	10.18	10.00	1.6	0.44	-0.05	5.	0.05	1875	185
HLP-48	175.2	0.1	78.6	9.96	9.99	1.5	0.386	-0.05	5.	0.05	1727	223
HLP-48	175.3	0.1	68.9	10.24	10.07	1.5	0.42	-0.05	6.	0.07	1460	178
HLP-48	175.3	0.1	68.9	10.10	10.17	1.5	0.412	-0.04	6.	0.05	1617	238
HLP-48	175.4	0.1	14.7	9.97	9.97	1.6	0.427	-0.03	5.	0.07	634	8
HLP-48	175.4	0.1	14.7	10.01	10.20	1.6	0.422	-0.02	6.	0.08	969	16
HLP-48	199.6	0.2	14.0	9.95	10.01	1.4	0.377	-0.04	5.	0.04	1278	47
HLP-48	199.6	0.2	14.0	10.02	10.08	1.4	0.389	-0.04	5.	0.03	1372	154
HLP-48	199.8	0.2	22.2	10.11	9.95	1.5	0.381	-0.06	5.	0.02	1582	248
HLP-48	199.8	0.2	22.2	10.05	10.02	1.4	0.389	-0.06	5.	0.05	1704	218
HLP-48	199.9	0.2	11.2	10.01	10.13	1.6	0.422	-0.04	5.	0.06	1057	10
HLP-48	199.9	0.2	11.2	10.01	10.03	1.6	0.422	-0.03	6.	0.05	1273	49
HLP-48	200.1	0.2	6.2	10.17	9.98	1.6	0.415	-0.03	5.	0.03	762	9
HLP-48	200.1	0.2	6.2	10.05	10.04	1.5	0.392	-0.03	5.	0.04	881	26
HLP-49	199.5	0.2	51.1	9.95	10.06	1.5	0.424	-0.10	8	0.03	617	31.7
HLP-49	199.7	0.2	88.0	10.13	10.12	1.4	0.409	-0.11	10	0.04	714	32.5
HLP-49	200.3	0.2	13.2	9.94	10.30	1.4	0.384	-0.02	6	0.01	200	2.3
HLP-49	200.4	0.2	7.1	10.02	10.03	1.5	0.407	-0.01	6	0.02	135	1.4
HLP-49	200.6	0.2	24.0	10.27	9.90	1.5	0.407	-0.04	6	0.03	527	6.8
HLP-51	150.6	0.1	214.7	9.84	10.09	1.3	0.359	-0.10	10	0.03	624	46
HLP-51	150.6	0.1	214.7	10.14	10.04	1.5	0.421	-0.04	10	0.03	468	31
HLP-51	150.7	0.1	188.6	10.10	10.00	1.5	0.421	-0.05	-	0.02	367	6
HLP-51	199.1	0.2	27.0	9.99	9.98	1.4	0.384	-0.05	10	0.04	671	116
HLP-51	199.6	0.2	14.0	10.05	10.00	1.5	0.411	-0.04	5.	0.00	547	75
HLP-51	199.8	0.2	22.2	10.03	10.07	1.5	0.412	-0.06	5.	0.04	586	29
HLP-51	199.8	0.2	22.2	10.07	10.01	1.5	0.395	-0.06	5.	0.02	472	44
HLP-51	199.9	0.2	11.2	10.01	9.96	1.6	0.418	-0.04	5.	0.01	274	14
HLP-51	199.9	0.2	11.2	10.08	10.05	1.5	0.393	-0.03	6.	0.02	407	31
HLP-51	200.1	0.2	33.2	9.96	10.05	1.5	0.391	-0.05	10	0.05	618	80
HLP-51	200.1	0.2	6.2	10.11	10.07	1.5	0.393	-0.03	5.	0.02	335	19
HLP-51	200.1	0.2	6.2	10.14	9.96	1.6	0.42	-0.03	5.	0.00	403	21
HLP-51	200.6	0.2	24.9	9.93	9.81	1.4	0.350	-0.05	6	0.02	484	2.7
HLP-52	200.5	0.2	3.0	10.11	10.08	1.5	0.419	-0.02	8	0.07	2056	-
HLP-52	200.5	0.2	1.6	10.06	10.10	1.5	0.390	-0.01	10	0.10	1791	129.0
HLP-52	200.5	0.2	1.0	10.06	10.06	1.4	0.400	-0.02	-	-	1512	124.4

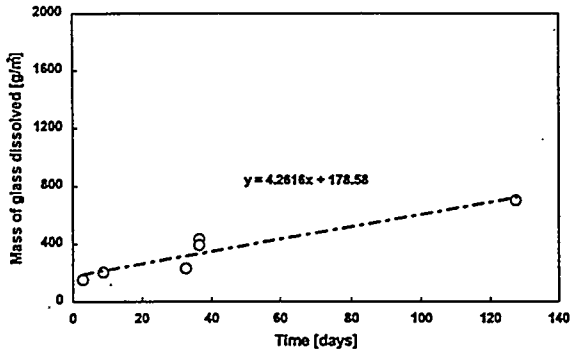
Table C-1 Continued

Glass	Termination Temperature [°C]	H_2O added [g]	Duration [days]	Sample's width [mm]	Sample's length [mm]	Sample's thickness [mm]	Sample mass [g]	Assembly mass change [g]	pH after termination	Sample mass gain [g]	Mass of glass dissolved [g/m^2]	Confidence interval 95%
HLP-52	200.5	0.2	0.5	10.15	10.04	1.5	0.398	-0.02	10	0.06	485	6.1
HLP-53	200.0	0.2	2.9	9.99	10.05	1.5	0.413	-0.02	10	0.06	1892	0.0
HLP-53	200.0	0.2	0.9	10.02	10.03	1.4	0.374	-0.07	10	0.00	185	3.1
HLP-53	200.0	0.2	2.0	9.86	10.06	1.4	0.390	-0.03	10	0.03	1376	89.3
HLP-53	200.3	0.2	1.5	10.05	9.98	1.5	0.424	-0.01	10	0.00	149	0.7
HLP-54	200.5	0.2	6.9	9.96	9.92	1.4	0.340	-0.02	6	0.03	537	7.9
HLP-54	200.6	0.2	14.0	9.98	10.13	1.5	0.380	-0.03	5	0.04	1103	49.3
HLP-54	200.6	0.2	10.1	9.92	10.01	1.4	0.349	-0.03	6	0.04	951	50.7
HLP-54	200.7	0.2	28.6	10.03	9.89	1.5	0.379	-0.06	10	0.02	1373	272.1
HLP-54	200.7	0.2	15.6	10.04	10.03	1.5	0.379	-0.05	8	0.03	1133	149.4
HLP-55	200.4	0.2	41.2	9.92	9.83	1.5	0.360	-0.07	6	-0.01	1433	151.7
HLP-55	200.5	0.2	6.9	9.97	9.98	1.5	0.360	-0.02	6	0.04	458	11.8
HLP-55	200.6	0.2	14.0	9.94	9.94	1.6	0.380	-0.03	5	0.02	733	32.0
HLP-55	200.6	0.2	33.9	9.78	9.92	1.5	0.364	-0.04	8	0.04	1101	89.5
HLP-55	200.7	0.2	8.1	9.82	9.87	1.4	0.341	-0.03	6	0.04	606	31.5
HLP-56	200.4	0.2	49.8	10.54	9.71	1.5	0.429	-0.07	7	0.00	199	2.0
HLP-56	200.5	0.2	34.8	10.36	9.64	1.4	0.382	-0.05	5.	0.00	169	5.5
HLP-56	200.8	0.2	69.0	10.60	9.41	1.5	0.407	-0.07	9	0.00	121	1.8
HLP-56	249.6	0.4	9.9	10.54	9.55	1.5	0.416	-0.07	6	0.05	1298	96.7
HLP-56	249.6	0.4	12.1	10.39	9.55	1.5	0.392	-0.09	6	0.03	1409	94.4
HLP-56	249.7	0.4	7.8	10.54	9.42	1.5	0.406	-0.06	7	0.05	1148	72.9
HLP-56	249.7	0.4	5.3	10.58	9.58	1.5	0.416	-0.05	10	0.02	813	6.3
HLP-56	299.3	0.8	2.5	9.58	10.50	1.5	0.418	-0.06	5.	0.05	1878	90.1
HLP-56	299.7	0.8	1.5	10.05	9.98	1.4	0.408	-0.04	6	0.04	1256	31.7
HLP-56	299.8	0.8	1.0	10.04	9.97	1.5	0.406	-0.03	8	0.04	981	17.9
HLP-56	299.8	0.8	2.0	10.07	9.93	1.3	0.342	-0.04	5.	0.06	1582	-

APPENDIX D

VHT Alteration Extent as a Function of Time (plots)

APPENDIX D
VHT Alteration Extent as a Function of Time (plots)



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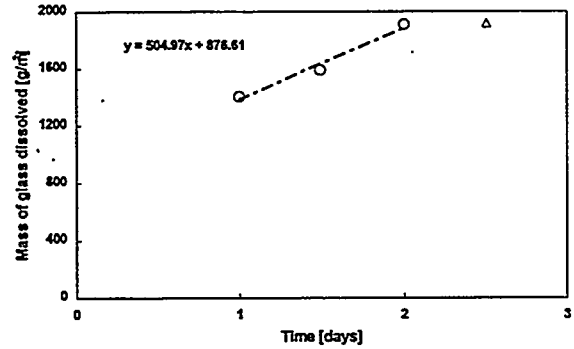

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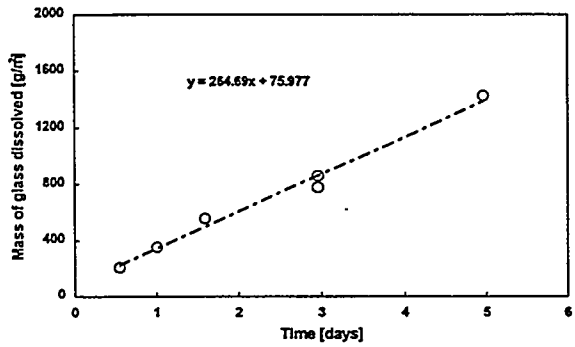

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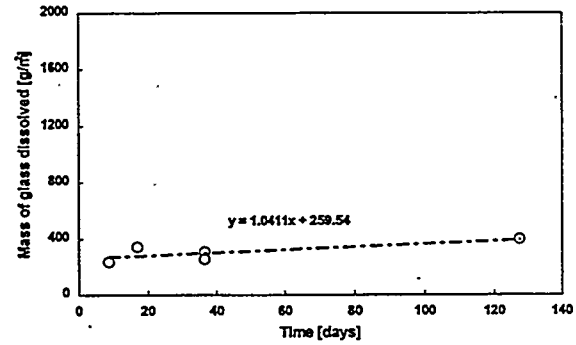

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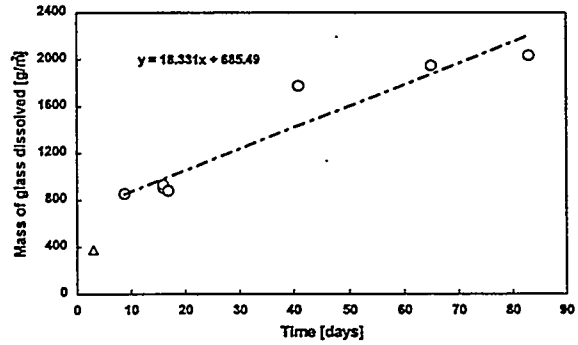

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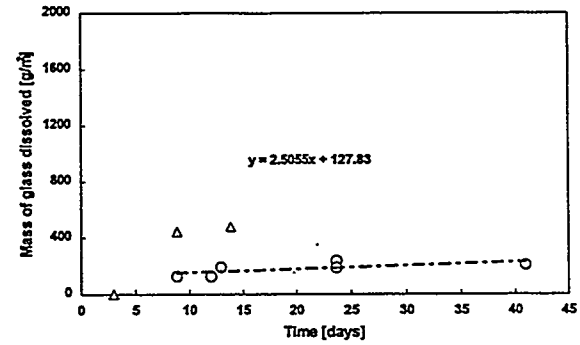

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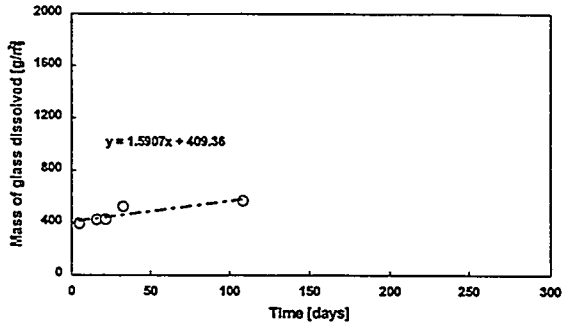

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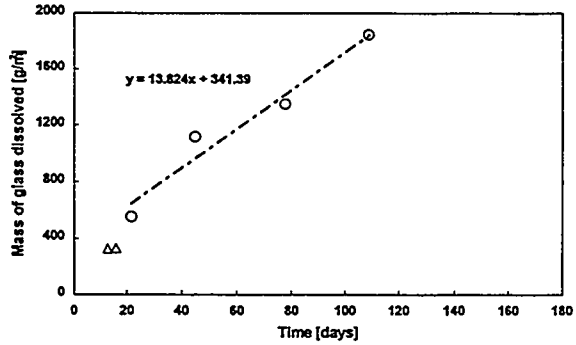

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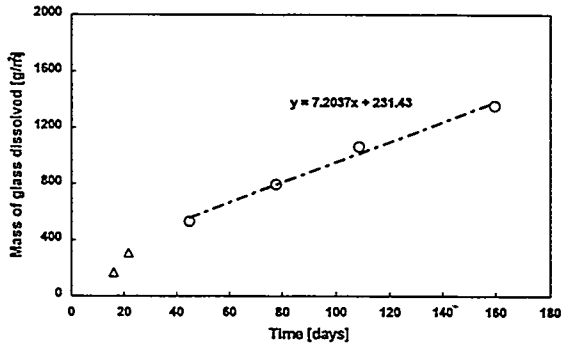

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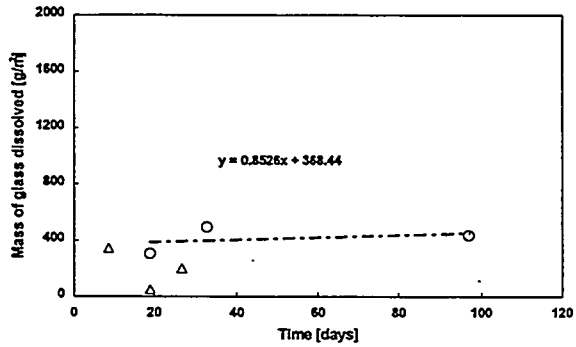

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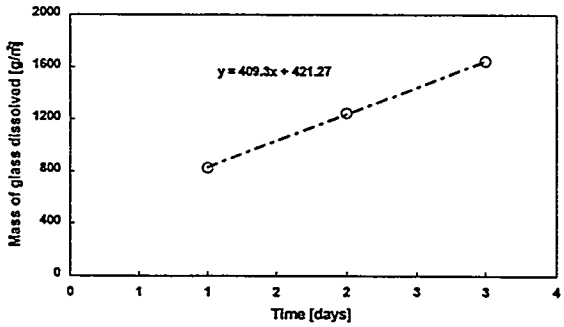

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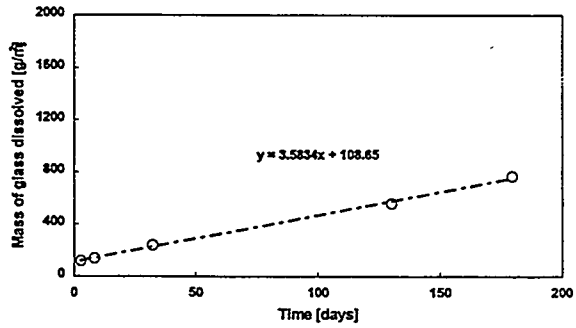

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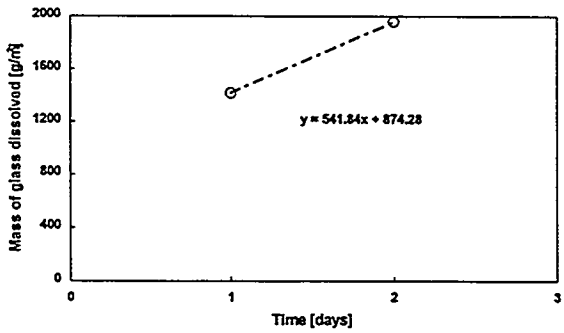

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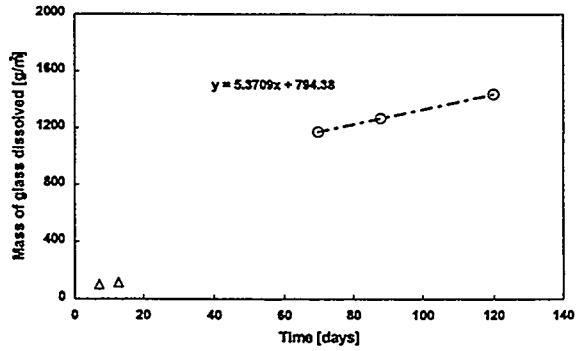

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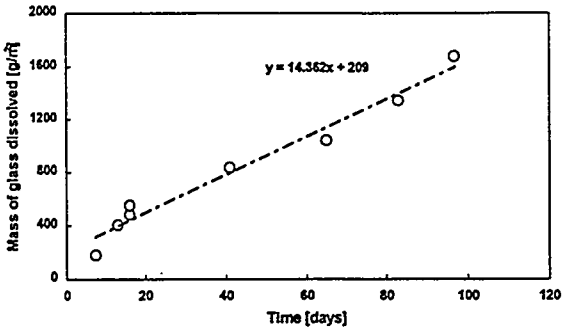

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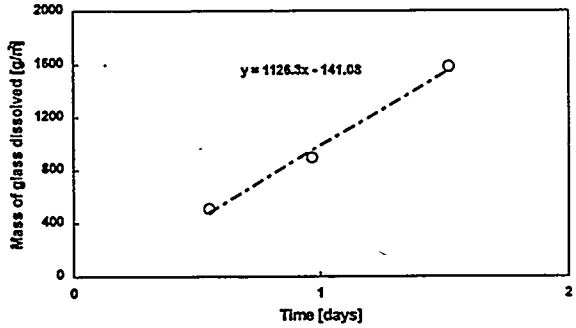

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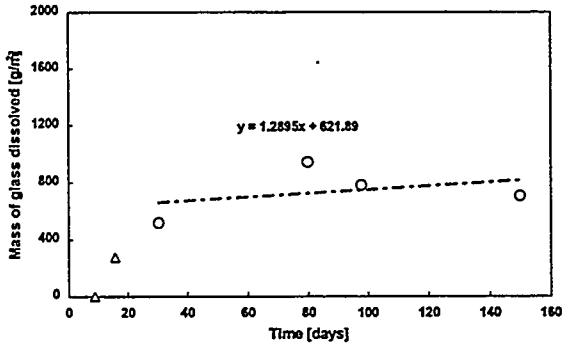

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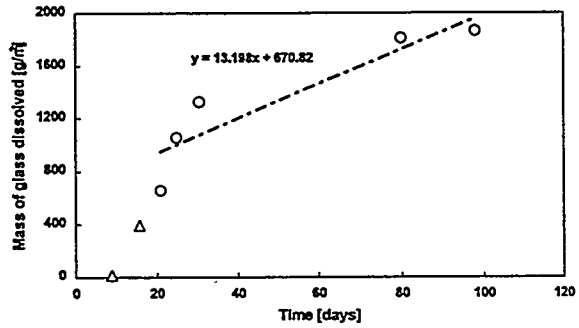

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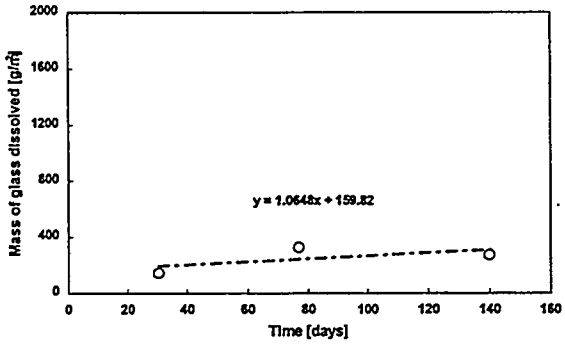

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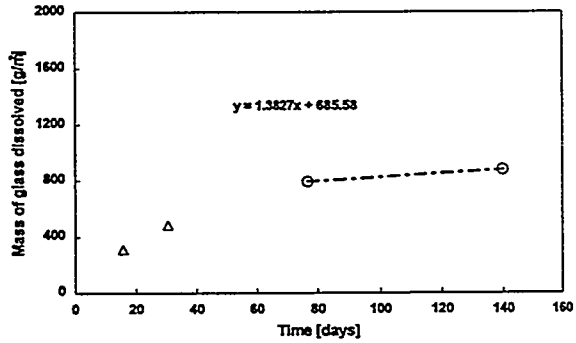

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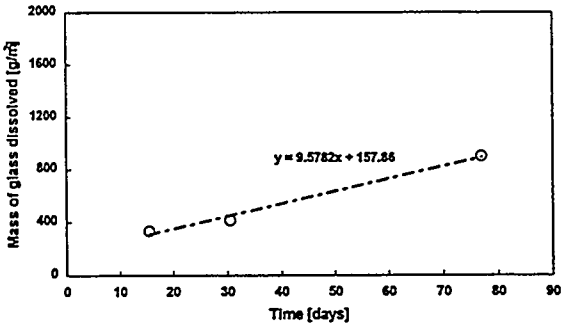

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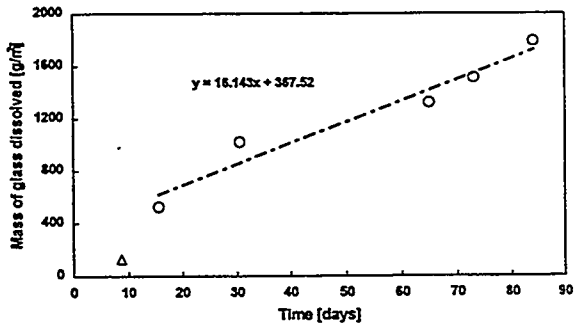

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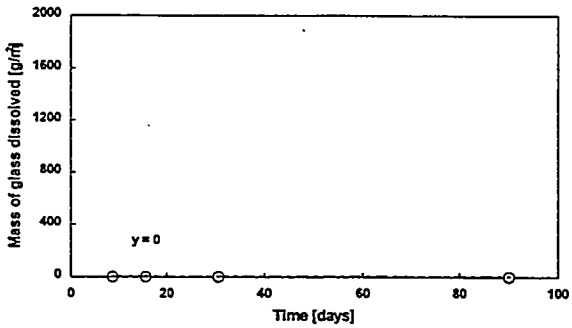

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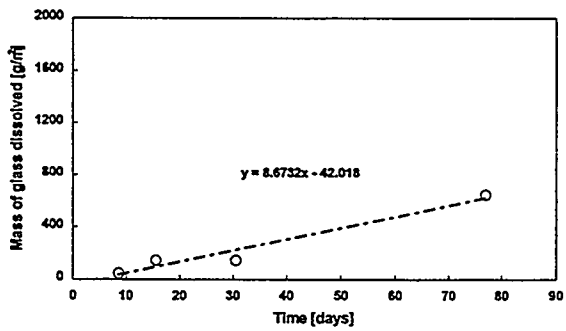
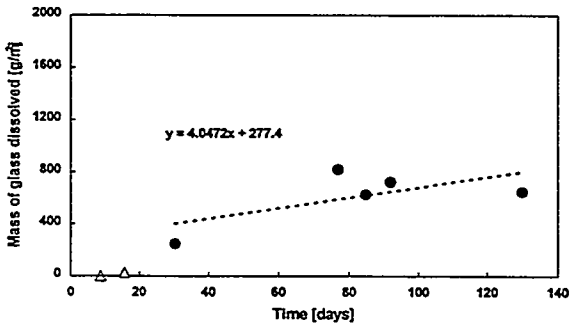
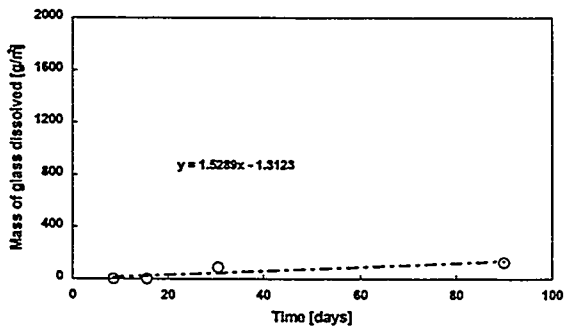


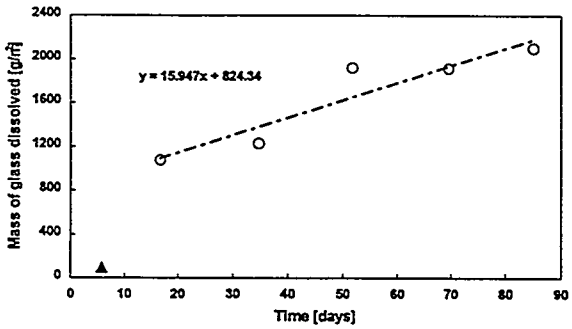
HLP-20, 200°C



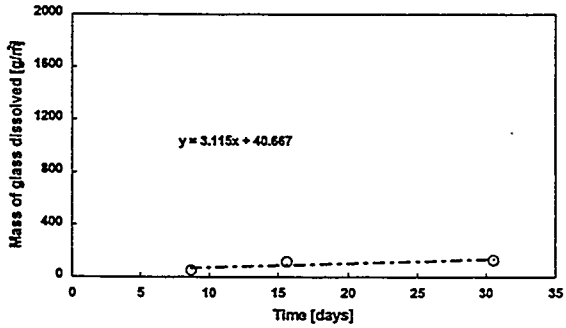
HLP-21, 200°C



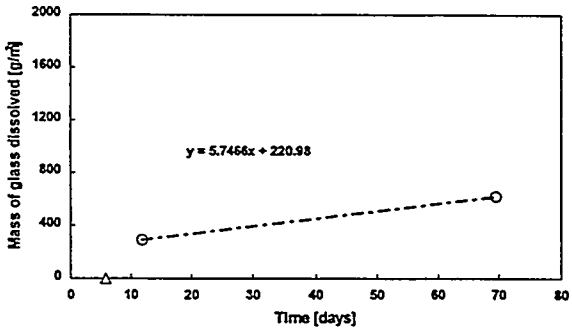
HLP-22, 200°C



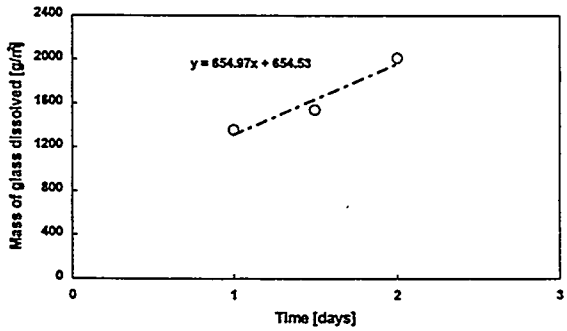
HLP-23, 200°C



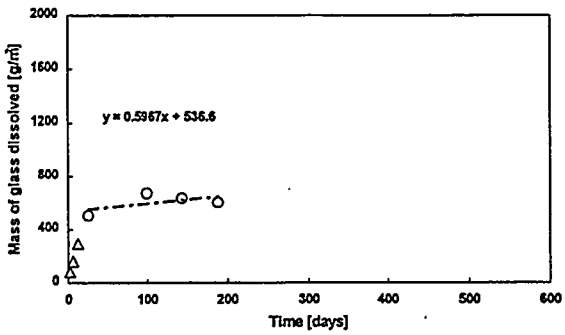
HLP-24, 200°C



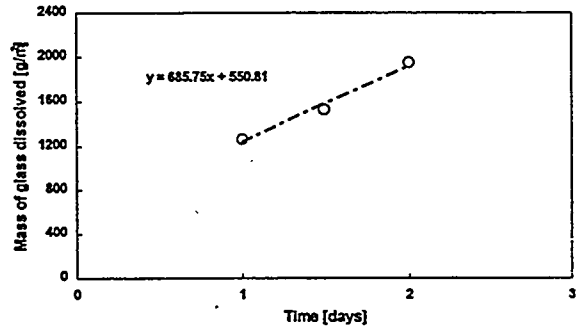
HLP-25, 200°C



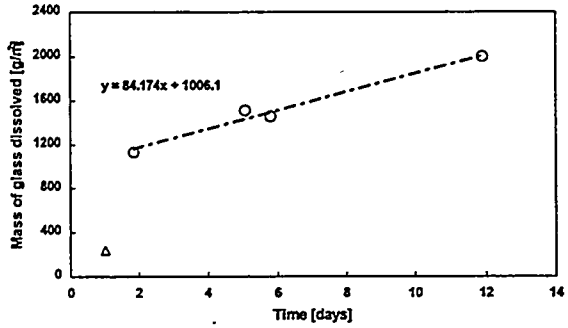
HLP-25, 300°C



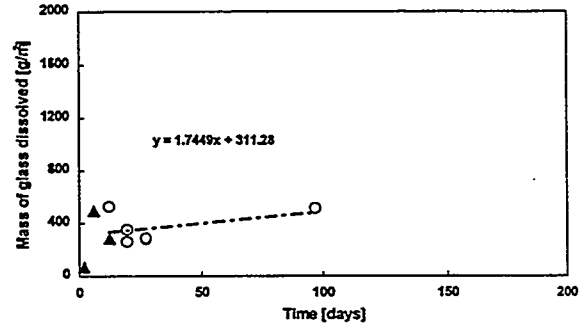
HLP-26, 200°C



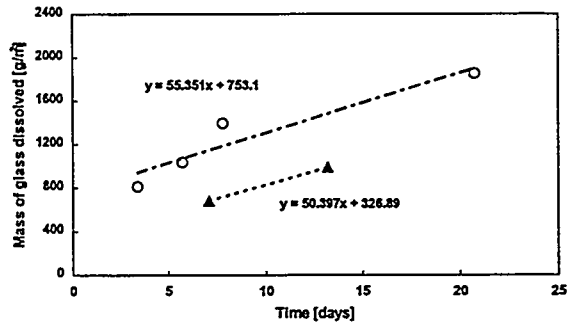
HLP-26, 300°C



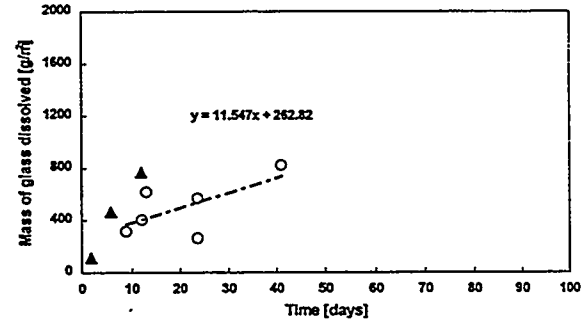
HLP-27, 200°C



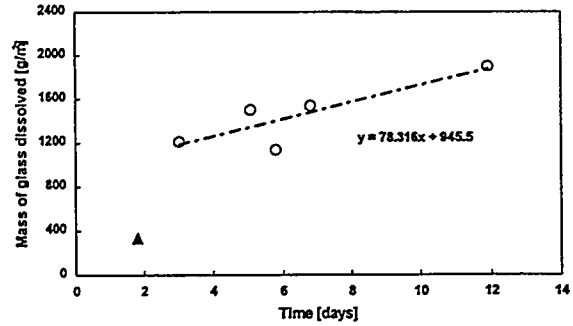
HLP-28, 200°C



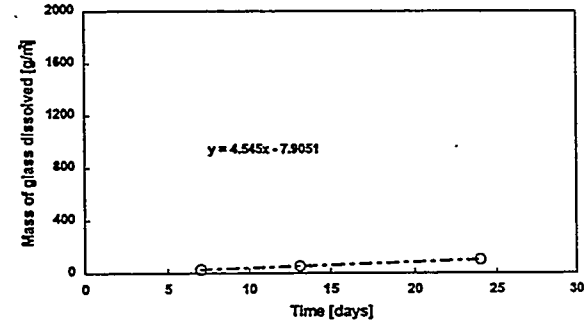
HLP-29, 200°C



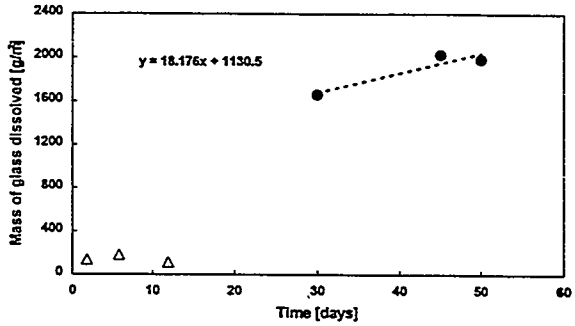
HLP-30, 200°C



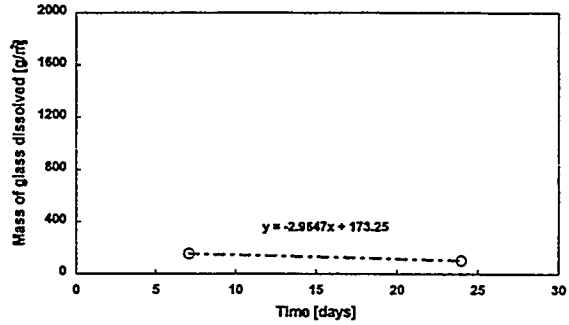
HLP-31, 200°C



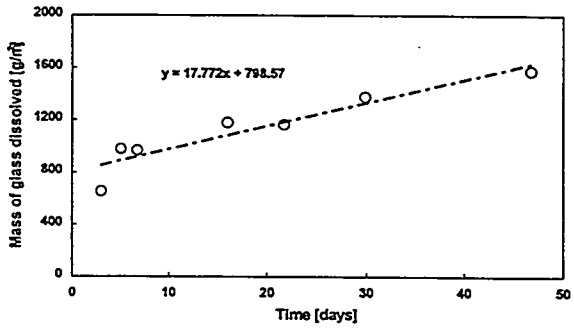
HLP-32, 200°C



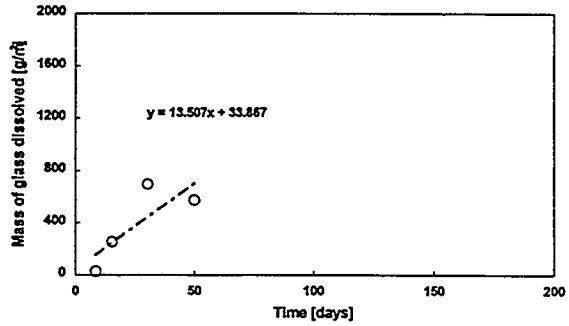
HLP-33, 200°C



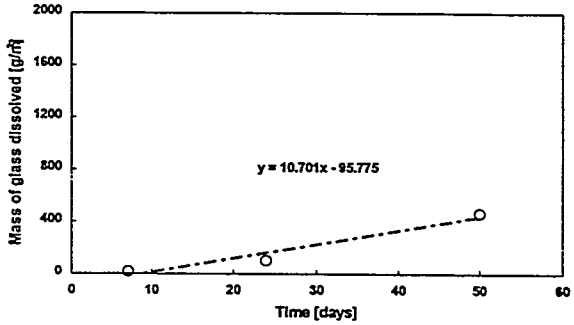
HLP-34, 200°C



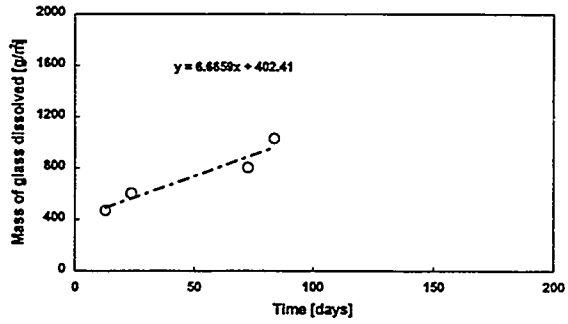
HLP-35, 200°C



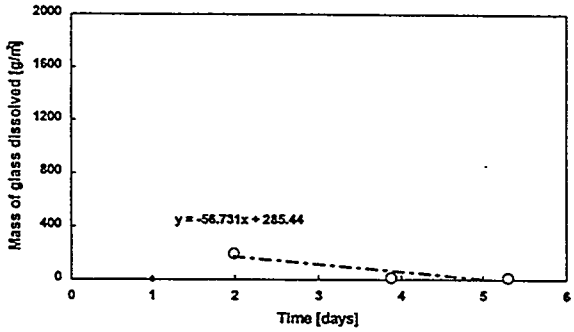
HLP-36, 200°C



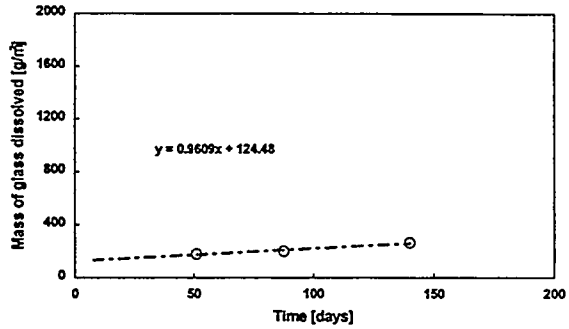
HLP-37, 200°C



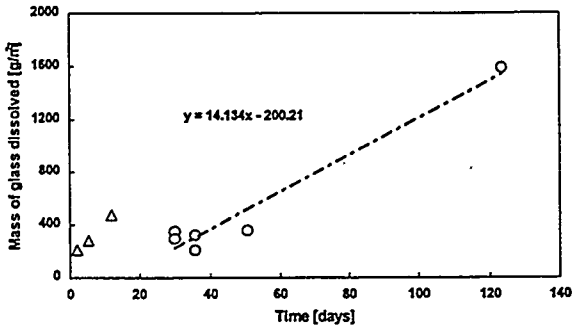
HLP-38, 200°C



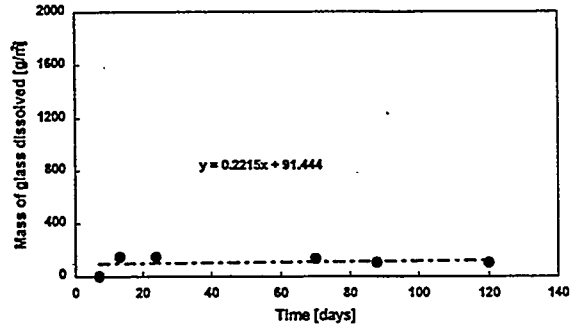
HLP-39, 200°C



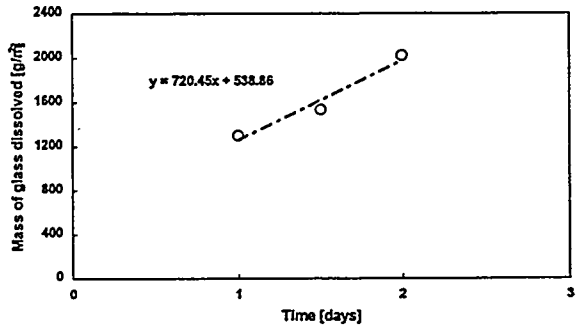
HLP-40, 200°C



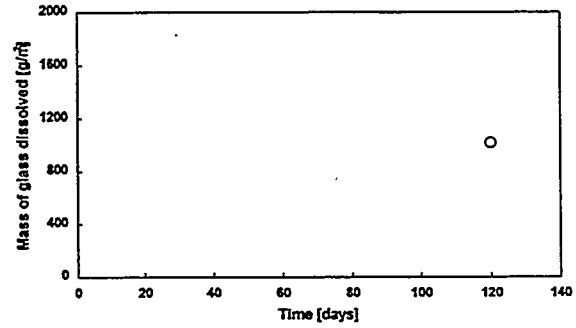
HLP-41, 200°C



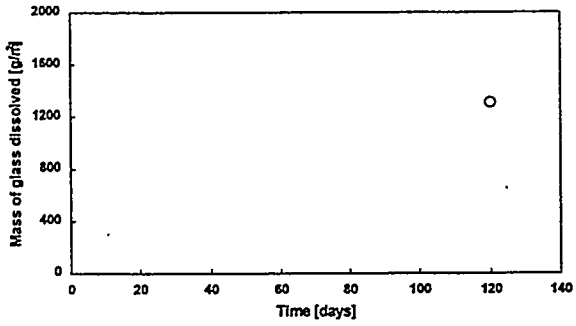
HLP-42, 200°C



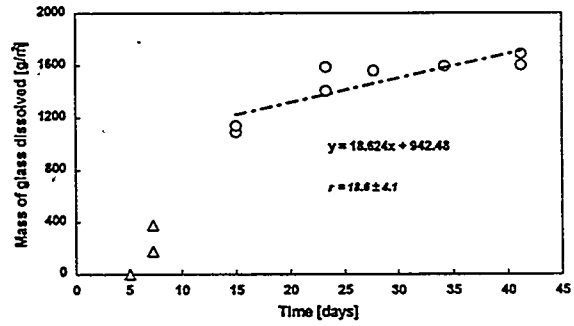
HLP-43, 300°C



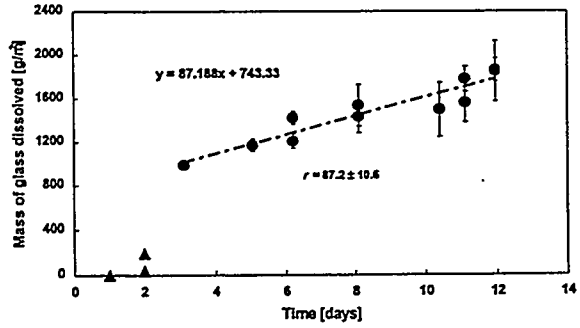
HLP-44, 200°C



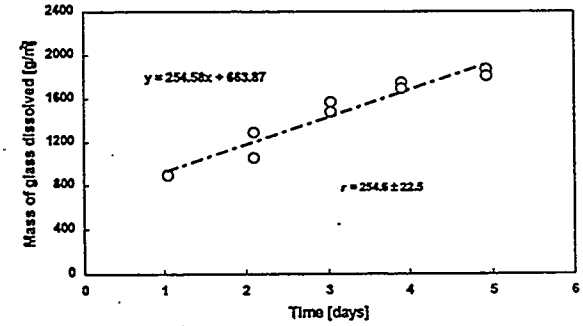
HLP-45, 200°C



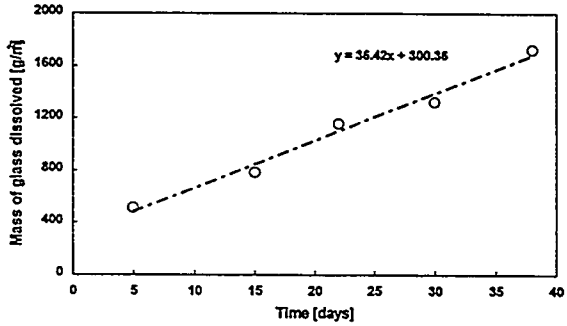
HLP-46, 150°C



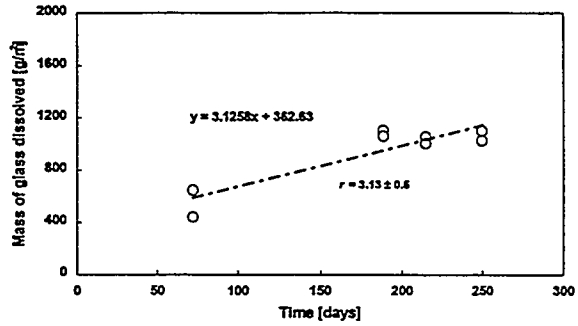
HLP-46, 175°C



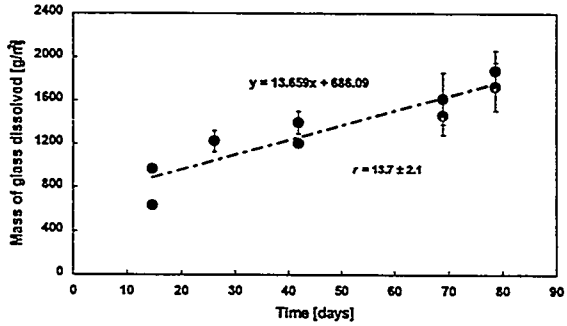
HLP-46, 200°C



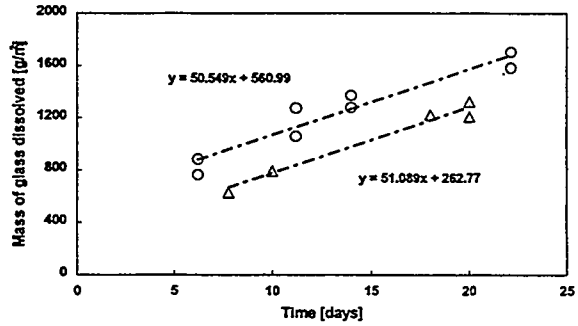
HLP-47, 200°C



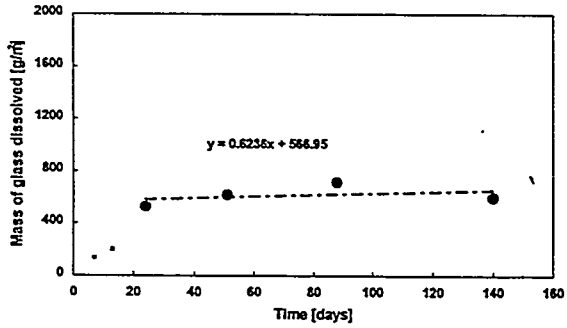
HLP-48, 150°C



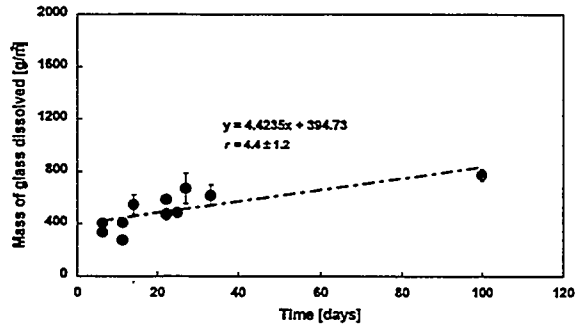
HLP-48, 175°C



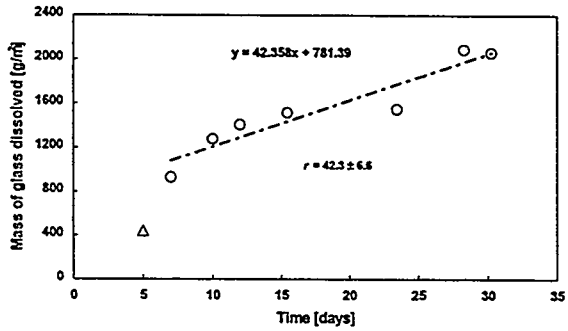
HLP-48, 200°C



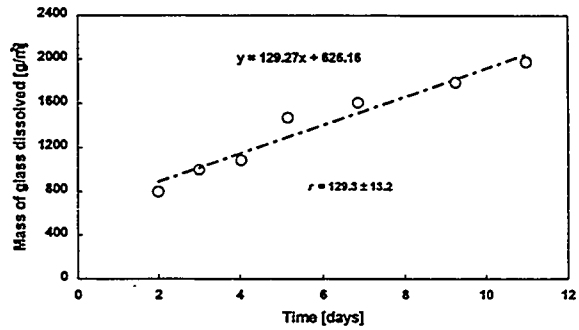
HLP-49, 200°C



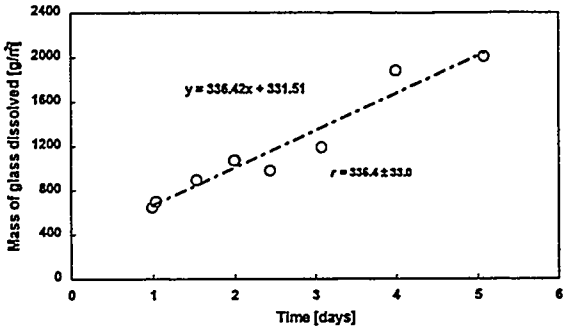
HLP-51, 200°C



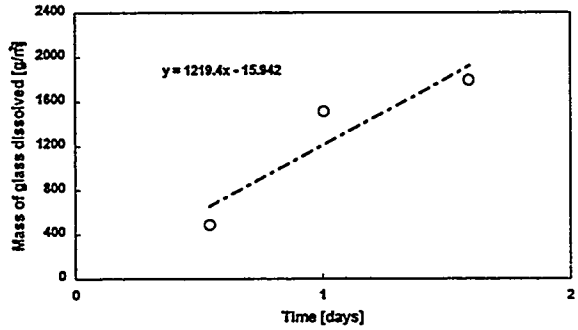
HLP-51, 250°C



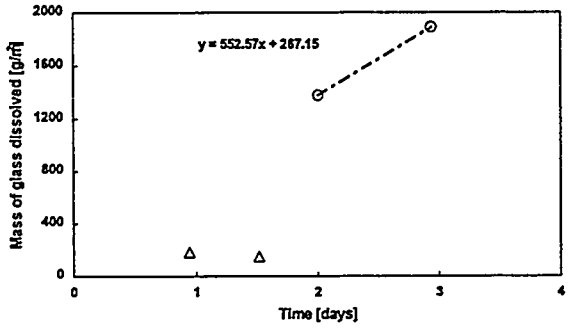
HLP-51, 275°C



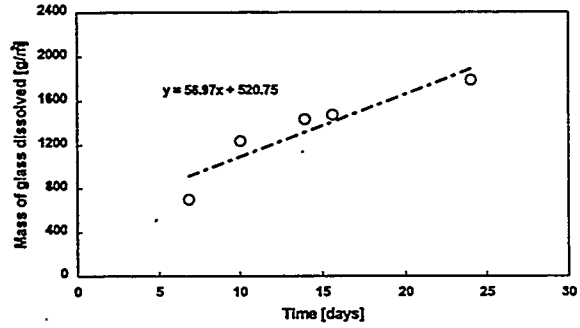
HLP-51, 300°C



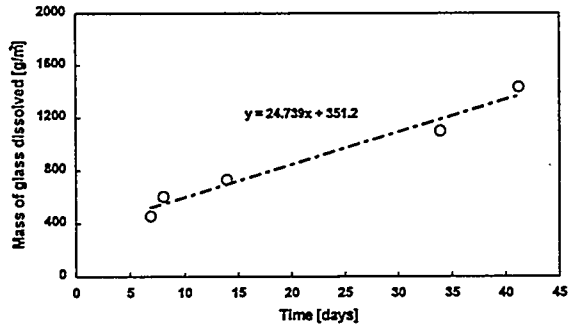
HLP-52, 200°C



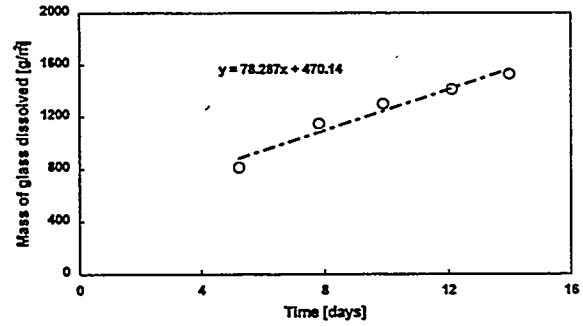
HLP-53, 200°C



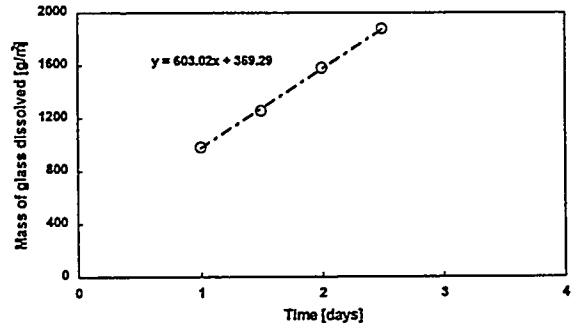
HLP-54, 200°C



HLP-55, 200°C



HLP-56, 250°C



HLP-56, 300°C

APPENDIX E

VHT Alteration from Literature

APPENDIX E
VHT Alteration from Literature

Results on HLP-46, HLP-55, and HLP-54 published by Feng et al. (1996) are summarized in Table E-1 together with results on HLP-48 are published in McGrail et al. (1999). All tests were conducted according to the Argonne National Laboratory vapor hydration test (VHT) procedure.

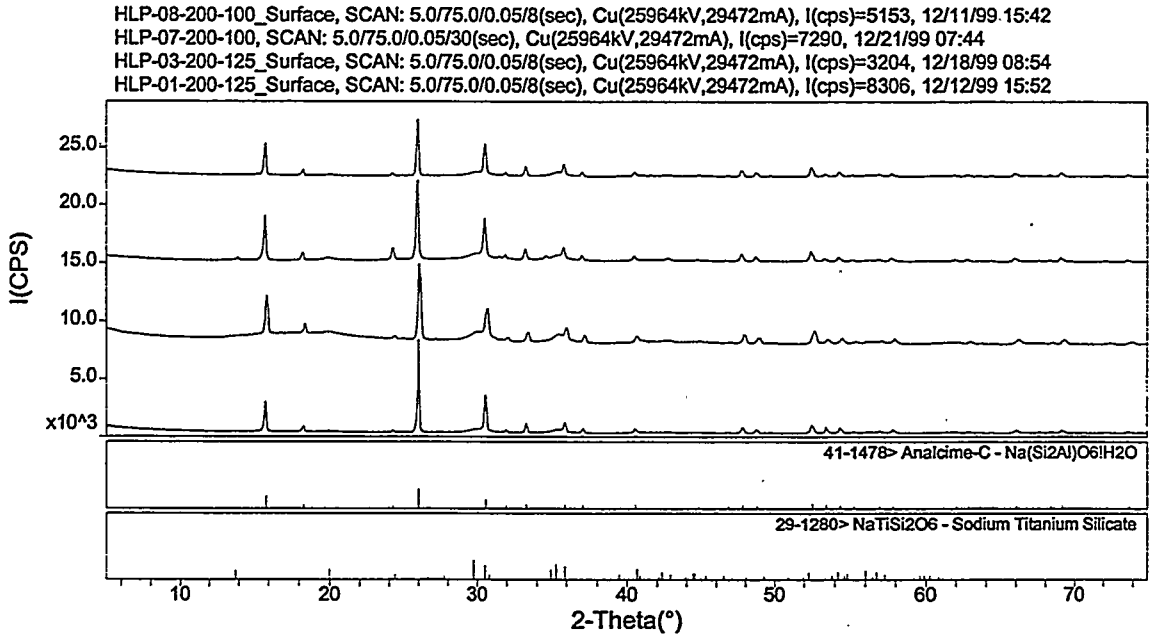
Table E-1. VHT Results Published in Literature

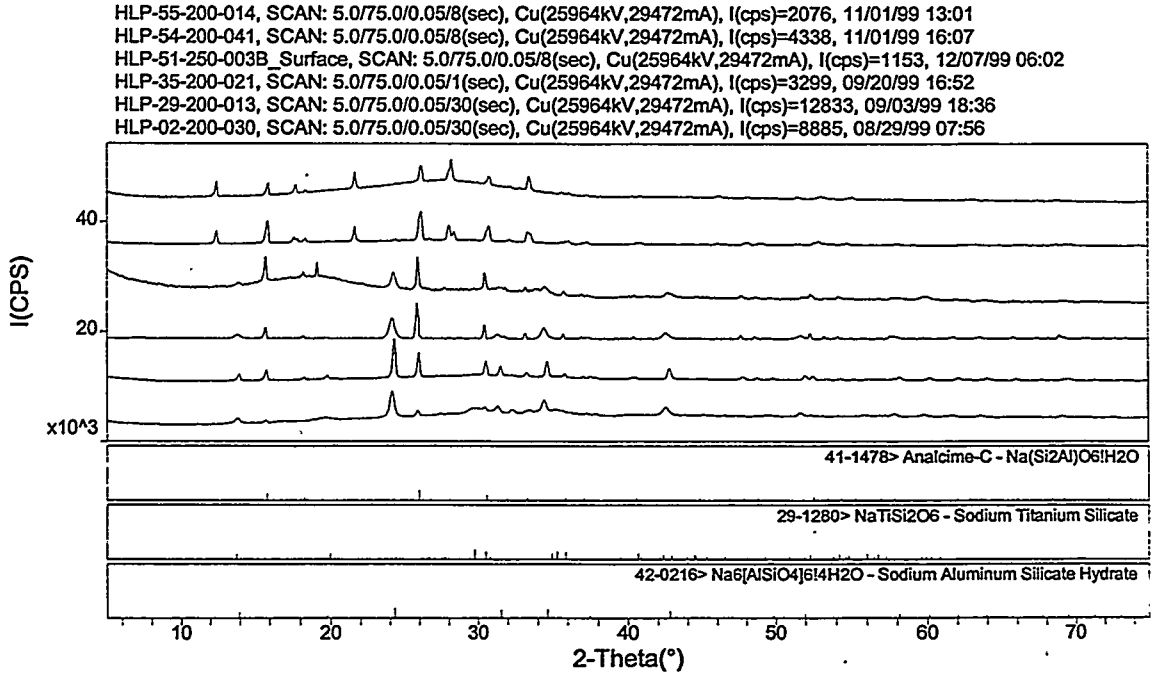
Glass ID	Description	Temperature [°C]	Duration [days]	Alteration layer thickness [μm]
HLP-46	LD6-5412	70	56	0
HLP-46	LD6-5412	120	28	0
HLP-46	LD6-5412	120	56	0
HLP-46	LD6-5412	150	3	0
HLP-46	LD6-5412	150	7	0
HLP-46	LD6-5412	150	11	200
HLP-46	LD6-5412	150	14	200
HLP-46	LD6-5412	150	18	Completely altered
HLP-46	LD6-5412	150	21	Completely altered
HLP-46	LD6-5412	175	1	200
HLP-46	LD6-5412	175	2	800
HLP-46	LD6-5412	175	3	1000
HLP-46	LD6-5412	175	5	800
HLP-46	LD6-5412	175	7	Completely reacted
HLP-46	LD6-5412	200	3	Completely reacted
HLP-46	LD6-5412	200	7	Completely reacted
HLP-48	LAWA33	150	14	0
HLP-48	LAWA33	150	28	5
HLP-48	LAWA33	150	57	40
HLP-48	LAWA33	150	77	300
HLP-48	LAWA33	175	6	1
HLP-48	LAWA33	175	14	50
HLP-48	LAWA33	175	28	250
HLP-54	L4-912	150	7	0
HLP-54	L4-912	150	14	0
HLP-54	L4-912	150	28	0
HLP-55	L4-99	150	7	0
HLP-55	L4-99	150	14	0
HLP-55	L4-99	150	28	0

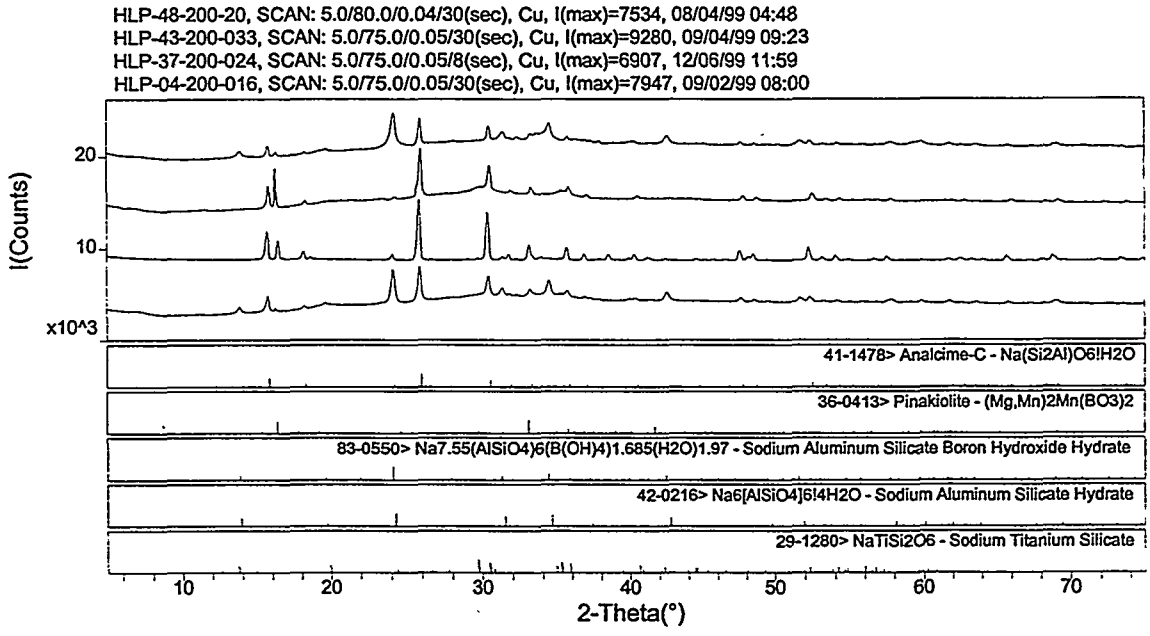
APPENDIX F

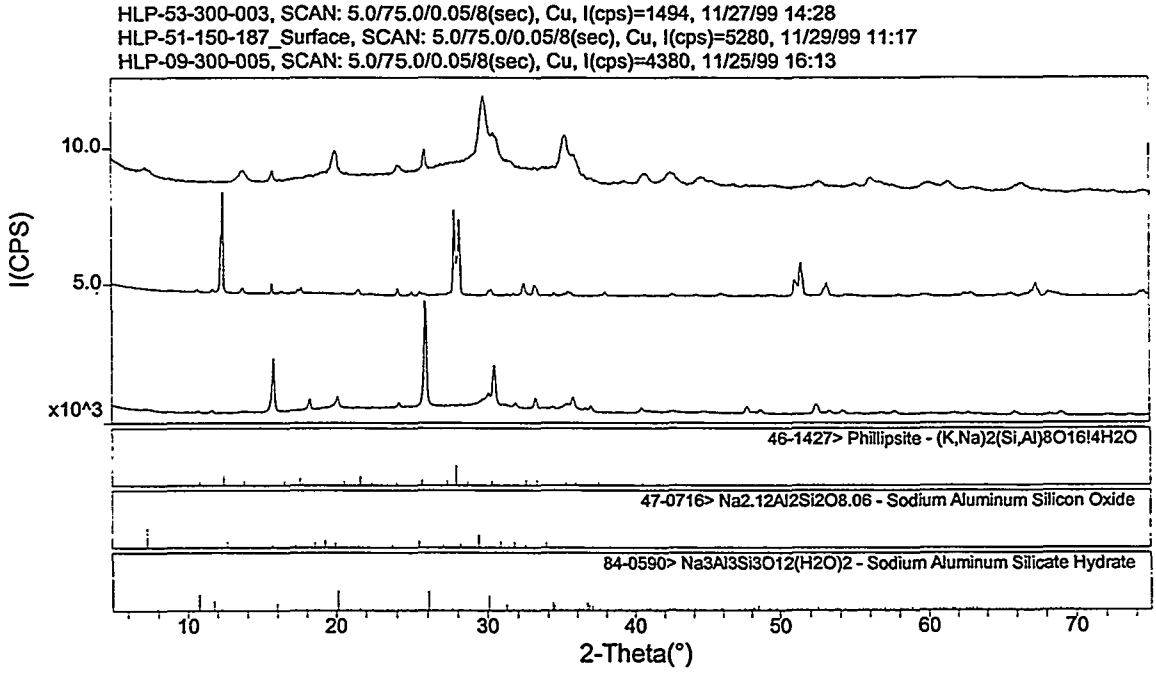
XRD Scans from VHT Samples

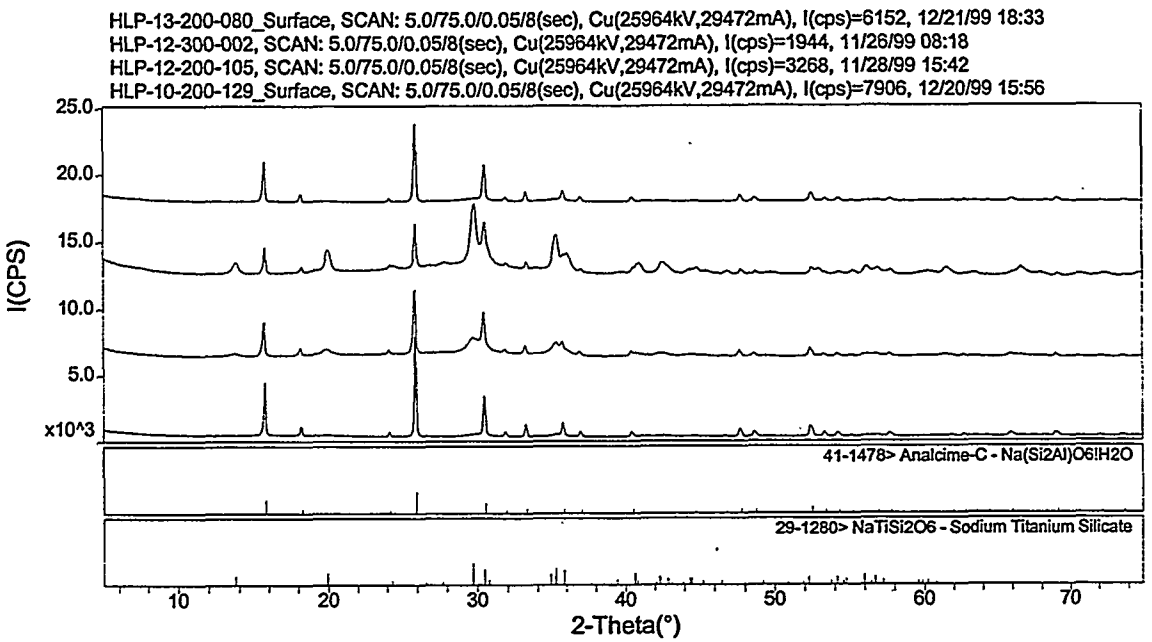
APPENDIX F
XRD Scans from VHT Samples

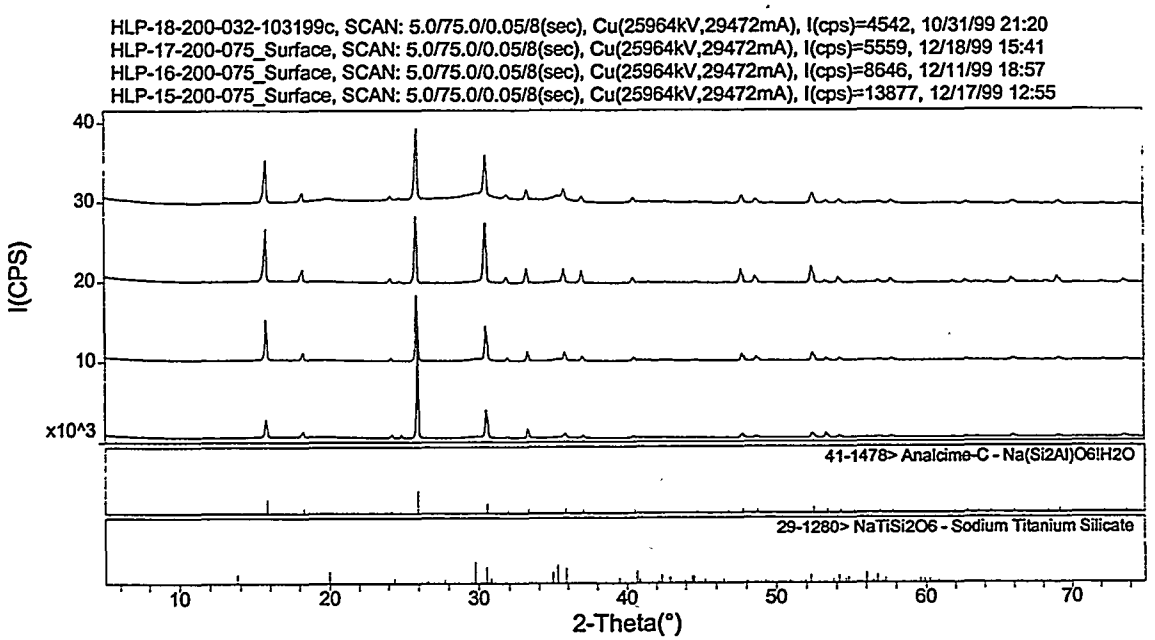


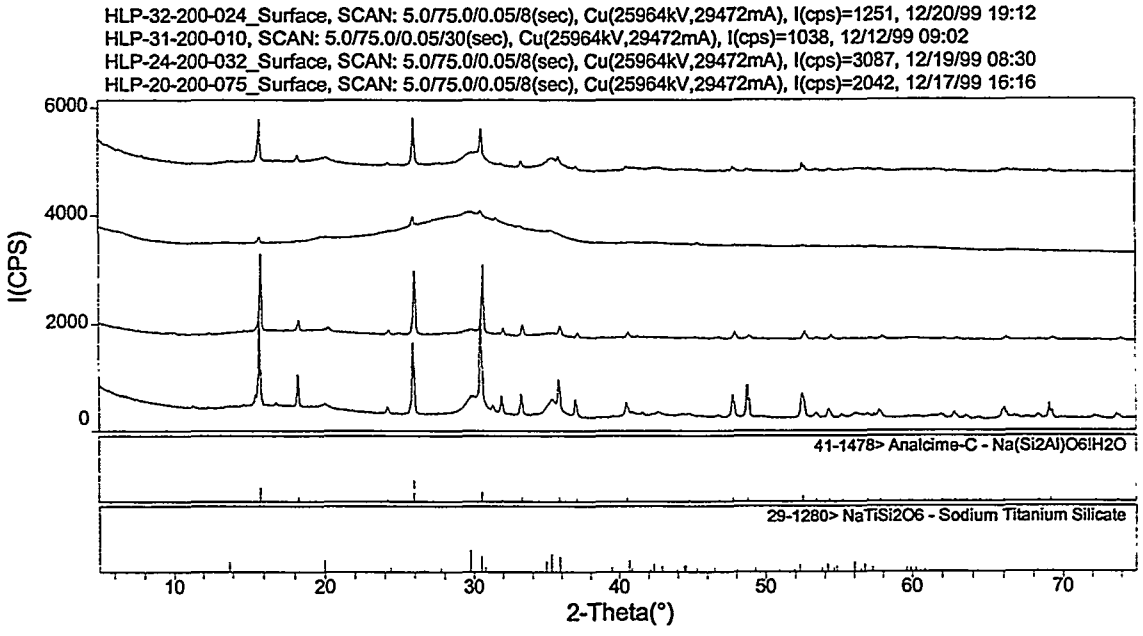


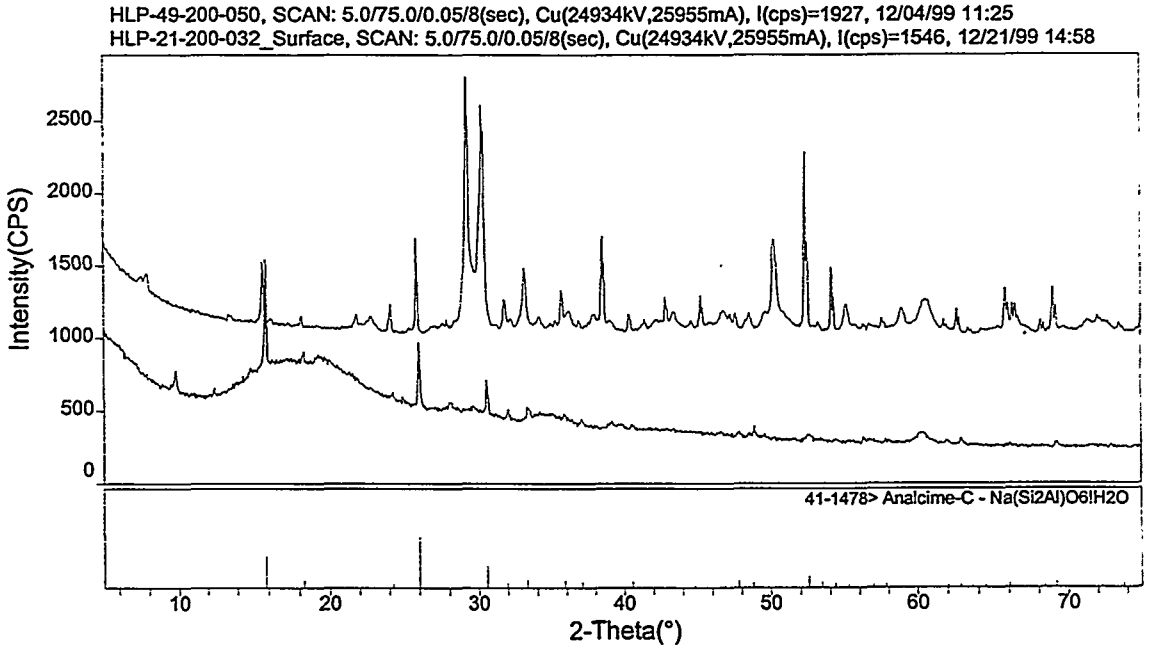

HLP-48-200-20, SCAN: 5.0/80.0/0.04/30(sec), Cu, I(max)=7534, 08/04/99 04:48
HLP-43-200-033, SCAN: 5.0/75.0/0.05/30(sec), Cu, I(max)=9280, 09/04/99 09:23
HLP-37-200-024, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(max)=6907, 12/06/99 11:59
HLP-04-200-016, SCAN: 5.0/75.0/0.05/30(sec), Cu, I(max)=7947, 09/02/99 08:00
I(Counts)
20
10
x10^3
41-1478> Analcime-C - Na(Si2Al)O6!H2O
36-0413> Pinakiolite - (Mg,Mn)2Mn(BO3)2
83-0550> Na7.55(AlSiO4)6(B(OH)4)1.685(H2O)1.97 - Sodium Aluminum Silicate Boron Hydroxide Hydrate
42-0216> Na6[AlSiO4]6!4H2O - Sodium Aluminum Silicate Hydrate
29-1280> NaTiSi2O6 - Sodium Titanium Silicate
10
20
30
40
50
60
70
2-Theta(°)


HLP-53-300-003, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(cps)=1494, 11/27/99 14:28
HLP-51-150-187_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(cps)=5280, 11/29/99 11:17
HLP-09-300-005, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(cps)=4380, 11/25/99 16:13
I(CPS)
10.0
5.0
x10^3
46-1427> Phillipsite - (K,Na)2(Si,Al)8O16!4H2O
47-0716> Na2.12Al2Si2O8.06 - Sodium Aluminum Silicon Oxide
84-0590> Na3Al3Si3O12(H2O)2 - Sodium Aluminum Silicate Hydrate
10
20
30
40
50
60
70
2-Theta(°)

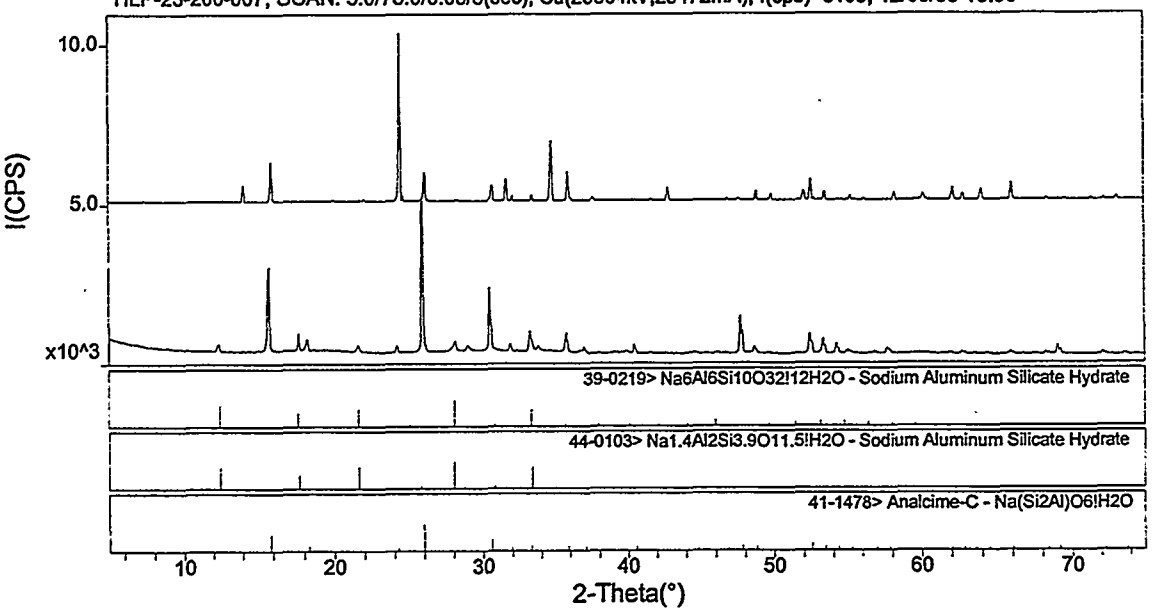

HLP-13-200-080_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=6152, 12/21/99 18:33
HLP-12-300-002, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=1944, 11/26/99 08:18
HLP-12-200-105, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=3268, 11/28/99 15:42
HLP-10-200-129_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=7906, 12/20/99 15:56
I(CPS)
25.0
20.0
15.0
10.0
5.0
x10^3
41-1478> Analcime-C - Na(Si2Al)O6!H2O
29-1280> NaTiSi2O6 - Sodium Titanium Silicate
10
20
30
40
50
60
70
2-Theta(°)


HLP-18-200-032-103199c, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=4542, 10/31/99 21:20
HLP-17-200-075_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=5559, 12/18/99 15:41
HLP-16-200-075_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=8646, 12/11/99 18:57
HLP-15-200-075_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=13877, 12/17/99 12:55
I(CPS)
40
30
20
10
x10^3
41-1478> Analcime-C - Na(Si2Al)O6!H2O
29-1280> NaTiSi2O6 - Sodium Titanium Silicate
10
20
30
40
50
60
70
2-Theta(°)

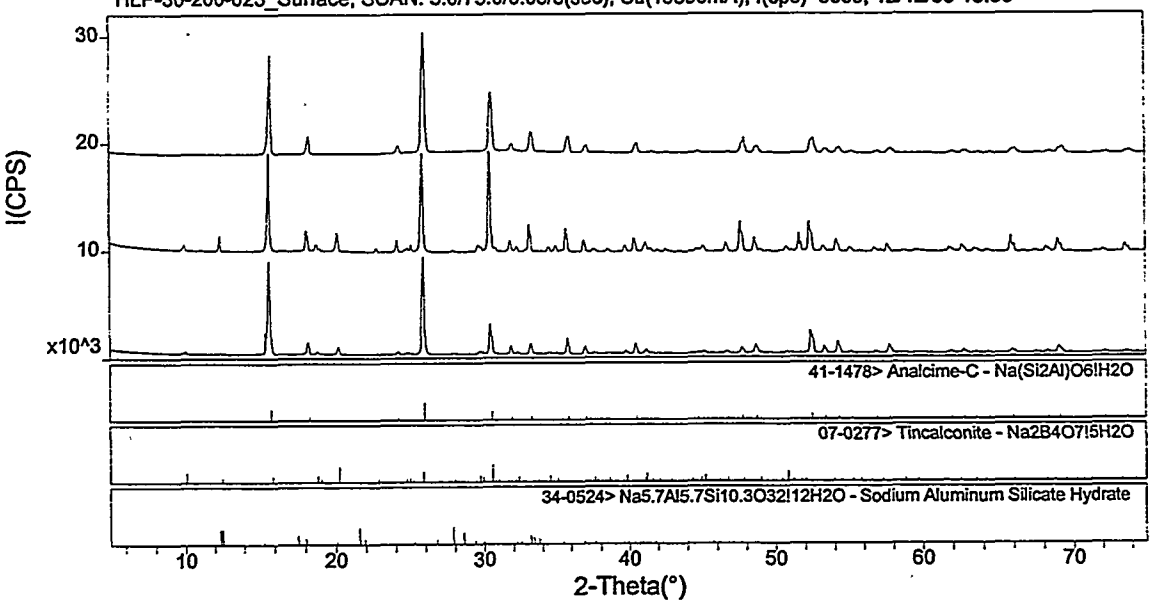

HLP-32-200-024_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=1251, 12/20/99 19:12
HLP-31-200-010, SCAN: 5.0/75.0/0.05/30(sec), Cu(25964kV,29472mA), I(cps)=1038, 12/12/99 09:02
HLP-24-200-032_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=3087, 12/19/99 08:30
HLP-20-200-075_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=2042, 12/17/99 16:16
I(CPS)
6000
4000
2000
0
41-1478> Analcime-C - Na(Si2Al)O6!H2O
29-1280> NaTiSi2O6 - Sodium Titanium Silicate
10
20
30
40
50
60
70
2-Theta(°)

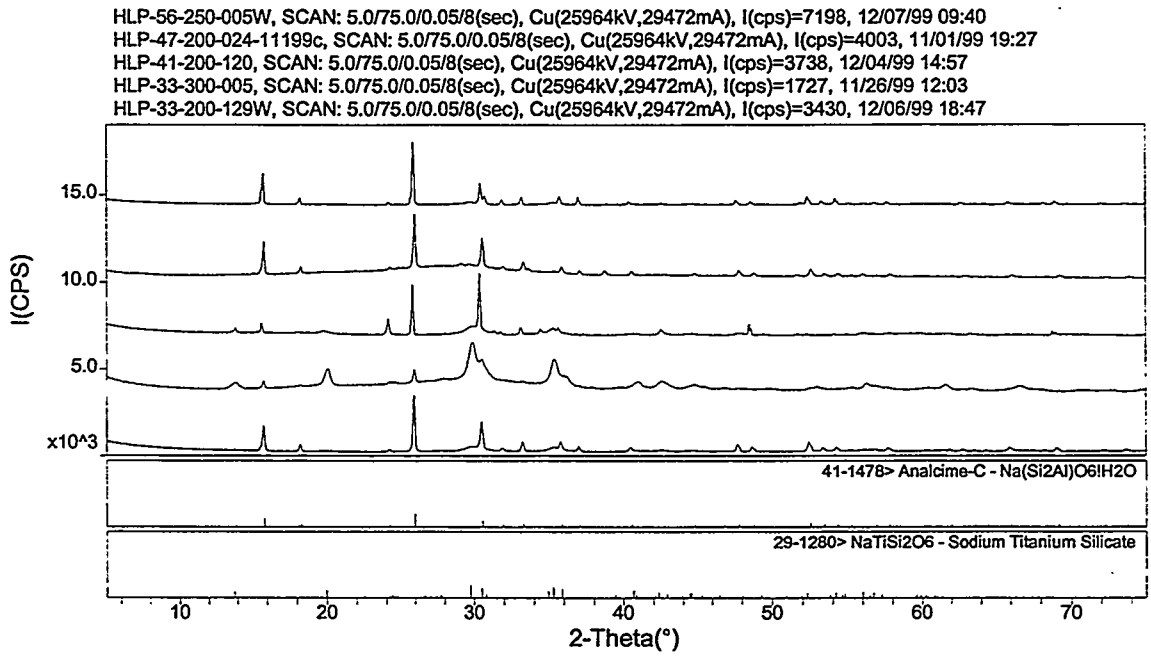

HLP-49-200-050, SCAN: 5.0/75.0/0.05/8(sec), Cu(24934kV,25955mA), I(cps)=1927, 12/04/99 11:25
HLP-21-200-032_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(24934kV,25955mA), I(cps)=1546, 12/21/99 14:58
Intensity(CPS)
2500
2000
1500
1000
500
0
41-1478> Analcime-C - Na(Si2Al)O6!H2O
10
20
30
40
50
60
70
2-Theta(°)

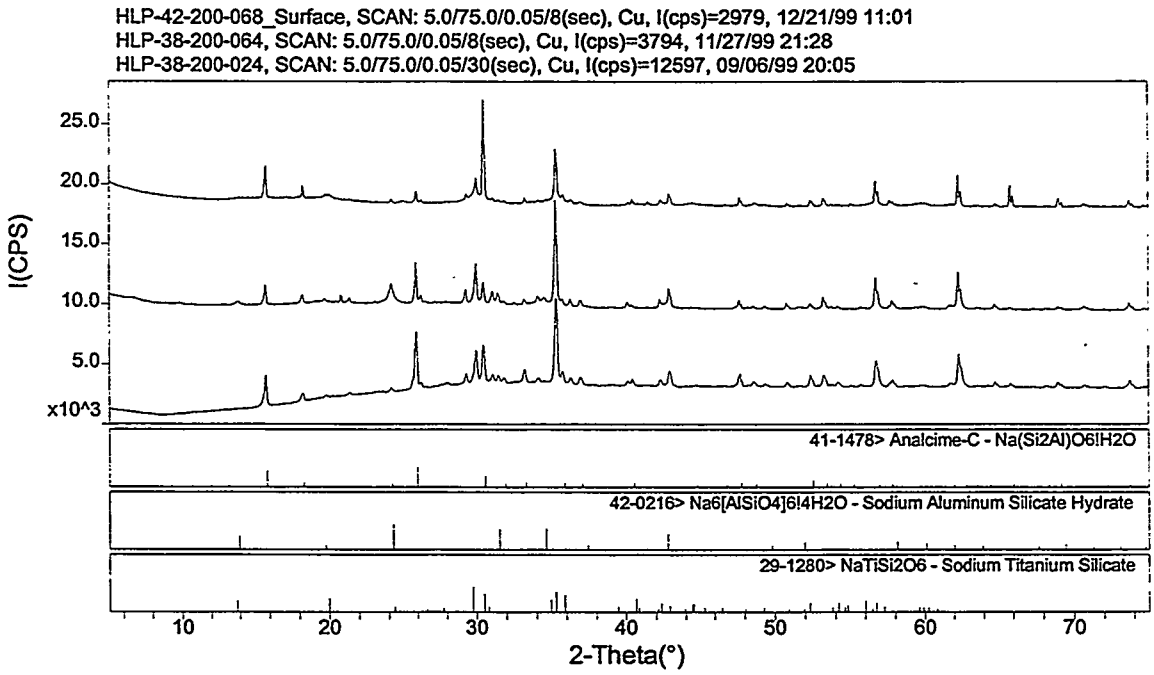
HLP-51 200-075, SCAN: 5.0/75.0/0.04/1(sec), Cu(25964kV,29472mA), I(cps)=5327, 12/14/99 08:00
HLP-23-200-007, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=5109, 12/05/99 16:33

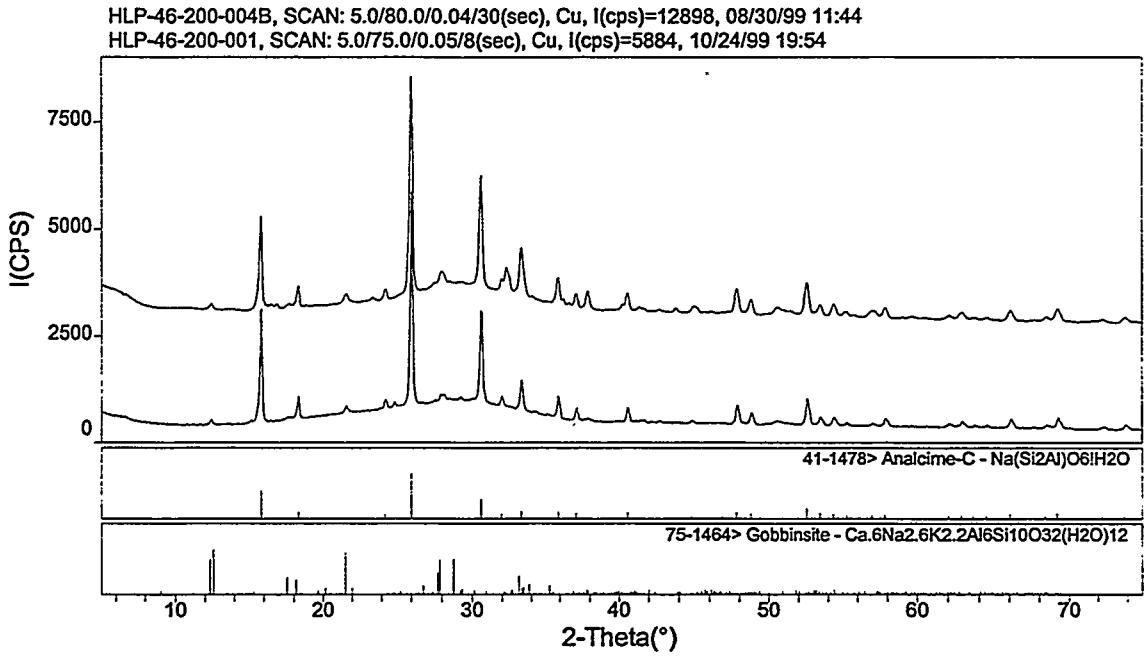


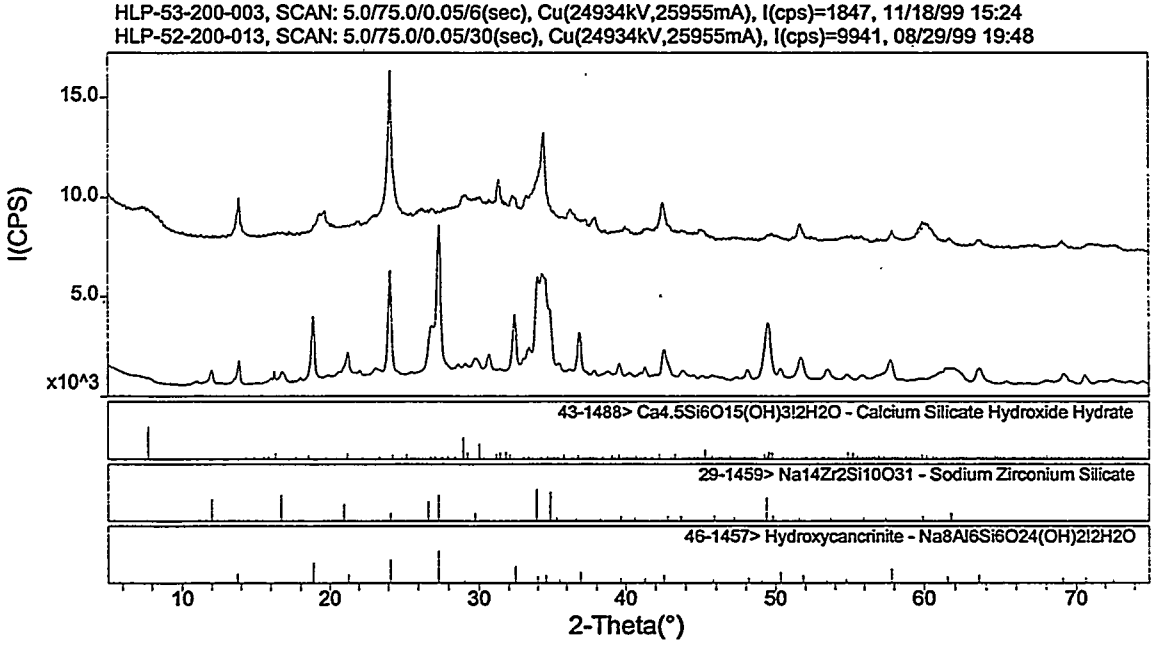
HLP-27-200-100, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=11810, 12/05/99 12:41
HLP-36-200-032_Whole sample, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=5523, 11/29/99 18:31
HLP-30-200-023_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu(16896mA), I(cps)=9359, 12/12/99 19:55




HLP-56-250-005W, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=7198, 12/07/99 09:40
HLP-47-200-024-11199c, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=4003, 11/01/99 19:27
HLP-41-200-120, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=3738, 12/04/99 14:57
HLP-33-300-005, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=1727, 11/26/99 12:03
HLP-33-200-129W, SCAN: 5.0/75.0/0.05/8(sec), Cu(25964kV,29472mA), I(cps)=3430, 12/06/99 18:47
I(CPS)
15.0
10.0
5.0
x10^3
41-1478> Analcime-C - Na(Si2Al)O6!H2O
29-1280> NaTiSi2O6 - Sodium Titanium Silicate
10
20
30
40
50
60
70
2-Theta(°)


HLP-42-200-068_Surface, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(cps)=2979, 12/21/99 11:01
HLP-38-200-064, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(cps)=3794, 11/27/99 21:28
HLP-38-200-024, SCAN: 5.0/75.0/0.05/30(sec), Cu, I(cps)=12597, 09/06/99 20:05
I(CPS)
25.0
20.0
15.0
10.0
5.0
x10^3
41-1478> Analcime-C - Na(Si2Al)O6!H2O
42-0216> Na6[AlSiO4]6!4H2O - Sodium Aluminum Silicate Hydrate
29-1280> NaTiSi2O6 - Sodium Titanium Silicate
10
20
30
40
50
60
70
2-Theta(°)


HLP-46-200-004B, SCAN: 5.0/80.0/0.04/30(sec), Cu, I(cps)=12898, 08/30/99 11:44
HLP-46-200-001, SCAN: 5.0/75.0/0.05/8(sec), Cu, I(cps)=5884, 10/24/99 19:54
I(CPS)
7500
5000
2500
0
41-1478> Analcime-C - Na(Si2Al)O6!H2O
75-1464> Gobbinsite - Ca.6Na2.6K2.2Al6Si10O32(H2O)12
10
20
30
40
50
60
70
2-Theta(°)


HLP-53-200-003, SCAN: 5.0/75.0/0.05/6(sec), Cu(24934kV,25955mA), I(cps)=1847, 11/18/99 15:24
HLP-52-200-013, SCAN: 5.0/75.0/0.05/30(sec), Cu(24934kV,25955mA), I(cps)=9941, 08/29/99 19:48
I(CPS)
15.0
10.0
5.0
x10^3
43-1488> Ca4.5Si6O15(OH)3!2H2O - Calcium Silicate Hydroxide Hydrate
29-1459> Na14Zr2Si10O31 - Sodium Zirconium Silicate
46-1457> Hydroxycancrinite - Na8Al6Si6O24(OH)2!2H2O
10
20
30
40
50
60
70
2-Theta(°)

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