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# **Enhanced Hanford Low-Activity Waste Glass Property Data Development: Phase 2**

**December 2019**

RL Russell  
BP McCarthy  
SK Cooley  
GF Piepel  
EA Cordova  
SE Sannoh  
V Gervasio  
MJ Schweiger  
JB Lang  
CH Skidmore  
CE Lonergan  
BA Stanfill  
JM Meline  
JD Vienna

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Pacific Northwest National Laboratory  
Richland, Washington 99354

## Executive Summary

This report summarizes and analyzes the data collected on a second test matrix of 42 low-activity waste (LAW) glass compositions intended to expand the LAW glass composition region over which glass property-composition models are valid. The 42 LAW glass compositions were selected using a statistical layered experimental design approach to explore a new glass composition region that overlaps and expands beyond the previously explored LAW glass composition region. The layered design of 42 LAW glasses consisted of 21 outer-layer glasses, 15 inner-layer glasses, a center glass (three replicates), and two glasses previously tested at another laboratory. The outer-layer glass compositions include extrema based on current projections of the LAW feeds and melter operating temperatures. One of the outer-layer compositions was eliminated due to the inability to form a glass. Therefore, only 41 glasses were analyzed. The analyses performed on these glasses include chemical composition (for target compositional verification), density, viscosity, electrical conductivity, crystal fraction, canister centerline cooling with crystal identification, the Product Consistency Test, sulfur solubility, and the Vapor Hydration Test. This report discusses in depth the results obtained from this testing.

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## Acronyms and Abbreviations

ARM	Approved Reference Material
BNI	Bechtel National, Inc.
CCC	canister centerline cooling (heat treatment)
CUA	The Catholic University of America
DIW	deionized water
DOE	U.S. Department of Energy
EA	Environmental Assessment
EC	electrical conductivity
EGCR	experimental glass composition region
EWG	Enhanced Waste Glass
$\eta$	Viscosity
HDI	“How Do I...?”
IA	image analysis
IC	ion chromatography
ICP-AES	inductively coupled plasma – atomic emissions spectroscopy
IL	inner layer
KH	potassium hydroxide digestion
LAW	low-activity waste
LM	lithium metaborate/tetraborate fusion
LRM	low-activity waste reference material
NIST	National Institute of Standards and Technology
NQAP	Nuclear Quality Assurance Program
OL	outer layer
OM	optical microscopy
ORP	Office of River Protection
PCT	Product Consistency Test
PF	sodium peroxide fusion
PNNL	Pacific Northwest National Laboratory
PSAL	Process Science Analytical Laboratory
PVDF	polyvinylidene difluoride
QA	quality assurance
QGCR	qualified glass composition region
R&D	research and development
SRNL	Savannah River National Laboratory
S/V	surface area-to-solution volume
VHT	Vapor Hydration Test
vol%	volume percent
VFT	Vogel-Fulcher-Tamman

wt%	weight percent
WTP	Hanford Tank Waste Treatment and Immobilization Plant
XRD	x-ray diffraction
XRF	x-ray fluorescence

## Contents

Summary .....	ii
Acknowledgments.....	iii
Acronyms and Abbreviations .....	iv
Contents .....	vi
1.0     Introduction.....	1.1
1.1     Status of LAW Experimental Glass Composition Regions and Waste Loading Constraints .....	1.1
1.2     Phase 2 Enhanced LAW Experimental Glass Composition Region and Test Matrix .....	1.3
1.3     Quality Assurance.....	1.11
1.3.1     PNNL QA Program .....	1.11
1.3.2     ORP Glass Support Work QA Program .....	1.11
2.0     Test Methods.....	2.1
2.1     Glass Fabrication .....	2.1
2.2     Matrix Glasses Needing Composition Modification .....	2.2
2.2.1     LP2-OL-03 .....	2.3
2.2.2     LP2-OL-06 .....	2.6
2.2.3     LP2-OL-08 .....	2.10
2.2.4     LP2-OL-10 .....	2.14
2.2.5     LP2-OL-16 .....	2.16
2.3     Chemical Analysis of Glass Composition .....	2.18
2.4     Glass Density .....	2.19
2.5     Viscosity .....	2.19
2.6     Electrical Conductivity .....	2.19
2.7     Equilibrium Crystal Fraction .....	2.20
2.8     Canister Centerline Cooling (CCC) and Crystal Identification .....	2.20
2.9     Product Consistency Test (PCT).....	2.22
2.10     Vapor Hydration Test (VHT).....	2.22
2.11     Sulfur Solubility.....	2.23
3.0     Results and Discussion .....	3.1
3.1     Chemical Analysis of Glass Composition .....	3.1
3.2     Density .....	3.3
3.3     Viscosity ( $\eta$ ).....	3.4
3.4     Electrical Conductivity (EC).....	3.8
3.5     Crystal Fraction of Heat-Treated Glasses .....	3.12
3.6     Crystal Identification in Canister Centerline Cooling (CCC) Glasses.....	3.14
3.7     Product Consistency Test (PCT).....	3.17

3.8	Vapor Hydration Test (VHT).....	3.24
3.9	Sulfur Solubility Results.....	3.32
4.0	Summary .....	4.2
5.0	References.....	5.1
	Appendix A – Morphology/Color of Each Quenched Glass .....	A.1
	Appendix B – Analyzed Glass Compositions.....	B.1
	Appendix C – Viscosity Data.....	C.1
	Appendix D – Electrical Conductivity Data .....	D.1
	Appendix E – Crystal Fraction (CF) of Heat-Treated Glasses Photographs.....	E.1
	Appendix F – XRD of Crystal Fraction (CF) Heat-Treated Glasses .....	F.1
	Appendix G – Canister Centerline Cooling (CCC) Glass Photographs.....	G.1
	Appendix H – XRD of Canister Centerline Cooling (CCC) Treated Glasses .....	H.1
	Appendix I – Vapor Hydration Test (VHT) Results.....	I.1
	Appendix J – Analyses for Baseline and Sulfur Saturated Glasses and Sulfur Wash Solutions .....	J.1

## Figures

Figure 1.1.	Plot of Glass Waste Loading Constraints for the Current WTP and Advanced ORP LAW Glasses as Projected Based on $\text{Na}_2\text{O}+0.66\text{K}_2\text{O}$ Versus $\text{SO}_3$ Concentrations in Glass (Vienna et al. 2016) .....	1.3
Figure 2.1.	Glass LP2-OL-03 Original Composition .....	2.4
Figure 2.2.	Glass LP2-OL-03 First Modified Composition after First Melt.....	2.5
Figure 2.3.	Glass LP2-OL-03 First Modified Composition after Third Melt .....	2.5
Figure 2.4.	Glass LP2-OL-03 First Modified Composition after Final Melt .....	2.6
Figure 2.5.	Glass LP2-OL-06 Original Composition .....	2.8
Figure 2.6.	Glass LP2-OL-06 First Modification.....	2.9
Figure 2.7.	Glass LP2-OL-06 Second Modification .....	2.9
Figure 2.8.	Glass LP2-OL-06 Third Modification .....	2.10
Figure 2.9.	Glass LP2-OL-08 Original Composition .....	2.12
Figure 2.10.	XRD Pattern of Original LP2-OL-08 Composition.....	2.13
Figure 2.11.	Glass LP2-OL-08 after First Modification .....	2.13
Figure 2.12.	Glass LP2-OL-10 Original Composition .....	2.15
Figure 2.13.	Glass LP2-OL-10 after First Modification .....	2.15
Figure 2.14.	Glass LP2-OL-16 Original Composition .....	2.17
Figure 2.15.	Glass LP2-OL-16 after First Modification .....	2.17
Figure 2.16.	Plot of Temperature Schedule During CCC Heat-Treatment of Hanford LAW Glasses .....	2.21
Figure 2.17.	Apparatus for Conducting VHTs .....	2.23
Figure 3.1.	Predicted versus Measured Density for Phase 2 Enhanced LAW Glasses .....	3.4

Figure 3.2.	Predicted Versus Measured Viscosity Data for Phase 2 Enhanced LAW Glasses .....	3.8
Figure 3.3.	Predicted versus Measured Electrical Conductivity at 1150°C for Phase 2 Enhanced LAW Glasses .....	3.11
Figure 3.4.	Glass LP2-OL-05 Cooled in a Pt Crucible with Crystals along Edge .....	3.16
Figure 3.5.	Glass LP2-OL-05 Cooled in a Quartz Crucible with Crystals along Edge.....	3.17
Figure 3.6.	Comparison of PCT Normalized Releases of B with Na (both g/m <sup>2</sup> ) for Quenched Samples of Phase 2 Enhanced LAW Glasses .....	3.20
Figure 3.7.	Comparison of PCT Normalized Releases of B with Na (g/m <sup>2</sup> ) for CCC Samples of Phase 2 Enhanced LAW Glasses.....	3.21
Figure 3.8.	Predicted Versus Measured Normalized Releases (g/m <sup>2</sup> ) of Boron and Sodium for Phase 2 Enhanced LAW Glasses .....	3.22
Figure 3.9.	Comparison of Natural Logarithm of PCT Normalized Release (g/L) of B and Na for Quenched and CCC-Treated Samples of Phase 2 Enhanced LAW Glasses that Contain Aluminosilicates.....	3.23
Figure 3.10.	VHT Response Compared to the Total Normalized Alkali [Nalk = Na <sub>2</sub> O + 0.66(K <sub>2</sub> O) + 2(Li <sub>2</sub> O)] Content of the Glass .....	3.29
Figure 3.11	Natural Logarithm of V Alteration Depth Results for CCC versus Quenched Versions of Phase 2 Enhanced LAW Glasses.....	3.30
Figure 3.12.	Natural Logarithm of VHT Alteration Depth Results Predicted using 15-Term Reduced Partial Cubic Mixture Model Versus Measured Values for Phase 2 Enhanced LAW Glasses .....	3.30
Figure 3.13.	Natural Logarithm of VHT Alteration Depth Results Predicted using 16-Term Reduced Partial Quadratic Mixture Model Versus Measured VHT Values for Phase 2 Enhanced LAW Glasses .....	3.31
Figure 3.14.	Analyzed Sulfur Concentration in the Baseline and the Sulfur-Saturated Glasses.....	3.36
Figure 3.15.	Predicted versus Measured SO <sub>3</sub> Solubility for Phase 2 Enhanced LAW Glasses .....	3.1

## Tables

Table 1.1.	Lower and Upper Bounds of Single-Component Constraints <sup>(a)</sup> for the Outer and Inner Layers of the 15-Component Enhanced Low-Activity Waste Experimental Glass Composition Region .....	1.4
Table 1.2.	Lower and Upper Bounds of Multiple-Component Constraints for the Outer and Inner Layers of a 15-Component Enhanced Low-Activity Waste Experimental Glass Composition Region .....	1.5
Table 1.3.	Targeted Compositions (mass fractions) for the Phase 2 Enhanced LAW Glasses.....	1.6
Table 1.4.	Targeted Compositions (mass fractions) for the Modified Outer Layer Phase 2 Enhanced LAW Glasses .....	1.10
Table 2.1.	Melting Temperatures and Times Used in Fabricating the Phase 2 Enhanced LAW Waste Glasses .....	2.2
Table 2.2.	Composition Modifications Made to Glass LP2-OL-03.....	2.3
Table 2.3.	Composition Modifications Made to Glass LP2-OL-06.....	2.7
Table 2.4.	Composition Modifications Made to Glass LP2-OL-08.....	2.11

Table 2.5.	Composition Modifications Made to Glass LP2-OL-10.....	2.14
Table 2.6.	Composition Modifications Made to Glass LP2-OL-16.....	2.16
Table 2.7.	Preparation and Measurement Methods Used in Reporting the Measured Concentrations of Each of the Analytes of the Study Glasses .....	2.18
Table 2.8.	Temperature Schedule during Canister Centerline Cooling (CCC) Treatment of Hanford LAW Glasses.....	2.21
Table 3.1.	Measured Densities of Phase 2 Enhanced LAW Glasses .....	3.3
Table 3.2.	Measured $\ln \eta$ (P) Values Versus Target Temperature (in the sequence of measurement) for the Phase 2 Enhanced LAW Glasses Tested .....	3.5
Table 3.3.	Fitted Coefficients of Arrhenius and VFT Models for Viscosity of LAW Phase 2 Enhanced Glasses .....	3.6
Table 3.4.	Measured Electrical Conductivity (S/m) Values versus Temperatures for the LAW Phase 2 Enhanced Glasses .....	3.9
Table 3.5.	List of Electrical Conductivity Model Components and Coefficients (Piepel et al. 2007).....	3.12
Table 3.6.	Weight Percent Crystallinity and Identification of Crystals by XRD in Heat-Treated Glasses .....	3.13
Table 3.7.	Weight Percent Crystallinity and Identification of Crystals by XRD in CCC-Treated Glasses .....	3.14
Table 3.8.	PCT Normalized Releases ( $\text{g}/\text{m}^2$ ) from Fox et al. (2017 and 2018) .....	3.18
Table 3.9.	Coefficients for PCT Boron Model (Piepel 2007).....	3.23
Table 3.10.	Coefficients for PCT Sodium Model (Piepel 2007).....	3.23
Table 3.11.	VHT Results from the LAW Phase 2 Enhanced Quenched Glasses .....	3.24
Table 3.12.	VHT Results from the LAW Phase 2 Enhanced CCC Glasses.....	3.26
Table 3.13.	Coefficients for 15-Term Reduced Partial Cubic Mixture Model Based on Alteration Depth for VHT Data (Piepel 2007).....	3.31
Table 3.14.	Coefficients for 16-Term Reduced Partial Quadratic Mixture Model Based on Alteration Depth (Piepel 2007).....	3.31
Table 3.15.	Target and Measured Values of $\text{SO}_3$ Mass Fraction .....	3.34
Table 3.16.	List of $\text{SO}_3$ Solubility Model Components and Coefficients (Vienna et al. 2016) .....	3.1

## 1.0 Introduction

The U.S. Department of Energy's (DOE) Office of River Protection (ORP) requested Pacific Northwest National Laboratory (PNNL) to support the River Protection Project vitrification in an effort to support operations upon completion of startup activities (DOE 2012). This work was performed under the PNNL project titled "ORP Glass Support Work." One task of this project—Enhanced Hanford Waste Glass Models—is the subject of this report. A previous task focused on generating property-composition data and models for the Hanford site low-activity waste (LAW) glasses with lower waste loadings, which are relevant to the commissioning of the LAW vitrification facility. The current task has the long-term objective of expanding the Hanford site LAW glass database and property-composition models for the balance of the Hanford site tank waste treatment and immobilization mission. During the balance of the mission, LAW glasses with higher waste loadings will be produced.

This report presents the glass compositions and glass property data developed in Phase 2 of the enhanced Hanford LAW glass property data development effort. When this effort is complete, enhanced LAW glass property models will be developed. Section 1.1 summarizes the status of the LAW glass composition regions and waste loading constraints prior to the data development effort documented in this report. Section 1.2 summarizes the LAW Phase 2 glass composition region and test matrix. Section 1.3 documents the quality assurance program used in performing the work discussed in this report.

### 1.1 Status of LAW Experimental Glass Composition Regions and Waste Loading Constraints

The Hanford Waste Treatment and Immobilization Plant (WTP) project has previously developed glass property-composition models to formulate LAW glass compositions and qualify LAW glasses for disposal (Piepel et al. 2007). These models are based on data from crucible-scale tests with simulants, crucible-scale tests with actual waste, and scaled-melter tests with simulants collected under the Bechtel National, Inc. (BNI) contract to design, construct, and commission the WTP (DOE 2000). The scope of the BNI contract is limited to operating the plant over a limited commissioning period with LAW glasses with limited waste loadings (i.e., the proportion of waste in the glass). Hence, the data and resulting glass property-composition models only cover a fraction of the LAW glass composition region needed for the entire Hanford site mission. In addition, the data and models developed by BNI are targeted at glasses that modestly exceed contract minimum waste loadings rather than maximum achievable waste loadings.

In this document, the term *experimental glass composition region* (EGCR) is used to refer to a composition region of glasses that has been (or will be) experimentally explored through fabricating glasses and testing their properties. Ideally, an EGCR should include all glass compositions that will satisfy processing and product-quality related constraints, as well as glass compositions that fail one or more constraints. Experimental data collected on glass compositions covering the EGCR then provide for developing property-composition models that can 1) discriminate between glass compositions that satisfy and fail the requirements, and 2) adequately predict glass properties of compositions that satisfy all requirements. The term *qualified glass composition region* (QGCR) refers to the subset of the EGCR where all processing and product-quality constraints are satisfied with sufficient confidence after accounting for applicable uncertainties.

EGCRs are specified using processing and product-quality constraints of two main kinds. Single-component constraints (SCCs) involve lower and/or upper limits on individual LAW glass components. Multiple-component constraints (MCCs) involve lower and/or upper limits on combinations of LAW glass components. For some MCCs, the combinations of components are existing property-composition models for LAW glasses. In other cases, the combinations are stand-in expressions for properties that

have not yet been modeled or are not easily measured or predicted. Examples of stand-in constraints are discussed in the following paragraph. The set of all SCCs and MCCs specifying the EGCR are referred to as *model validity constraints* because these constraints specify the region of qualified data available for developing models to predict the LAW glass properties of interest.

Stand-in constraints are used in lieu of constraints on the properties to be controlled. For example, we previously limited the weight percent (wt%) SO<sub>3</sub> targeted in glass because the salt accumulation in the melter was not predictable. We also limited the equilibrium fraction of crystals at 950°C to one volume percent (vol%) because crystal blockages of the melter pour-spout are not currently predictable. To determine the ultimate waste loading of glass, these constraints based on limited data availability need to be replaced with constraints based on true operating and product performance property limits. To this end, we seek to develop (1) glass property data across broader glass composition regions to increase waste loadings and (2) methods to measure (directly or indirectly) and model the properties that fundamentally limit the melter operations or the performance of the glass.

The LAW is dominated by sodium salts (DOE 2000). The ratio of sulfur (as SO<sub>3</sub>) to sodium (as Na<sub>2</sub>O) in the waste is a key determinant of waste loading and glass formulation. At high-alkali concentrations, the waste loading is limited primarily by the chemical durability (measured by the VHT and PCT responses) of the resulting LAW glass. At high SO<sub>3</sub> concentrations, the waste loading is limited primarily by salt accumulation in the melter.

The LAW glasses currently formulated for WTP (Kim and Vienna 2012) have relatively conservative alkali and SO<sub>3</sub> loading limits, as shown by the red constraint in Figure 1.1. The waste loading is currently determined by the ratio of normalized alkali (Na<sub>2</sub>O+0.66K<sub>2</sub>O) to SO<sub>3</sub> in the waste. Where the (Na<sub>2</sub>O+0.66K<sub>2</sub>O):SO<sub>3</sub> ratio for a waste intersects the red line determines the loading of that waste in glass using the current WTP LAW glass constraints. Additional constraints are used to limit the concentrations of halides in the glass, which are functions of chromium, phosphorus, and potassium (Kim and Vienna 2012).

More recently, new high waste loading formulations have been developed by The Catholic University of America (CUA) and PNNL in support of ORP (Matlack et al. 2005a, 2005b, 2006a, 2006b, 2007, 2009; Vienna et al. 2003a, 2004a, 2004b; and Kim et al. 2003). The resulting data are summarized in Muller et al. (2012, 2015), Vienna et al. (2013, 2016), and Russell et al. (2017), with some newer data not yet reported. The basic conclusions of these studies are that loadings for specific wastes in glass can be increased significantly over what would be allowed by current WTP constraints. Examples of the gains made in recent studies include the following:

- Glass SO<sub>3</sub> loadings of >1.5 wt% were successfully processed, which is double the 0.77 wt% allowed by the current WTP LAW EGCR.
- LAW normalized alkali loadings of 26 wt% have been achieved compared to the 21 wt% maximum in the current WTP LAW EGCR.

These advances (upper blue line) are compared with the WTP baseline waste loading constraints (lower red line) in Figure 1.1. In this figure, the SO<sub>3</sub> limits (SO<sub>3</sub> = 0.77 or 1.5 wt%) are used to reduce the risk of salt accumulation in the melter. If salt does accumulate in the melter, the useful life of components that are adjacent to or pass through the melt line may be significantly reduced. The horizontal lines represent alkali limits in glass (Na<sub>2</sub>O+0.66K<sub>2</sub>O = 21.5 or 24 wt%) above which there is high risk of exceeding the current WTP contract specifications for the Product Consistency Test (PCT) and the Vapor Hydration Test (VHT) responses for glass durability (DOE 2000). The sloped lines between these two end constraints represent the limits of the formulations tested to date in trading off how high SO<sub>3</sub> or alkali can be when the other is at its upper limit. Therefore, glasses can be formulated for high SO<sub>3</sub> loading or for

high-alkali loading, but compromises must be made to achieve high concentrations of both. The sloped lines therefore represent the current state of formulations tested to achieve this balance. Future testing and modeling efforts are underway to describe each of the fundamental properties (e.g., salt formation, PCT and VHT responses, viscosity, electrical conductivity) as functions of target glass compositions. Although these models exist for projecting the amount of glass to be expected during Hanford's mission (Vienna et al. 2016), they need to be updated for WTP processing within the expanded glass composition region to ensure that optimized glasses simultaneously satisfy all the processing and product-quality constraints.

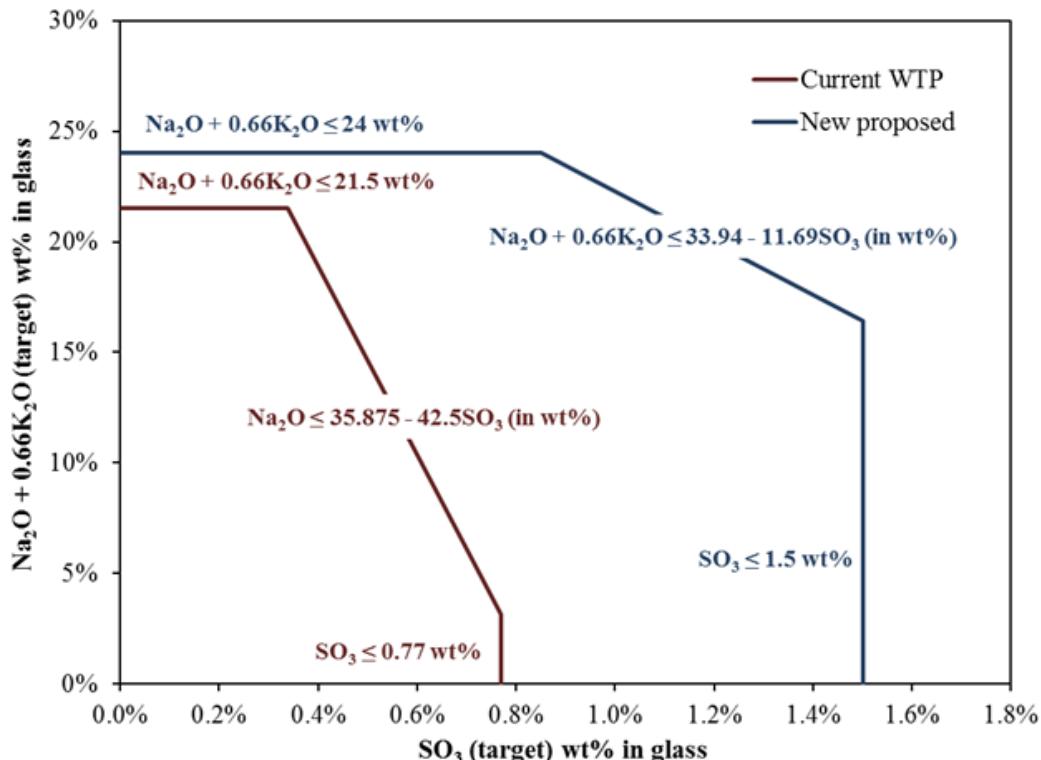


Figure 1.1. Plot of Glass Waste Loading Constraints for the Current WTP and Advanced ORP LAW Glasses as Projected Based on  $\text{Na}_2\text{O}+0.66\text{K}_2\text{O}$  Versus  $\text{SO}_3$  Concentrations in Glass (Vienna et al. 2016)

The LAW glass compositions that have available property data have two somewhat distinct composition sub-regions (the current WTP and the advanced ORP glasses). The question is raised whether we need to develop 1) a single, combined EGCR, or 2) an advanced LAW EGCR without ties to the subregion with lower waste loadings. This question is being addressed by current property-composition modeling work at PNNL. For this Phase 2 study, PNNL explored only the advanced LAW EGCR corresponding to the subregion with higher waste loadings. The current CUA testing program is attempting to bridge the gap between the two sub-regions (Muller et al. 2013a, 2013b, 2015, 2017).

## 1.2 Phase 2 Enhanced LAW Experimental Glass Composition Region and Test Matrix

The objective of this task was to generate data for different LAW glass compositions to ultimately support the development, validation, and implementation of glass property models that can achieve high waste loading for the full region of Hanford LAW compositions. To extend the models beyond our current knowledge space, a new enhanced LAW EGCR was developed. Table 1.1 lists the 15 LAW glass

components selected for variation in the experimental work, including an Others component mix. Certain components were chosen for variation in the experimental work for specific reasons. The components  $\text{SnO}_2$  and  $\text{ZrO}_2$  were included because they can decrease the VHT response. The components  $\text{V}_2\text{O}_5$  and  $\text{Li}_2\text{O}$  were included because they can increase the  $\text{SO}_3$  tolerance in the melter. Finally, the components  $\text{ZnO}$  and  $\text{Cr}_2\text{O}_3$  were included because they can decrease refractory corrosion.

Table 1.1. Lower and Upper Bounds of Single-Component Constraints<sup>(a)</sup> for the Outer and Inner Layers of the 15-Component Enhanced Low-Activity Waste Experimental Glass Composition Region

Component	Outer Layer		Inner Layer		Center Point
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	
$\text{Al}_2\text{O}_3$	0.06	0.125	0.075	0.1075	0.10
$\text{B}_2\text{O}_3$	0.06	0.1375	0.08	0.12	0.095
$\text{CaO}$	0.02	0.11	0.02	0.08	0.05
$\text{Cr}_2\text{O}_3$	0.003	0.006	0.00375	0.00525	0.0045
$\text{Fe}_2\text{O}_3$	0.00	0.015	0.002	0.01	0.006
$\text{K}_2\text{O}$	0.00	0.0575	0.005	0.02	0.01
$\text{Li}_2\text{O}$	0.00	0.00	0.00	0.00	0.00
$\text{MgO}$	0.00	0.0135	0.003	0.01	0.0065
$\text{Na}_2\text{O}$	0.21	0.26	0.22	0.245	0.23
$\text{SiO}_2$	0.349	0.47	0.37	0.43	0.388
$\text{SO}_3$	0.001	0.02	0.002	0.008	0.005
$\text{SnO}_2$	0.00	0.035	0.005	0.025	0.015
$\text{V}_2\text{O}_5$	0.00	0.04	0.005	0.02	0.01
$\text{ZnO}$	0.02	0.036	0.024	0.032	0.028
$\text{ZrO}_2$	0.0295	0.065	0.03	0.055	0.04
Others <sup>(b)</sup>	0.0036	0.0269	0.01	0.02	0.012

(a) The lower and upper bounds of the SCCs are in terms of mass fractions of the components, such that the mass fractions of all 15 components must sum to 1.0000.

(b) The Others component was composed of the following mixture of three minor components (expressed as mass fractions): Cl = 0.173, F = 0.263, and  $\text{P}_2\text{O}_5$  = 0.564.

The enhanced LAW EGCR was specified by the SCCs listed in Table 1.1 and the MCCs listed in Table 1.2. Table 1.1 and Table 1.2 list SCCs and MCCs separately for the outer and inner layers of the enhanced LAW EGCR. The outer-layer SCCs and MCCs were chosen to overlap and expand beyond the previously explored EGCR and to include more extreme LAW glass compositions based on current projections of the LAW feed.

Table 1.2. Lower and Upper Bounds of Multiple-Component Constraints for the Outer and Inner Layers of a 15-Component Enhanced Low-Activity Waste Experimental Glass Composition Region

Expression (units) <sup>(a)</sup>	Outer Layer		Inner Layer	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nalk (mf) <sup>(b)</sup>	0.15	0.265	0.195	0.2515
ZrO <sub>2</sub> +SnO <sub>2</sub> (mf)	0.03	0.11	0.04	0.08
$\eta_{1150}$ (poise) <sup>(c)</sup>	10	100	30	70
SO <sub>3</sub> Solubility (wt%)	—	Solubility Limit <sup>(d)</sup>	—	Solubility Limit <sup>(d)</sup>

(a) mf = mass fraction, wt% = weight percent.  
(b) Nalk = Na<sub>2</sub>O + 0.66(K<sub>2</sub>O) + 2(Li<sub>2</sub>O)  
(c)  $\eta_{1150}$  = viscosity at 1150°C, expressed as a linear mixture model, as discussed by Piepel et al. (2015, 2016).  
(d) The SO<sub>3</sub> solubility limit is expressed as a partial quadratic mixture model, as discussed by Piepel et al. (2015, 2016).

The 42 Phase 2 enhanced LAW glass compositions that were tested comprise a statistical layered design (Piepel et al. 1993; Cooley et al. 2003; Piepel et al. 2005) consisting of 21 outer-layer glasses, 15 inner-layer glasses, a center glass (three replicates), and two glasses previously tested at another laboratory. The 42 LAW glass compositions are listed in Table 1.3.

Four of the glasses in this study required some modifications to their compositions for them to melt and form glasses. These glasses had sulfate salts segregate from the melt, and therefore had to have the sulfate decreased in their final glass compositions. These four glasses also were opaque, which required their compositions to be modified. One other glass, LP2-OL-06, was eliminated because of continual chemical dissolution issues that caused it not to form a glass even after a couple of modifications. This is understandable because LP2-OL-06 was an outer-layer extreme vertex of the EGCR. The test matrix included outer-layer extreme vertices of to investigate LAW glasses with significantly higher waste loadings. This topic is discussed in more detail in Section 2.2. The modified glass compositions are listed in Table 1.4, with the extension “MOD” added to the glass identification. One glass, LP2-OL-03, required two modifications to obtain a glass and therefore is noted as “MOD2”. Note that glass property data were generated only for the “MOD” glasses, not their original “as-designed” counterparts.

This report summarizes the experimental methods used at PNNL to fabricate, heat treat, and test the remaining and modified 41 glasses in the LAW Phase 2 test matrix. These 41 glasses included the following:

- 20 outer-layer glass compositions (after one glass composition eliminated)
- 15 inner-layer glass compositions
- a repeated outer-layer glass composition (LP2-OL-10)
- a centroid glass, EWG-LAW-Centroid (three replicates; named LP2-IL-16, LP2-OL-2, and LP2-OL-21)
- a CUA-tested glass designated as LAW-ORP- LD1 (named LP2-OL-7)
- a CUA-tested glass designated as ORLEC33 (named LP2-IL-17).

Measured values of glass-quality and processing properties for the 41 Phase 2 LAW glasses are described in this report and data are provided in appendices.

Table 1.3. Targeted Compositions (mass fractions) for the Phase 2 Enhanced LAW Glasses

Component	Glass ID												
	LP2-IL-01	LP2-IL-02	LP2-IL-03	LP2-IL-04	LP2-IL-05	LP2-IL-06	LP2-IL-07	LP2-IL-08	LP2-IL-09	LP2-IL-10	LP2-IL-11	LP2-IL-12	LP2-IL-13
Al <sub>2</sub> O <sub>3</sub>	0.07500	0.07500	0.08725	0.07500	0.07500	0.10680	0.07500	0.07500	0.07500	0.10000	0.09000	0.07500	0.07500
B <sub>2</sub> O <sub>3</sub>	0.08000	0.08129	0.08732	0.08000	0.12000	0.12000	0.12000	0.08000	0.12000	0.09500	0.08000	0.08000	0.11255
CaO	0.07617	0.02000	0.02000	0.07494	0.07025	0.02000	0.05147	0.08000	0.02000	0.05000	0.03080	0.03117	0.02320
Cl	0.00174	0.00174	0.00347	0.00347	0.00347	0.00347	0.00347	0.00347	0.00173	0.00208	0.00347	0.00347	0.00174
Cr <sub>2</sub> O <sub>3</sub>	0.00525	0.00375	0.00525	0.00525	0.00375	0.00525	0.00375	0.00525	0.00525	0.00450	0.00375	0.00375	0.00525
F	0.00263	0.00263	0.00526	0.00527	0.00526	0.00526	0.00527	0.00526	0.00263	0.00316	0.00526	0.00527	0.00263
Fe <sub>2</sub> O <sub>3</sub>	0.00200	0.00577	0.00200	0.01000	0.00200	0.00200	0.00200	0.01000	0.01000	0.00600	0.01000	0.00200	0.01000
K <sub>2</sub> O	0.02000	0.02000	0.00758	0.02000	0.00500	0.02000	0.02000	0.00500	0.00500	0.01000	0.02000	0.00500	0.02000
MgO	0.00300	0.01000	0.00300	0.01000	0.00300	0.01000	0.01000	0.01000	0.00650	0.00300	0.01000	0.00300	0.00300
Na <sub>2</sub> O	0.23680	0.23680	0.24500	0.23680	0.22000	0.22000	0.22327	0.22000	0.24373	0.23000	0.22000	0.23787	0.22000
P <sub>2</sub> O <sub>5</sub>	0.00563	0.00563	0.01127	0.01127	0.01127	0.01127	0.01127	0.01127	0.00563	0.00676	0.01127	0.01127	0.00563
SiO <sub>2</sub>	0.37978	0.41808	0.40360	0.38200	0.37000	0.37000	0.39450	0.38975	0.37000	0.38800	0.38845	0.42920	0.43000
SO <sub>3</sub>	0.00800	0.00800	0.00200	0.00200	0.00200	0.00800	0.00800	0.00800	0.00200	0.00500	0.00200	0.00200	0.00200
SnO <sub>2</sub>	0.00500	0.02500	0.02500	0.02500	0.02500	0.00820	0.00500	0.00500	0.02203	0.01500	0.02500	0.00500	0.00500
V <sub>2</sub> O <sub>5</sub>	0.02000	0.00500	0.00500	0.00500	0.00500	0.01075	0.00500	0.00500	0.02000	0.01000	0.02000	0.02000	0.00500
ZnO	0.02400	0.02631	0.03200	0.02400	0.02400	0.02400	0.03200	0.03200	0.02800	0.03200	0.02400	0.02400	0.02400
ZrO <sub>2</sub>	0.05500	0.05500	0.05500	0.03000	0.05500	0.05500	0.03000	0.05500	0.05500	0.04000	0.05500	0.05500	0.05500
<b>Total</b>	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Table 1.3. Targeted Compositions (mass fractions) for the Phase 2 Enhanced LAW Glasses (cont.)

Component	Glass ID																														
	LP2-IL-14			LP2-IL-15			LP2-IL-16 (Centroid)			LP2-OL-01 (CUA ORLEC33)			LP2-OL-02			LP2-OL-03 (Centroid)			LP2-OL-04			LP2-OL-05			LP2-OL-06 (eliminated)			LP2-OL-07 (CUA LD1)		LP2-OL-08	
	LP2-IL-17																														
Al <sub>2</sub> O <sub>3</sub>	0.08795	0.07500	0.10000	0.09227	0.06000	0.10000	0.10550	0.10500	0.12500	0.12500	0.10150	0.06000																			
B <sub>2</sub> O <sub>3</sub>	0.12000	0.10752	0.09500	0.11000	0.06000	0.09500	0.06000	0.06000	0.06000	0.06000	0.12040	0.06000																			
CaO	0.03830	0.02000	0.05000	0.02500	0.0909	0.05000	0.10714	0.07840	0.11000	0.09130	0.08010	0.10664																			
Cl	0.00347	0.00347	0.00208	0.00073	0.00062	0.00208	0.00062	0.00062	0.00467	0.00467	0.00330	0.00062																			
Cr <sub>2</sub> O <sub>3</sub>	0.00375	0.00525	0.00450	0.00080	0.00600	0.00450	0.00600	0.00600	0.00300	0.00600	0.00500	0.00600																			
Cs <sub>2</sub> O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00130	0.00000																			
F	0.00526	0.00527	0.00316	0.00110	0.00095	0.00316	0.00095	0.00095	0.00708	0.00708	0.00170	0.00095																			
Fe <sub>2</sub> O <sub>3</sub>	0.01000	0.01000	0.00600	0.00200	0.00000	0.00600	0.00000	0.01500	0.01500	0.00000	0.01000	0.01500																			
K <sub>2</sub> O	0.00500	0.00500	0.01000	0.00500	0.00000	0.01000	0.00000	0.05750	0.00000	0.05750	0.00160	0.00000																			
MgO	0.00300	0.00300	0.00650	0.01000	0.01350	0.00650	0.01350	0.01350	0.00000	0.00000	0.01000	0.00000																			
Na <sub>2</sub> O	0.24500	0.22000	0.23000	0.23000	0.21000	0.23000	0.26000	0.21000	0.21000	0.21000	0.20980	0.26000																			
NiO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00040	0.00000																			
P <sub>2</sub> O <sub>5</sub>	0.01127	0.01127	0.00676	0.00237	0.00203	0.00676	0.00203	0.00203	0.01515	0.01515	0.00290	0.00203																			
SiO <sub>2</sub>	0.37000	0.42722	0.38800	0.40943	0.47000	0.38800	0.34900	0.34900	0.39080	0.34900	0.37140	0.34900																			
SO <sub>3</sub>	0.00800	0.00800	0.00500	0.01000	0.00100	0.00500	0.01076	0.00100	0.00980	0.00880	0.01060	0.01476																			
SnO <sub>2</sub>	0.00500	0.02500	0.01500	0.00000	0.00000	0.01500	0.03500	0.00000	0.00000	0.00000	0.00000	0.00000																			
V <sub>2</sub> O <sub>5</sub>	0.00500	0.02000	0.01000	0.02100	0.00000	0.01000	0.00000	0.00000	0.00000	0.00000	0.01000	0.04000																			
ZnO	0.02400	0.02400	0.02800	0.03000	0.02000	0.02800	0.02000	0.03600	0.02000	0.03600	0.03000	0.02000																			
ZrO <sub>2</sub>	0.05500	0.03000	0.04000	0.05030	0.06500	0.04000	0.02950	0.06500	0.02950	0.02950	0.03000	0.06500																			
<b>Total<sup>(a)</sup></b>	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000																			

Table 1.3. Targeted Compositions (mass fractions) for the Phase 2 Enhanced LAW Glasses (cont.)

Component	Glass ID											
	LP2-OL-09	LP2-OL-10 (Rep. of LP2-OL-5)										
		LP2-OL-11	LP2-OL-12	LP2-OL-13	LP2-OL-14	LP2-OL-15	LP2-OL-16	LP2-OL-17	LP2-OL-18	LP2-OL-19	LP2-OL-20	
Al <sub>2</sub> O <sub>3</sub>	0.12500	0.12500	0.06000	0.06000	0.06000	0.06000	0.06000	0.06000	0.06000	0.06000	0.06000	0.06000
B <sub>2</sub> O <sub>3</sub>	0.13750	0.06000	0.13750	0.13750	0.06000	0.13750	0.13750	0.07474	0.06000	0.06000	0.06000	0.06000
CaO	0.02000	0.11000	0.07990	0.07991	0.11000	0.07171	0.11000	0.03050	0.04550	0.08723	0.03345	0.08050
Cl	0.00062	0.00467	0.00062	0.00467	0.00467	0.00062	0.00062	0.00467	0.00467	0.00062	0.00062	0.00062
Cr <sub>2</sub> O <sub>3</sub>	0.00600	0.00300	0.00300	0.00600	0.00300	0.00600	0.00600	0.00300	0.00600	0.00300	0.00300	0.00300
Cs <sub>2</sub> O	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
F	0.00095	0.00708	0.00095	0.00708	0.00708	0.00095	0.00095	0.00708	0.00708	0.00095	0.00095	0.00095
Fe <sub>2</sub> O <sub>3</sub>	0.00000	0.01500	0.00000	0.01500	0.00000	0.00000	0.01500	0.01500	0.01500	0.01500	0.01500	0.00000
K <sub>2</sub> O	0.00000	0.00000	0.05750	0.00000	0.05750	0.05750	0.00000	0.05750	0.00000	0.05750	0.00000	0.00000
MgO	0.00000	0.00000	0.01350	0.01350	0.00000	0.00000	0.01350	0.01350	0.01350	0.00000	0.00000	0.00000
Na <sub>2</sub> O	0.21000	0.21000	0.21000	0.25941	0.22205	0.21000	0.21000	0.22205	0.21000	0.21000	0.21000	0.26000
NiO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
P <sub>2</sub> O <sub>5</sub>	0.00203	0.01515	0.00203	0.01515	0.01515	0.00203	0.00203	0.01515	0.01515	0.00203	0.00203	0.00203
SiO <sub>2</sub>	0.39190	0.39080	0.34900	0.35128	0.35405	0.34900	0.35640	0.47000	0.37105	0.34900	0.46499	0.46640
SO <sub>3</sub>	0.00100	0.00980	0.00100	0.00100	0.00100	0.01519	0.00100	0.01116	0.00100	0.01137	0.00796	0.00100
SnO <sub>2</sub>	0.01550	0.00000	0.00000	0.00000	0.00000	0.00000	0.03500	0.00000	0.03500	0.03500	0.03500	0.00000
V <sub>2</sub> O <sub>5</sub>	0.04000	0.00000	0.00000	0.00000	0.04000	0.04000	0.00000	0.04000	0.04000	0.04000	0.00000	0.00000
ZnO	0.02000	0.02000	0.02000	0.02000	0.03600	0.02000	0.03600	0.03600	0.02000	0.03600	0.02000	0.03600
ZrO <sub>2</sub>	0.02950	0.02950	0.06500	0.02950	0.02950	0.02950	0.02950	0.02950	0.02950	0.06500	0.02950	0.02950
<b>Total</b>	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Table 1.3. Targeted Compositions (mass fractions) for the Phase 2 Enhanced LAW Glasses (cont.)

Component	Glass ID				
	LP2-OL-21 (Centroid)	LP2-OL-22	LP2-OL-23	LP2-OL-24	LP2-OL-25
Al <sub>2</sub> O <sub>3</sub>	0.10000	0.07000	0.06000	0.12500	0.06000
B <sub>2</sub> O <sub>3</sub>	0.09500	0.06000	0.13725	0.06000	0.13750
CaO	0.05000	0.11000	0.11000	0.07245	0.02578
Cl	0.00208	0.00062	0.00062	0.00062	0.00062
Cr <sub>2</sub> O <sub>3</sub>	0.00450	0.00300	0.00300	0.00300	0.00300
Cs <sub>2</sub> O	0.00000	0.00000	0.00000	0.00000	0.00000
F	0.00316	0.00095	0.00095	0.00095	0.00095
Fe <sub>2</sub> O <sub>3</sub>	0.00600	0.01500	0.00000	0.01500	0.01500
K <sub>2</sub> O	0.01000	0.00000	0.00000	0.00000	0.00000
MgO	0.00650	0.00000	0.01350	0.01350	0.00000
Na <sub>2</sub> O	0.23000	0.21000	0.21000	0.25195	0.26000
NiO	0.00000	0.00000	0.00000	0.00000	0.00000
P <sub>2</sub> O <sub>5</sub>	0.00676	0.00203	0.00203	0.00203	0.00203
SiO <sub>2</sub>	0.38800	0.36740	0.34900	0.34900	0.34900
SO <sub>3</sub>	0.00500	0.00100	0.01315	0.00100	0.01012
SnO <sub>2</sub>	0.01500	0.03500	0.03500	0.00000	0.03500
V <sub>2</sub> O <sub>5</sub>	0.01000	0.04000	0.00000	0.04000	0.00000
ZnO	0.02800	0.02000	0.03600	0.03600	0.03600
ZrO <sub>2</sub>	0.04000	0.06500	0.02950	0.02950	0.06500
<b>Total</b>	1.00000	1.00000	1.00000	1.00000	1.00000

Table 1.4. Targeted Compositions (mass fractions) for the Modified Outer-Layer Phase 2 Enhanced LAW Glasses

Component	Glass ID			
	LP2-OL-03-MOD2	LP2-OL-08-MOD	LP2-OL-10-MOD	LP2-OL-16-MOD
Al <sub>2</sub> O <sub>3</sub>	0.10738	0.06121	0.12523	0.06008
B <sub>2</sub> O <sub>3</sub>	0.06107	0.06121	0.06011	0.07483
CaO	0.10905	0.10879	0.11020	0.03054
Cl	0.00063	0.00063	0.00468	0.00062
Cr <sub>2</sub> O <sub>3</sub>	0.00611	0.00612	0.00301	0.00601
F	0.00097	0.00097	0.00709	0.00095
Fe <sub>2</sub> O <sub>3</sub>	0.00000	0.01530	0.01503	0.01502
K <sub>2</sub> O	0.00000	0.00000	0.00000	0.00000
MgO	0.01374	0.00000	0.00000	0.01352
Na <sub>2</sub> O	0.26464	0.26524	0.21038	0.21026
P <sub>2</sub> O <sub>5</sub>	0.00207	0.00207	0.01518	0.00203
SiO <sub>2</sub>	0.35523	0.35604	0.39151	0.47059
SO <sub>3</sub>	0.00754	0.00816	0.00800	0.00992
SnO <sub>2</sub>	0.02779	0.00000	0.00000	0.00000
V <sub>2</sub> O <sub>5</sub>	0.00000	0.04081	0.00000	0.04005
ZnO	0.02036	0.02040	0.02004	0.03605
ZrO <sub>2</sub>	0.02342	0.05305	0.02955	0.02954
<b>Total</b>	1.00000	1.00000	1.00000	1.00000

## 1.3 Quality Assurance

### 1.3.1 PNNL QA Program

The PNNL Quality Assurance (QA) Program is based upon the requirements as defined in the DOE Order 414.1D, *Quality Assurance*, and 10 CFR 830, *Energy/Nuclear Safety Management*, Subpart A, *Quality Assurance Requirements* (a.k.a., the Quality Rule). PNNL has chosen to implement the following consensus standards in a graded approach:

- ASME NQA-1-2000, *Quality Assurance Requirements for Nuclear Facility Applications*, Part I, “Requirements for Quality Assurance Programs for Nuclear Facilities”
- ASME NQA-1-2000, Part II, Subpart 2.7, “Quality Assurance Requirements for Computer Software for Nuclear Facility Applications”, including problem reporting and corrective action
- ASME NQA-1-2000, Part IV, Subpart 4.2, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

The PNNL *Quality Assurance Program Description/Quality Management M&O Program Description* describes the Laboratory-level QA program that applies to all work performed by PNNL. Laboratory-level procedures for implementing the QA requirements described in the standards identified above are deployed through PNNL’s web-based “How Do I...?” (HDI) system, a standards-based system for managing and deploying requirements and procedures to PNNL staff. The HDI procedures (called Workflows and Work Controls) provide detailed guidance for performing tasks, such as protecting classified information and procuring items and services, as well as general guidelines for performing research-related tasks, such as preparing and reviewing calculations and calibrating and controlling measuring and test equipment.

### 1.3.2 ORP Glass Support Work QA Program

The ORP Glass Support Work project is performed under the PNNL nuclear quality assurance program (NQAP); this program establishes an ASME NQA-1-2012, 10 CFR 830, Subpart A DOE Order (O) 414.1D compliant QA program for use by research and development (R&D) projects and programs that are compatible with the editions of ASME NQA-1 2000 through 2012.

The work of this report was performed to the QA level of applied research:

*Applied research work activities (or deliverables) apply to nuclear and non-nuclear R&D (work activities or deliverables) that are processes initiated-with-the-intent of solving a specific problem or meeting a practical need. For applied research activities, grading is minimal and largely contingent upon the complexity of the research and the ability to duplicate the research if data were lost. The elements of QA grading, including the level of documentation, were applied to the program-, project-, and task-levels.*

## 2.0 Test Methods

This section describes how the data were obtained for the 41 enhanced LAW glasses described in Section 1.0. The descriptions include the methods for 1) glass fabrication, 2) needed composition modification 3) chemical composition analysis, 4) density determination, 5) viscosity measurement, 6) electrical conductivity (EC) measurement, 7) crystal fraction (CF) determination, 8) secondary phase identification from canister centerline cooling (CCC), 9) PCT response, 10) VHT response, and 11) sulfate solubility measurement.

### 2.1 Glass Fabrication

Glass fabrication was performed according to the PNNL procedure, *Glass Batching and Melting* (WFDL-GBM-1, Rev 2).<sup>1</sup> Single metal oxides, single metal carbonates, and sodium salts were weighed out in the appropriate masses to form the target glass composition for each glass and then placed in a plastic bag. After thoroughly mixing in the plastic bag for at least 30 s until uniform color developed, the powders were transferred into an agate milling chamber and milled for 2 min in the Angstrom vibratory mill. The powders were then transferred to a clean Pt-10%Rh crucible for melting using a two-step melt process. The first melt was of the raw materials after mixing in the agate milling chamber. Initial melting was performed at a temperature of 1150°C for 1 h to 1.8 h for the compositions to melt and form macroscopically homogenous glasses. A second melt of the glass was accomplished after the first melt was quenched and the glass was ground to a fine powder in a tungsten carbide vibratory mill. Some glasses required a third melt or more to be performed. Generally, the second melt and subsequent melts were at the same temperature, or 25°C to 100°C higher, than the initial melt, and 1 h to 2.3 h in duration. See Table 2.1 for specific melt times and temperatures used for each glass.

Four of the matrix glasses required a melt temperature of 1200°C, with one glass requiring a melt temperature of 1250°C. In addition, 18 of the glasses required more than two iterations of grinding and melting to fully dissolve all the starting materials and adequately melt the glasses. Using a higher melting temperature is deemed to be an acceptable method of fabricating challenging glass compositions. The laboratory crucible-scale fabrication of glasses is not intended to mimic the actual melter process or feed processing. Rather, it is intended to fabricate a glass sample with a controlled composition for property testing. Composition is the primary variable in determining glass properties. The other primary impact of temperature history of glass melts is the impact on phase assemblage. Both liquid and crystalline phase separation may occur in some glasses. The impacts of thermal history on phase assemblage is measured for test glasses by systematic isothermal heat treatments at a range of temperatures and the CCC heat treatments bounding the anticipated behavior in the plant.

The morphology and color of each quenched glass is shown in Appendix A.

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(1) Russell, RL. 2016. *Glass Batching and Melting*. WFDL-GBM-1, Rev. 2.

Table 2.1. Melting Temperatures and Times Used in Fabricating the Phase 2 Enhanced LAW Waste Glasses

Glass ID	First Melt			Second and More Melts		
	Date	Temp. (°C)	Time (h)	Date	Temp. (°C)	Time (h)
LP2-IL-01	1/12/17	1150	1	1/13/17, 1/20/17	1150, 1175	1.5, 1
LP2-IL-02	1/11/17	1150	1	1/12/17, 1/13/17, 1/16/17, 1/17/17	1150, 1150, 1150, 1150	1.5, 0.5, 0.5, 0.33
LP2-IL-03	1/20/17	1150	1	1/24/17	1150	1.5
LP2-IL-04	1/23/17	1150	1	1/23/17	1150	2.3
LP2-IL-05	1/26/17	1150	1	1/27/17	1150	1.5
LP2-IL-06	2/20/17	1175	1	2/22/17, 2/27/17, 3/3/17	1175, 1175, 1175	2, 1, 1
LP2-IL-07	1/26/17	1150	1	1/27/17	1150	1
LP2-IL-08	2/27/17	1150	1	2/28/17, 3/3/17, 3/3/17	1175, 1175, 1200	1.5, 1, 1
LP2-IL-09	1/30/17	1150	1	1/31/17, 2/2/17	1150, 1175	1.75, 1
LP2-IL-10	2/3/17	1150	1	2/6/17, 2/10/17	1150, 1175	1, 1.5
LP2-IL-11	2/10/17	1150	1	2/13/17, 2/14/17	1150, 1175	1.5, 1
LP2-IL-12	2/16/17	1150	1	2/16/17, 2/17/17	1150, 1175	1.5, 1
LP2-IL-13	2/16/17	1150	1	2/17/17	1150	1.5
LP2-IL-14	2/20/17	1150	1	2/21/17, 2/22/17	1150, 1150	1.5, 0.75
LP2-IL-15	2/21/17	1150	1	2/23/17, 2/23/17	1150, 1150	1.5, 1
LP2-IL-16	3/3/17	1150	1	3/3/17, 3/4/17	1175, 1175	1.5, 0.75
LP2-IL-17	2/24/17	1150	1	2/24/17	1150	1.5
LP2-OL-01-3	10/31/17	1150	1.5	11/1/17	1150	NR
LP2-OL-02-1	11/8/17	1150	1.5	11/8/17	1150	1.33
LP2-OL-03-MOD2	3/5/18	1150	1.7	3/6/18, 3/1/18	1150, 1200	1.5, 1.3
LP2-OL-04-1	11/2/17	1150	1.6	11/6/17	1150	1.5
LP2-OL-05	10/23/17	1150	1.5	10/24/17, 10/26/17	1150, 1150	1.5, 1.5
LP2-OL-07-1	11/14/17	1150	1.5	11/14/17	1150	NR
LP2-OL-08-MOD	2/26/18	1150	1.6	2/27/18	1150	1.4
LP2-OL-09-1	11/20/17	1150	1.5	11/20/17	1150	1.5
LP2-OL-10-MOD	2/22/18	1150	1.5	2/26/18, 2/27/18	1150, 1150	1.5, 1.6
LP2-OL-11	11/21/17	1150	1.4	11/21/17	1150	1.6
LP2-OL-12	11/22/17	1150	1.5	11/27/17	1150	1.5
LP2-OL-13	11/27/17	1150	1.5	11/28/17	1150	1.7
LP2-OL-14	11/28/17	1150	1.5	11/29/17	1150	1.5
LP2-OL-15	11/29/17	1150	1.5	11/30/17	1150	1.5
LP2-OL-16-MOD	2/20/18	1150	1.5	2/20/18, 2/21/18	1150, 1200	1.5, 2
LP2-OL-17	12/4/17	1150	1.8	12/5/17	1150	1.5
LP2-OL-18	12/5/17	1150	1.5	12/5/17, 12/28/17	1150, 1250	1.3, 1.6
LP2-OL-19	12/8/17	1150	1.5	12/11/17	1150	1.5
LP2-OL-20	12/11/17	1150	1.5	12/12/17	1150	1.5
LP2-OL-21	12/12/17	1150	1.5	12/14/17	1150	1.4
LP2-OL-22	12/14/17	1150	1.6	12/17/17, 12/21/17	1150, 1150	1.4, 1.5
LP2-OL-23	12/18/17	1150	1.4	12/18/17	1150	1.5
LP2-OL-24	12/17/17	1150	1.6	12/19/17, 12/28/17	1150, 1200	1.5, 1.7
LP2-OL-25	12/20/17	1150	1.5	12/20/17	1150	1.4

NR = not recorded

## 2.2 Matrix Glasses Needing Composition Modification

Five outer-layer matrix glasses needed some modification to their compositions to form homogeneous glasses. Modifications to these glasses are discussed in detail in the following sections.

## 2.2.1 LP2-OL-03

The original composition of the LP2-OL-03 glass had salt segregation on the glass surface and around the crucible edges (see Figure 2.1) following the third melt at 1150°C for 95 min. Iterations of composition modifications made to this glass are shown in Table 2.2 with the changes in boldface.

The first modification of the LP2-OL-03 glass decreased the SO<sub>3</sub> by ~15% (from 0.01076 to 0.01058 mf) and renormalized the composition. This modified composition was melted five times. The first three times it was melted at 1150°C for 90 min each. The next two times it was melted at 1200°C for 120 min and 30 min, respectively. The first three melts all showed undissolved particles and sulfur on the crucible walls, as shown in Figure 2.2 and Figure 2.3. By the fourth melt, the undissolved particles were gone, but sulfur was still being deposited on the crucible walls. After the last melt, there also appeared to be phase separation, as the glass touching the pour plate was transparent, but the top part of the glass was cloudy (see Figure 2.4).

Table 2.2. Composition Modifications Made to Glass LP2-OL-03

Component	Glass Oxide Fraction		
	Original	1 <sup>st</sup> Mod	2 <sup>nd</sup> Mod and Final
SiO <sub>2</sub>	0.34900	0.34906	0.35523
Al <sub>2</sub> O <sub>3</sub>	0.10550	0.10552	0.10738
B <sub>2</sub> O <sub>3</sub>	0.06000	0.06001	0.06107
Na <sub>2</sub> O	0.26000	0.26005	0.26464
Fe <sub>2</sub> O <sub>3</sub>	0.00000	0.00000	0.00000
CaO	0.10714	0.10716	0.10905
SnO <sub>2</sub>	0.03500	0.03501	<b>0.02779</b>
ZnO	0.02000	0.02000	0.02036
ZrO <sub>2</sub>	0.02950	0.02951	<b>0.02342</b>
V <sub>2</sub> O <sub>5</sub>	0.00000	0.00000	0.00000
Cl	0.00062	0.00062	0.00063
Cr <sub>2</sub> O <sub>3</sub>	0.00600	0.00600	0.00611
K <sub>2</sub> O	0.00000	0.00000	0.00000
MgO	0.01350	0.01350	0.01374
P <sub>2</sub> O <sub>5</sub>	0.00203	0.00203	0.00207
F	0.00095	0.00095	0.00097
SO <sub>3</sub>	0.01076	<b>0.01058</b>	<b>0.00754</b>
Sum	1.00000	1.00000	1.00000
Melt Temp (°C)	1150/1150/1150	1150/1150/1150/ <b>1200/1200</b>	1150/1150
Melt Time (min)	90/95/95	90/90/90/ <b>120/30</b>	102/90



Figure 2.1. Glass LP2-OL-03 Original Composition



Figure 2.2. Glass LP2-OL-03 First Modified Composition after First Melt



Figure 2.3. Glass LP2-OL-03 First Modified Composition after Third Melt



Figure 2.4. Glass LP2-OL-03 First Modified Composition after Final Melt

Due to the appearance of a phase separation, the glass composition was modified again. The second modification of the LP2-OL-03 glass composition decreased the  $\text{SO}_3$  by 30% (from 0.01508 to 0.00754 mf) as well as decreasing the  $\text{SnO}_2$  and  $\text{ZrO}_2$  together by ~22% (from 0.03501 to 0.02779 mf for  $\text{SnO}_2$  and from 0.02951 to 0.02342 mf for  $\text{ZrO}_2$ ) based on the first modification. The entire composition was then renormalized to a sum of 1.00000 and is shown in Table 2.2. After the first melt of this modified composition at 1150°C for 102 min, a few big undissolved particles were observed, but there was no sulfur on the edges. After a second melt at the same temperature for 90 min, the glass was transparent with no sulfur or undissolved particles present. Therefore, it was decided that this would be the final composition, which would be characterized.

## 2.2.2 LP2-OL-06

The original composition of the LP2-OL-06 glass had salt segregation and undissolved particles following the third melt at 1150°C for 95 min (see Figure 2.5). Iterations of composition modifications made to this glass are shown in Table 2.3 with the changes in boldface.

For the first modification, the  $\text{SO}_3$  was reduced by 11% (from 0.00880 to 0.00787 mf) and the composition was renormalized, as shown in Table 2.3. After three melts at 1150°C for 90 min each, the glass was still opaque, with evidence of sulfur and undissolved particles (see Figure 2.6). Due to the evidence of sulfur and undissolved particles, another modification was performed.

For the second modification, the  $\text{SO}_3$  was reduced by 20% (from 0.00787 to 0.00612 mf) from the first modified value and the  $\text{P}_2\text{O}_5$  was reduced by 50% from the original value (from 0.01515 to 0.00765 mf). Then, the composition was renormalized and is shown in Table 2.3. After two melts at 1150°C for 90 min each, there was still a large amount of undissolved particles and sulfur on the surface of the glass (see Figure 2.7).

Table 2.3. Composition Modifications Made to Glass LP2-OL-06

<b>Component</b>	<b>Glass Oxide Fraction</b>			
	<b>Original</b>	<b>1<sup>st</sup> Mod</b>	<b>2<sup>nd</sup> Mod</b>	<b>3<sup>rd</sup> Mod</b>
SiO <sub>2</sub>	0.34900	0.34933	0.35264	0.35551
Al <sub>2</sub> O <sub>3</sub>	0.12500	0.12512	0.12630	0.12733
B <sub>2</sub> O <sub>3</sub>	0.06000	0.06006	0.06063	0.06112
Na <sub>2</sub> O	0.21000	0.21020	0.21219	0.21392
Fe <sub>2</sub> O <sub>3</sub>	0.00000	0.00000	0.00000	0.00000
CaO	0.09130	0.09138	0.09225	0.09300
SnO <sub>2</sub>	0.00000	0.00000	0.00000	0.00000
ZnO	0.03600	0.03603	0.03638	0.03667
ZrO <sub>2</sub>	0.02950	0.02953	0.02981	<b>0.02344</b>
V <sub>2</sub> O <sub>5</sub>	0.00000	0.00000	0.00000	0.00000
Cl	0.00467	0.00467	0.00472	0.00476
Cr <sub>2</sub> O <sub>3</sub>	0.00600	0.00601	0.00606	0.00611
K <sub>2</sub> O	0.05750	0.05755	0.05810	0.05857
MgO	0.00000	0.00000	0.00000	0.00000
P <sub>2</sub> O <sub>5</sub>	0.01515	0.01516	<b>0.00765</b>	<b>0.00772</b>
F	0.00708	0.00709	0.00715	0.00721
SO <sub>3</sub>	0.00880	<b>0.00787</b>	<b>0.00612</b>	<b>0.00463</b>
Sum	1.00000	1.00000	1.00000	0.99999
Melt Temp (°C)	1150/1150/1150	1150/1150/1150	1150/1150	1150/1150/1150
Melt Time (min)	90/90/95	91/91/100	90/110	90/90/90



Figure 2.5. Glass LP2-OL-06 Original Composition

For the third modification, the  $\text{SO}_3$  was reduced another 25% from the second modification (from 0.00612 to 0.00463 mf), the  $\text{ZrO}_2$  was reduced 21% (from 0.02981 to 0.02344 mf), and the  $\text{P}_2\text{O}_5$  was kept at the level of the second modification. The composition was then renormalized, as shown in Table 2.3. Although the number of undissolved particles appeared to decrease after three melts at 1150°C for 90 min each, there still appeared to be streaks of sulfur present with a slightly opaque glass (see Figure 2.8). Therefore, it was decided to eliminate this glass from further testing.



Figure 2.6. Glass LP2-OL-06 First Modification



Figure 2.7. Glass LP2-OL-06 Second Modification



Figure 2.8. Glass LP2-OL-06 Third Modification

### 2.2.3 LP2-OL-08

When melted at 1150°C for 90 min, the original composition of LP2-OL-08 formed clear glass on the bottom, but crystals formed upon cooling in the rest of the glass (causing it to be very opaque, Figure 2.9). An XRD analysis found the crystals to be sodium sulfate (Figure 2.10). Iterations of composition modifications made to this glass are shown in Table 2.4 with the changes in boldface.

For the first modification, shown in Table 2.4, the SO<sub>3</sub> was decreased by 45% (from 0.01476 to 0.00816 mf) and the ZrO<sub>2</sub> was decreased by 20% (from 0.06500 to 0.05305). Then, the composition with modified values was renormalized. The batch was melted at 1150°C for ~90 min twice, and then the temperature was increased to 1200°C for ~80 min due to the presence of undissolved particles. Raising the temperature of the melt resulted in a smooth and shiny glass (Figure 2.11), so the modified and renormalized composition was determined to be final.

Table 2.4. Composition Modifications Made to Glass LP2-OL-08

Component	Glass Oxide Mass Fractions	
	Original	1 <sup>st</sup> Mod and Final
SiO <sub>2</sub>	0.34900	0.35604
Al <sub>2</sub> O <sub>3</sub>	0.06000	0.06121
B <sub>2</sub> O <sub>3</sub>	0.06000	0.06121
Na <sub>2</sub> O	0.26000	0.26524
Fe <sub>2</sub> O <sub>3</sub>	0.01500	0.01530
CaO	0.10664	0.10879
SnO <sub>2</sub>	0.00000	0.00000
V <sub>2</sub> O <sub>5</sub>	0.04000	0.04081
ZnO	0.02000	0.02040
ZrO <sub>2</sub>	0.06500	<b>0.05305</b>
Cl	0.00062	0.00063
Cr <sub>2</sub> O <sub>3</sub>	0.00600	0.00612
K <sub>2</sub> O	0.00000	0.00000
MgO	0.00000	0.00000
P <sub>2</sub> O <sub>5</sub>	0.00203	0.00207
F	0.00095	0.00097
SO <sub>3</sub>	0.01476	<b>0.00816</b>
Sum	1.00000	1.00000
Melt Temp (°C)	1150/1150	1150/1150/ <b>1200</b>
Melt Time (min)	90/90	91/82/79



Figure 2.9. Glass LP2-OL-08 Original Composition

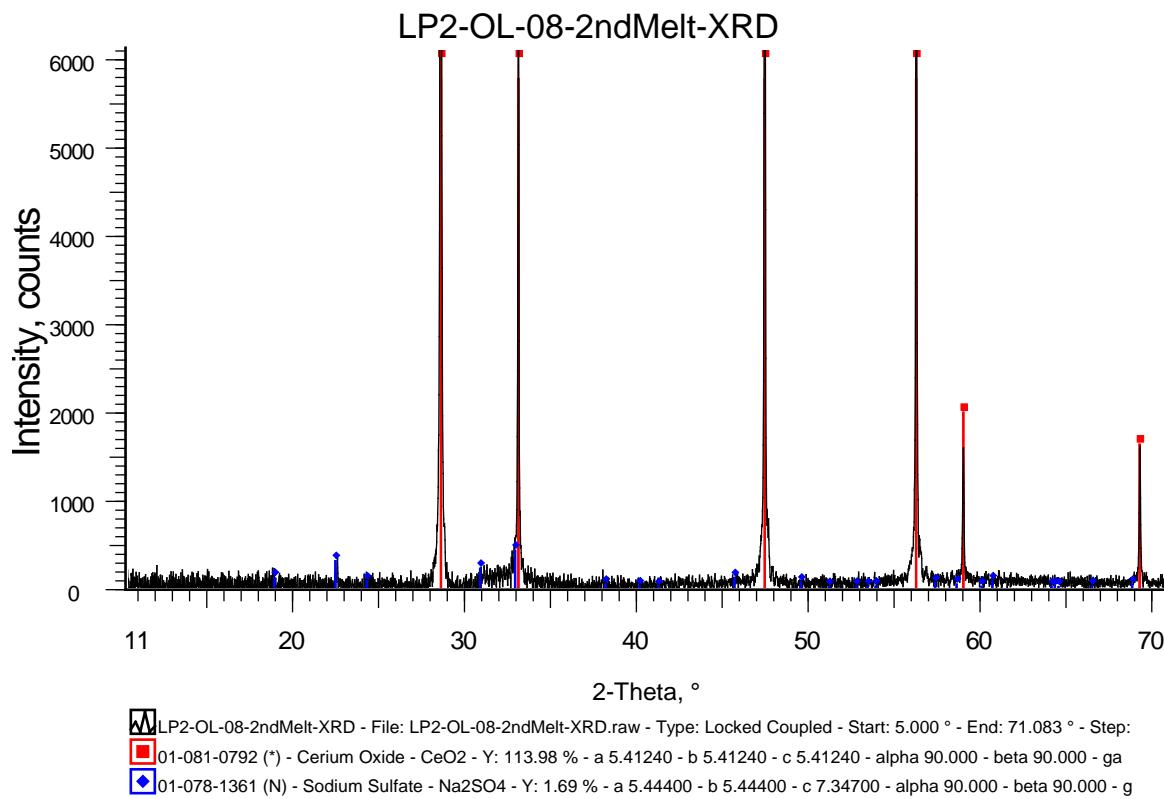


Figure 2.10. XRD Pattern of Original LP2-OL-08 Composition

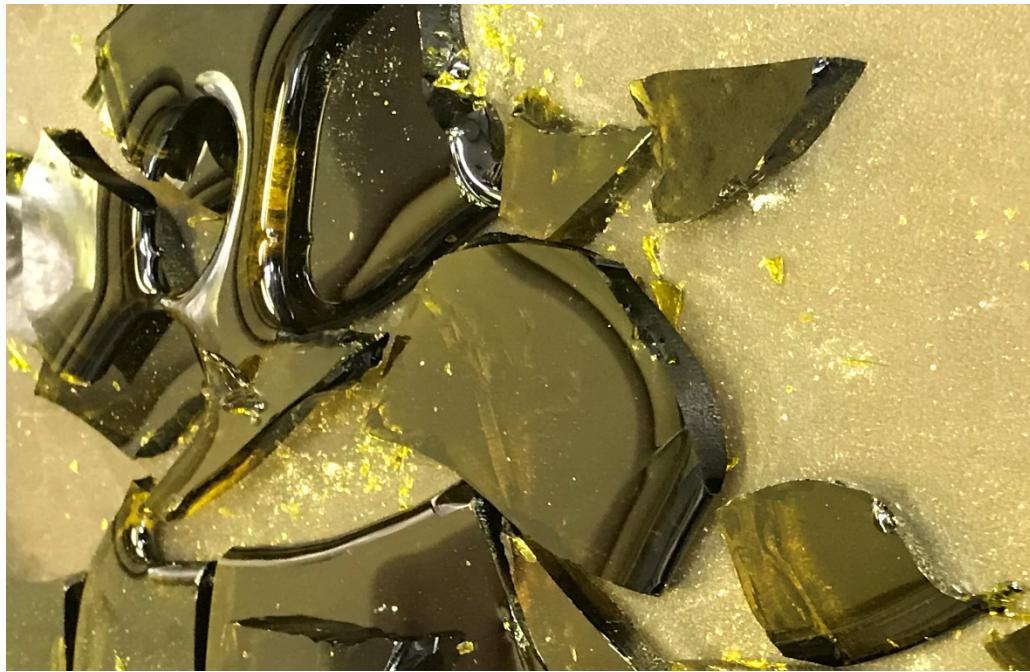


Figure 2.11. Glass LP2-OL-08 after First Modification

## 2.2.4 LP2-OL-10

When melted three times at 1150°C for 90 min, the original composition of LP2-OL-10 formed an opaque glass with a slight amount of sulfate salt, as shown in Figure 2.12. Iterations of composition modifications made to this glass are shown in Table 2.5 with the changes in boldface.

For the first modification, the SO<sub>3</sub> was reduced by 20% (from 0.00980 to 0.00800 mf) and the modified composition was renormalized. The batch was melted at 1150°C three times. This composition resulted in a smooth and shiny glass (Figure 2.13), and therefore was determined to be the final composition.

Table 2.5. Composition Modifications Made to Glass LP2-OL-10

Component	Glass Oxide Mass Fractions	
	Original	1 <sup>st</sup> Mod and Final
SiO <sub>2</sub>	0.39080	0.39151
Al <sub>2</sub> O <sub>3</sub>	0.12500	0.12523
B <sub>2</sub> O <sub>3</sub>	0.06000	0.06011
Na <sub>2</sub> O	0.21000	0.21038
Fe <sub>2</sub> O <sub>3</sub>	0.01500	0.01503
CaO	0.11000	0.11020
SnO <sub>2</sub>	0.00000	0.00000
V <sub>2</sub> O <sub>5</sub>	0.00000	0.00000
ZnO	0.02000	0.02004
ZrO <sub>2</sub>	0.02950	0.02955
Cl	0.00467	0.00468
Cr <sub>2</sub> O <sub>3</sub>	0.00300	0.00301
K <sub>2</sub> O	0.00000	0.00000
MgO	0.00000	0.00000
P <sub>2</sub> O <sub>5</sub>	0.01515	0.01518
F	0.00708	0.00709
SO <sub>3</sub>	0.00980	<b>0.00800</b>
Sum	1.00000	1.00001
Melt Temp (°C)	1150/1150/1150	1150/1150/1150
Melt Time (min)	90/90/95	90/150/34



Figure 2.12. Glass LP2-OL-10 Original Composition

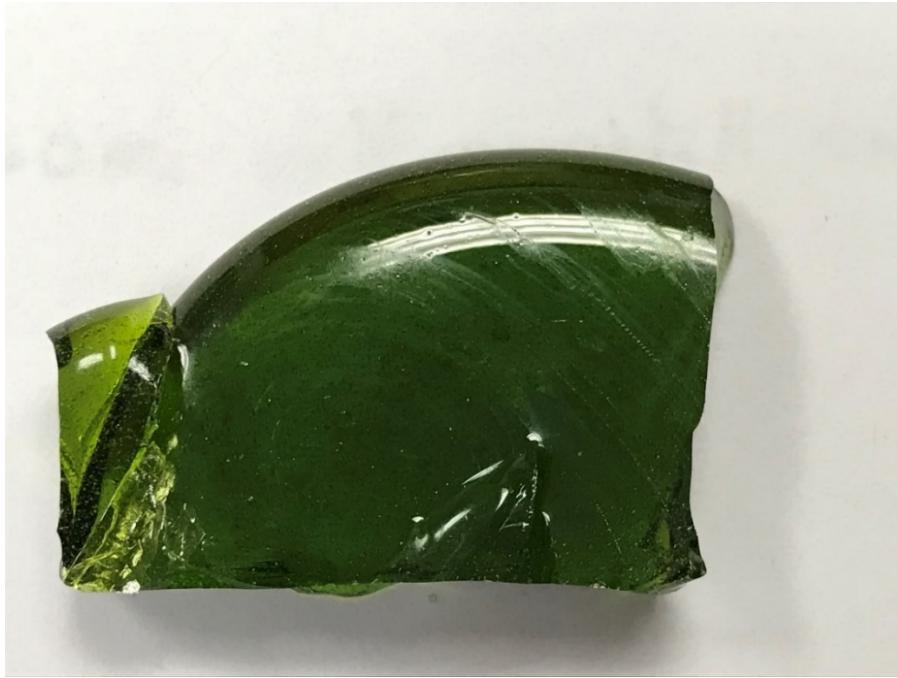


Figure 2.13. Glass LP2-OL-10 after First Modification

## 2.2.5 LP2-OL-16

When melted twice at 1150°C for 90 min, the original composition of the LP2-OL-16 formed an opaque glass with a small amount of sulfate salt present, as shown in Figure 2.14. Iterations of composition modifications made to this glass are shown in Table 2.6 with the changes in bold face.

For the first modification, the SO<sub>3</sub> was reduced by 11% (from 0.01116 to 0.00992 mf) and the modified composition was renormalized. The batch was melted at 1150°C twice for 90 min each, and then the temperature was increased to 1200°C for 120 min due to the presence of undissolved particles. Raising the temperature of the melt resulted in a smooth and shiny glass (Figure 2.15), and therefore was determined to be the final composition.

Table 2.6. Composition Modifications Made to Glass LP2-OL-16

Component	Glass Oxide Mass Fractions	
	Original	1 <sup>st</sup> Mod and Final
SiO <sub>2</sub>	0.47000	0.47059
Al <sub>2</sub> O <sub>3</sub>	0.06000	0.06008
B <sub>2</sub> O <sub>3</sub>	0.07474	0.07483
Na <sub>2</sub> O	0.21000	0.21026
Fe <sub>2</sub> O <sub>3</sub>	0.01500	0.01502
CaO	0.03050	0.03054
SnO <sub>2</sub>	0.00000	0.00000
V <sub>2</sub> O <sub>5</sub>	0.04000	0.04005
ZnO	0.03600	0.03605
ZrO <sub>2</sub>	0.02950	0.02954
Cl	0.00062	0.00062
Cr <sub>2</sub> O <sub>3</sub>	0.00600	0.00601
K <sub>2</sub> O	0.00000	0.00000
MgO	0.01350	0.01352
P <sub>2</sub> O <sub>5</sub>	0.00203	0.00203
F	0.00095	0.00095
SO <sub>3</sub>	0.01116	<b>0.00992</b>
Sum	1.00000	1.00001
Melt Temp (°C)	1150/1150	1150/1150/ <b>1200</b>
Melt Time (min)	85/100	90/87/ <b>120</b>



Figure 2.14. Glass LP2-OL-16 Original Composition



Figure 2.15. Glass LP2-OL-16 after First Modification

## 2.3 Chemical Analysis of Glass Composition

To confirm that the “as-fabricated” glasses corresponded to the specified target compositions, a representative sample of each glass was chemically analyzed at the Savannah River National Laboratory (SRNL) Process Science Analytical Laboratory (PSAL). Three preparation techniques, including sodium peroxide fusion (PF), lithium metaborate/tetraborate fusion (LM), and potassium hydroxide digestion (KH), were used to prepare duplicate glass samples for analysis.

Each of the six preparations (two duplicate glass samples for each for the three preparation techniques) was analyzed twice by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). All elements of interest and appropriate for a given preparation method were determined for each analysis. The duplicate samples were analyzed twice resulting in four measurements of each element. These measurements were then averaged, and the average value was reported. Glass composition standards were also intermittently prepared and analyzed to assess the performance of the ICP-AES instrument over the course of these analyses. Specifically, several samples of the low-activity reference material (LRM) (Ebert and Wolfe 1999) were included as part of the SRNL-PSAL analytical plan. The anions (Cl and F) were analyzed by ion chromatography (IC) also. The preparation and measurement methods used for each of the reported glass elements are listed in Table 2.7.

A detailed data analysis of the chemical composition measurements is published elsewhere (Fox et al. 2017, 2018). A short summary of these data analyses is included in Section 3.1.

Table 2.7. Preparation and Measurement Methods Used in Reporting the Measured Concentrations of Each of the Elements of the Study Glasses

Element	Preparation Method	Measurement Method
Al	PF	ICP-AES
B	PF	ICP-AES
Ca	LM	ICP-AES
Cl	KH	IC
Cr	LM	ICP-AES
F	KH	IC
Fe	PF	ICP-AES
K	LM	ICP-AES
Li	PF	ICP-AES
Mg	LM	ICP-AES
Na	LM	ICP-AES
P	LM	ICP-AES
Si	PF	ICP-AES
Sn	PF	ICP-AES
S	LM	ICP-AES
V	LM	ICP-AES
Zn	LM	ICP-AES
Zr	LM	ICP-AES

PF = peroxide fusion

LM = lithium metaborate/tetraborate fusion

KH = potassium hydroxide digestion

ICP-AES = inductively coupled plasma-atomic emission spectrometry

IC = ion chromatography

## 2.4 Glass Density

The room temperature density of each glass was measured according to PNNL procedure, *Density Using a Gas Pycnometer* (EWG-OP-0045),<sup>2</sup> using a MicroMeritics AccuPyc II 1340 gas pycnometer (MicroMeritics, Norcross, GA) with approximately 0.1 mg of glass pieces. The glass was loaded into a vial and placed within the instrument. The instrument then determined the density by the difference in amount of helium gas needed to fill the vial with and without the glass present. After five runs for each glass, the average glass density for that glass was calculated. The pycnometer was calibrated before and after measurements for that day using a National Institute of Standards and Technology (NIST) traceable standard tungsten carbide ball. These results are discussed in Section 3.2.

## 2.5 Viscosity

The viscosities ( $\eta$ ) of the quenched glasses were measured as a function of temperature, with a fully automated Anton Parr FRS 1600 Furnace Rheometer System, according to the PNNL procedure, *High-Temperature Viscosity Measurement Using Anton Paar FRS1600* (EWG-OP-0046, Rev. 0.0).<sup>3</sup>

Approximately 200 g of each glass was first crushed in a tungsten carbide mill for 0.05 min and about 25–30 mL, or ~70 g, of glass was placed into a Pt-alloy cylindrical cup. It was then heated to ~1150°C and maintained until thermal equilibrium was reached. A Pt-alloy spindle was then lowered into the cup of molten glass. An initial torque reading (at a constant spindle speed) was taken at ~1150°C. Subsequent measurements were taken at both higher and lower temperatures, ranging from 950°C to 1250°C, using a hysteresis approach. The hysteresis approach allows for the potential impacts of crystallization (at lower temperatures) to be assessed (via reproducibility). Duplicate measurements were taken at approximately the melting temperature ( $T_M$ ) and volatilization (at higher temperatures) was minimized by measuring viscosity at temperatures above  $T_M$  as the final viscosity measurement(s). The temperature sequence used was 1150°C, 1050°C, 950°C, 1150°C, 1250°C, and then 1150°C a third time. The soak time was 30 min at each temperature. Prior to quenched glass viscosity measurements, the test instrumentation was calibrated using a standard glass (Defense Waste Processing Facility (DWPF) Startup Frit) as discussed in the literature (Crum et al. 2012). These results are discussed in Section 3.3.

## 2.6 Electrical Conductivity

The electrical conductivities (ECs) of the quenched glasses were measured with an Anton Parr FRS 1600 Furnace Rheometer System as the high-temperature furnace and a Solartron Analytical 1455 Cell Test System (Solartron Analytical, Oak Ridge, TN) impedance analyzer according to PNNL procedure, *High-Temperature Electrical Conductivity Measurement* (EWG-OP-0047, Rev. 0.0).<sup>4</sup> Platinum plates (1.3 in. long by 0.28 in. wide) were placed parallel to each other with a separation of 0.367 in. A 30-mL glass sample was used for EC measurement in a Pt-alloy crucible. Before measuring ECs of the test matrix glasses, calibration was conducted at room temperature with reference solutions of KCl (0.1 M and 1 M) by measuring the resistance values over a range of frequencies (between 0.1 Hz and 1 MHz). Four readings were taken at each frequency over a period of two to five minutes. The calibration was then checked with DWPF standard glass at the higher temperatures (Crum et al. 2012). The averaged values of the four readings were then used to calculate the cell constant. For glass measurement, the sample was first heated to melting temperature and the probe was slowly lowered into the molten glass to a depth of

(2) Russell RL. 2017. *Density Using a Gas Pycnometer*. EWG-OP-0045, Rev. 0.0.

(3) McCarthy, BM. 2017. *High-Temperature Viscosity Measurement Using Anton Paar FRS1600*. EWG-OP-0046, Rev. 0.0.

(4) McCarthy, BM. 2017. *High-Temperature Electrical Conductivity Measurement*. EWG-OP-0047, Rev. 0.0.

12.7-mm. After the temperature was stabilized, a scan from 1 MHz to 0.1 Hz in 3 min was conducted and resistance at 1 kHz was used to calculate the EC. Two scans were made for each temperature after the glass was held for 10 min at each temperature before measurement for temperature stabilization. The EC was measured at four different temperatures in a range around the melting temperature of the glass. These results are discussed in Section 3.4.

## 2.7 Equilibrium Crystal Fraction

Equilibrium crystal fraction at a fixed temperature was measured in Pt-alloy crucibles and boats with tight fitting lids (to minimize volatility) according to the ASTM International standard procedure, *Standard Test Method for Determining Liquidus Temperature of Immobilized Waste Glasses and Simulated Waste Glasses* (ASTM C1720). The heat treatment times and temperatures were  $24 \pm 2$  h at  $950^{\circ}\text{C}$  to ensure equilibrium was achieved without excessive volatility. The samples were then quenched and analyzed by x-ray diffraction (XRD).

The crystal fraction formed during heat treatment was analyzed by XRD according to Section 12.4.4 of the ASTM International standard procedure, *Standard Test Method for Determining Liquidus Temperature of Immobilized Waste Glasses and Simulated Waste Glasses* (ASTM C1720). Powdered glass samples were prepared using 5 wt% CeO<sub>2</sub> as an internal standard phase with between 1.5 g and 2.5 g of glass powder. Glass and CeO<sub>2</sub> were milled together for 2 min in a 10 cm<sup>3</sup> tungsten carbide disc mill. The powdered samples were loaded into XRD sample holders and scanned at a  $0.04^{\circ} 2\theta$  step size, 4 sec dwell time, from  $10^{\circ}$  to  $70^{\circ} 2\theta$  scan range. XRD spectra were analyzed with TOPAS® 4.2 Software (Bruker AXS Inc., Madison, Wisconsin) for phase identification and Rietveld refinement to semi-quantify the amounts of crystal phases in some samples with high crystalline content. These results are discussed in Section 3.5.

## 2.8 Canister Centerline Cooling (CCC) and Crystal Identification

A portion (~30 g) of each test glass was subjected to the simulated CCC temperature profile shown in Table 2.8 and Figure 2.16. This profile is the temperature schedule of CCC heat-treatment for Hanford LAW glasses planned for use at WTP<sup>5</sup> and modified by PNNL. Pieces of quenched glass, <1cm in diameter, were placed in a Pt-alloy crucible and covered with a Pt-alloy lid. The glass samples were brought to a target temperature of the glass melt temperature and held for 30 min. Then they were quickly cooled to  $1114^{\circ}\text{C}$ . The cooling profile was then started from  $1114^{\circ}\text{C}$  to room temperature based on nine cooling segments (see Table 2.3). The starting temperature for the seven segments of cooling are melting temperature,  $1114^{\circ}\text{C}$ ,  $1000^{\circ}\text{C}$ ,  $900^{\circ}\text{C}$ ,  $825^{\circ}\text{C}$ ,  $775^{\circ}\text{C}$ ,  $725^{\circ}\text{C}$ ,  $600^{\circ}\text{C}$ , and room temperature.

Several of the glasses formed a crystalline layer around the edge of the Pt-alloy crucible during the CCC heat-treatment. Therefore, a quartz crucible was tried in order to eliminate the crystals. However, when a quartz crucible was used, it was found that the glass still formed a layer of crystals around the crucible walls. Therefore, this phenomenon did not appear to be due to the Pt.

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(5) Memorandum, Canister Centerline Cooling Data, Revision 1, CCN: 074851, RPP-WTP, October 29, 2003.

Table 2.8. Temperature Schedule During Canister Centerline Cooling (CCC) Treatment of Hanford LAW Glasses

Segment	Time (min)	Start Temp. (°C)	Rate (°C/min)
1	-30	Melt temp.	0
2	0	1114	-7.125
3	0-16	1000	-1.754
4	16-73	900	-0.615
5	73-195	825	-0.312
6	195-355	775	-0.175
7	355-640	725	-0.130
8	640-1600	600	-0.095
9	1600-3710	Room temp.	NA

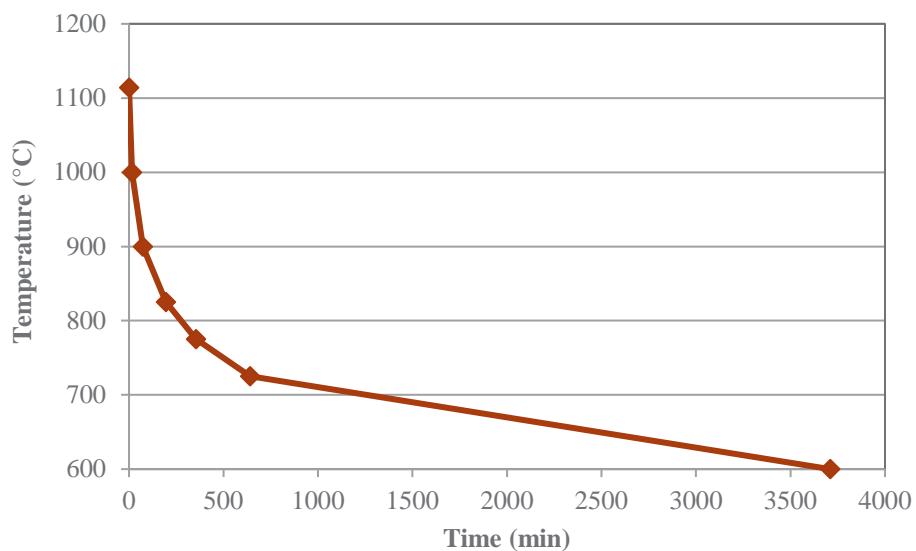


Figure 2.16. Plot of Temperature Schedule During CCC Heat-Treatment of Hanford LAW Glasses

The amount and type of crystalline phases that formed during CCC heat-treatment were analyzed by XRD according to Section 12.4.4 of the ASTM International standard procedure, *Standard Test Method for Determining Liquidus Temperature of Immobilized Waste Glasses and Simulated Waste Glasses* (ASTM C1720). Powdered glass samples were prepared using 5 wt% CeO<sub>2</sub> as an internal standard phase with between 1.5 g and 2.5 g of powdered glass. Glass and CeO<sub>2</sub> were milled together for 2 min in a 10 cm<sup>3</sup> tungsten carbide disc mill. The powdered glass samples were loaded into XRD sample holders and scanned at a 0.04° 2θ step size, 4 sec dwell time, from 10° to 70° 2θ scan range. XRD spectra were analyzed with TOPAS® 4.2 Software (Bruker AXS Inc., Madison, Wisconsin) for phase identification and Rietveld refinement to semi-quantify the amounts of crystal phases in some samples with high crystalline content. These results are discussed in Section 3.6.

## 2.9 Product Consistency Test (PCT)

PCT responses were measured in triplicate at SRNL for quenched and CCC samples of each glass using Method A of the ASTM International standard procedure, *Standard Test Methods for Determining Chemical Durability of Nuclear, Hazardous, and Mixed Waste Glasses and Multiphase Glass Ceramics: The Product Consistency Test (PCT)* (ASTM C1285). Also included in the PCT experimental test matrix and tested in triplicate were the Approved Reference Material (ARM) glass (Mellinger and Daniel 1984) and blanks. Glass samples were ground, sieved to -100 +200 mesh, washed, and prepared according to the ASTM C1285 procedure. The prepared glass was added to deionized water in a 1 g to 10 mL ratio, resulting in a surface area-to-solution volume (S/V) ratio of approximately 2000 m<sup>-1</sup>. The vessels used were desensitized Type 304L stainless steel. The vessels were closed, sealed, and placed into an oven at 90 ± 2°C for 7 days ± 3 h.

After the seven days at 90°C, the vessels were removed from the oven and allowed to cool to room temperature. The final mass of the vessel and the solution pH were recorded on a data sheet. Each test solution was then filtered through a 0.45-μm-size filter and acidified with concentrated, high-purity HNO<sub>3</sub> to 1 vol% to assure that the cations present remained in solution. The resulting solutions were analyzed by SRNL for Si, Na, B, and Li. Samples of a multi-element, standard solution were also analyzed as a check on the accuracy of the ICP-AES. Normalized releases (g/L) were calculated based on both target and measured compositions using the average of the logarithms of the leachate concentrations. Results from the PCT work are published elsewhere (Fox et al. 2017, 2018), and a short summary of these results is included in Section 3.7.

## 2.10 Vapor Hydration Test (VHT)

In the VHT, monolithic glass samples were exposed to water vapor at 200°C in sealed stainless-steel vessels according to the ASTM International standard procedure, *Standard Test Method for Measuring Waste Glass or Glass Ceramic Durability by Vapor Hydration Test* (ASTM C1663). Roughly 1-mm by 10-mm by 10-mm samples were cut from annealed or CCC-treated LAW glass bars using a diamond-impregnated saw. All sides of the cut sample were polished to 600-grit surface finishes with silicon carbide paper.

Polished samples were hung from stainless-steel supports on Pt wire within a stainless-steel container (see Figure 2.17). Deionized water (DIW) was added to the bottom of the vessel so that enough water was present to react with the specimen without enough water to reflux during testing (~0.20 g). The samples were heated and held at 200°C in a convection oven for either 7, 11, or 24 days. All samples were initially tested for 24 days. Samples found to fully react in 24 days were then tested for shorter times to enable estimating a numerical alteration rate (as opposed to > values).

After removal from the oven, vessels were weighed and then quenched in cold water. The specimens were removed from the vessels and cross-sectioned with or without epoxy (depending on the stability of each sample) for analysis by optical microscopy-image analysis (OM-IA) to determine the amount of glass altered during the test.

The remaining glass thickness of the VHT specimen was determined by performing at least 10 measurements distributed (roughly equally) across the crack-free cross section of the sample. Then, the average and standard deviation of the 10 thickness measurements of the remaining glass were calculated. The amount of glass altered per unit surface area of specimen was determined from the average thickness of unaltered glass according to Equation (2.1):

$$m = \frac{1}{2} \rho (d_i - d_r) = \frac{m_i}{2w_i l_i} \left( 1 - \frac{d_r}{d_i} \right) \quad (2.1)$$

where  $w_i, d_i, l_i$  = initial width, thickness, and length of the specimen, respectively (m)  
 $d_r$  = average thickness of remaining glass layer (m)  
 $m_i$  = initial specimen mass (g)  
 $m$  = mass of glass converted to alteration products per unit surface area ( $\text{g}/\text{m}^2$ )  
 $\rho$  = glass density ( $\text{g}/\text{m}^2$ ).

The average rate of corrosion was calculated as  $r_a = m/t$ , where  $t$  is the corrosion time. Vienna et al. (2001) showed that, if the average rate of corrosion at 200°C is

$$r_a = m / t < 50 \text{ g}/(\text{m}^2 \cdot \text{d}) \quad (2.2)$$

then the final rate of corrosion,  $r_\infty < 50 \text{ g}/(\text{m}^2 \cdot \text{d})$ , meets the current ORP requirement for LAW glass performance. Although the contract limit for VHT response is stated in rates ( $50 \text{ g}/\text{m}^2/\text{d}$ ), the test directly measures alteration depth (D) in  $\mu\text{m}$  at different times. In previous studies (Piepel et al. 2007 and Muller et al. 2014), the directly measured parameter of D in  $\mu\text{m}$  after 24 days was modeled. This value can be converted to a rate by:  $D (\mu\text{m}) * 10^{-6} (\text{m}/\mu\text{m}) * \text{density} (\text{g}/\text{cm}^3) * 10^6 (\text{cm}^3/\text{m}^3)/t(\text{d})$ . Assuming a density of  $2.65 \text{ g}/\text{cm}^3$ , the limit of  $50 \text{ g}/\text{m}^2/\text{d}$  is equivalent to a D of  $453 \mu\text{m}$  for a 24-d test duration.

These results are discussed in Section 3.8.

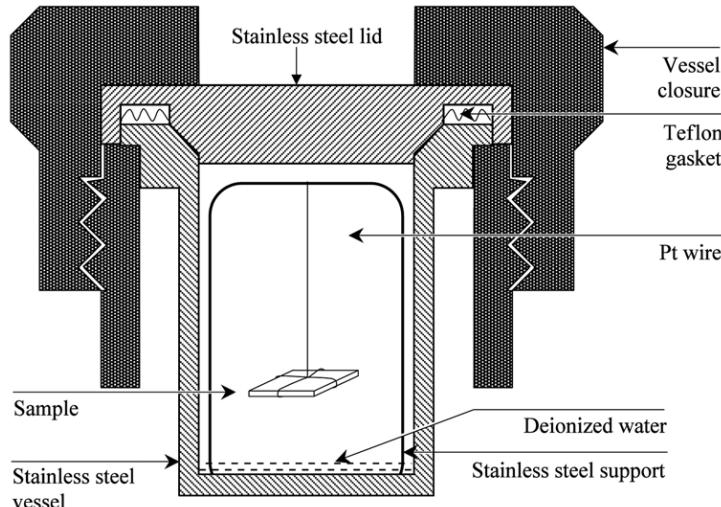


Figure 2.17. Apparatus for Conducting VHTs

## 2.11 Sulfur Solubility

Sulfur solubility was measured on the quenched glass samples. The procedure was developed by PNNL using *Test Instruction for Sulfate Solubility for LAW Phase 1 Matrix Glasses* (EWG-TI-026).<sup>6</sup>

(6) Jin, T. 2016. *Test Instruction for Sulfate Solubility for LAW Phase 1 Matrix Glasses*. EWG-TI-026.

There are three primary phases of testing with each glass:

1. Saturation with sodium sulfate
2. DIW wash
3. Analysis

Saturation with sodium sulfate was performed by taking 50 or 100 g of each LAW matrix glass for melting with sodium sulfate. The baseline glass was ground and sieved through a #120 sieve (125 µm). Then, 7.64 g of Na<sub>2</sub>SO<sub>4</sub> per 100 g of glass was added to the sieved powdered glass to maintain 4 mol% SO<sub>3</sub> in the glass/salt system, and the combination was mixed for homogeneity. The mixture of baseline glass and Na<sub>2</sub>SO<sub>4</sub> was melted at 1150°C for 1 h in a Pt-alloy crucible with a tight-fitting lid. After melting, the mixture was poured onto a steel plate and quenched. The mixture was again mixed by crushing and sieving through a #120 sieve (125 µm) and placed back into the Pt-alloy crucible to melt at 1150°C for 1 h the second time. After the second melting, the mixture was quenched by pouring on a steel plate, mixed by crushing and sieving, and melted under the same conditions for the third time. The glass, after three times re-melting and re-mixing, was crushed and sieved through the #120 sieve (125 µm) sieve.

Each of the melted samples that were ground and sieved three times were then washed with DIW to remove excess salt prior to further analysis. This was done by adding 4 g of glass/salt mixture to a beaker and then adding 50 g of DIW to the beaker. The beaker was placed in an ultrasonic bath for 3 min to wash the glass powder. After washing, the water and glass from the beaker were vacuum filtered through a 0.2 µm polyvinylidene difluoride (PVDF) membrane disc filter installed on a 47-mm magnetic filter funnel. An additional 50 g DIW was used to rinse all of the glass powder from the beaker and the glass powder sample in the filter funnel. A total of 100 g DIW was used for washing one sample. The washed and filtered glass was then dried at 90°C.

The washed and filtered glasses and the wash solutions recovered from filtering were then analyzed by ICP-AES and IC at SRNL. A total of 18 elements were analyzed. The following 16 elements were analyzed by ICP-AES: Al, B, Ca, Cr, Fe, K, Li, Mg, Na, P, Si, S, Sn, V, Zn, and Zr. The elements Cl and F were analyzed by IC. The results are discussed in Section 3.9.

## 3.0 Results and Discussion

This section describes the test results for the chemical composition, density, viscosity, EC, crystal fraction, secondary phase identification, PCT, VHT, and sulfate solubility for the LAW glasses studied.

As a part of the discussion of the property data for the Phase 2 enhanced LAW glasses, a previously developed property-composition model for each property is used to predict the property values. Often these models are the most recent ones developed prior to collecting the Phase 2 enhanced LAW glass data. In this report, attention is limited to plotting the model-predicted versus measured property values and assessing how well the previous model predicts the measured values for Phase 2 enhanced LAW glasses.

### 3.1 Chemical Analysis of Glass Composition

The targeted and average measured component concentrations (wt%) in the quenched glasses are presented in Appendix B along with the percent differences. The composition analyses of the glass samples were performed as described in Section 2.3. The purpose of these comparisons was to identify whether (i) any Phase 2 enhanced LAW glass(es) was(were) mis-batched, (ii) there was non-negligible volatility in any component(s) during glass melting, or (iii) whether there were any component(s) that was(were) not completely incorporated into the glass melts. The analyzed compositions are not intended for use in modeling glass properties, except for the measured semi-volatile component SO<sub>3</sub>. Compositions for property modeling will be the measured SO<sub>3</sub> concentrations and target compositions renormalized to sum to one minus the measured SO<sub>3</sub>. This approach was selected due to the relatively high uncertainty in analyzed component concentrations (5 to 20 relative percent) compared to the relatively low uncertainty in chemical additive concentrations (typically 98 to 99% pure) and weighing methods.

The results presented in this section are summarized from the reports by Fox et al. (2017, 2018). The analytical sequences of the measurements were reviewed, the average chemical composition for each glass was determined, and comparisons were made between the measurements and the targeted compositions of the glasses. JMP™ Pro Version 11.2.1 (SAS Institute, Inc.) was used to support these data analyses. Ideally, Fox et al. (2017, 2018) would have used statistical methods for objective comparisons rather than relying on subjective assessment of tables and graphs of data and data summary values. That way differences that were statistically significant could have been detected. However, the data analyses they performed were minimally sufficient for the project needs.

Plots of the wt% glass component concentrations measured for each sample by oxide and analytical block were provided in Fox et al. (2017, 2018). The plots were in analytical sequence within each calibration block, with different symbols and colors being used to represent each of the study and standard glasses. These plots include all the measurement data. Plotting the data in this format provides an opportunity to identify gross trends in performance of the analytical instruments within and among calibration blocks. A review of these plots did not identify any gross patterns or trends in the analytical process over the course of these measurements. Only minor, block-to-block calibration shifts were seen. For example, minor calibration effects were visible between the two sub-blocks within each analytical block for the Na<sub>2</sub>O measurements. Minor calibration effects were also visible between the two sub-blocks of Block 1 for the SnO<sub>2</sub> measurements. In all cases, the instrument check standards were within specification. These small calibration effects are typical of ICP-AES analyses and are “averaged out” by taking the mean of the measurements for each element.

Plots showing the individual measurements across the duplicates of each preparation method and the two instrument calibrations for each glass were also prepared in Fox et al. (2017, 2018). Plotting the data in this format provides an opportunity to review the values for each individual glass as a function of the duplicate preparations and duplicate measurements. A review of the plots reveals the repeatability of the four individual values for each oxide for each glass. Some degree of scatter among the Al<sub>2</sub>O<sub>3</sub>, B<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, SiO<sub>2</sub>, SnO<sub>2</sub>, and ZrO<sub>2</sub> measurements was noted for the study glasses. There were no indications of an error in preparation or measurement that had to be addressed in treatment of the data. Therefore, the entire set of measurement data were used in determining representative, measured compositions for the study glasses.

A comparison of the LRM results to their acceptability limits was performed by SRNL. The review was in the form of plots of the measurements arranged by preparation method and element, framed by upper and lower acceptability limits for the concentration of the element in question. The results show that all the measurements for the elements present in the LRM standard glass were within the acceptability limits utilized by SRNL in conducting instrument and procedure assessments during the execution of these analyses.

The four measurements (duplicates of two glass preparations) for each oxide in each glass were averaged to determine a representative chemical composition for each glass. A sum of oxide wt% values was also computed for each glass based upon the averaged, measured values. The following observations were noted based on these results:

- The measured concentrations of Cl and F were on average ~20% low (compared to targeted values) for most of the study glasses. This is most likely due to volatility during melting.
- The measured concentrations of P<sub>2</sub>O<sub>5</sub> were below the targeted values for those glasses that targeted higher concentrations of this component (>1 wt %). ZrO<sub>2</sub> concentrations were below the targeted values for several of the study glasses. As described in Fox et al. (2018), this appears to be related to the dissolution method used in analysis.
- The measured concentration of Cr<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> were on average ~20% above the targeted values for the outer-layer glasses, most likely due to how close the concentrations were to the detection limit.
- There were some deviations in the measured SiO<sub>2</sub> concentrations of the outer-layer glasses, both above and below the targeted values of the outer-layer glasses.
- All the sums of measured oxides for the study glasses fell within the interval of 97.8 to 101.7 wt % for the inner-layer glasses and 94.7 to 101.9 wt% for the outer-layer glasses, indicating excellent recovery of the glass components.

Based on the observations above, along with the overall analysis results shown in Appendix B, it was determined that analyzed glass compositions are subject to biased analyses and volatility. Hence, analyzed glass compositions are useful only for assessing if (i) glasses were correctly batched according to their targeted compositions, and (ii) if any components were subject to non-negligible volatility during melting. It was concluded by SRNL that the glasses had been batched correctly and there were no components subject to non-negligible volatility. However, as anticipated, the targeted concentrations of SO<sub>3</sub> were not always incorporated into the Phase 2 enhanced LAW glasses.

Hence, it was decided that the targeted values of components (except for SO<sub>3</sub> for which measured values were used) were best used in the subsequent calculations. Specifically, the Phase 2 enhanced LAW glass compositions were obtained by normalizing the targeted compositions with the measured SO<sub>3</sub> value used instead of the targeted value. Also, target values of B and Na were used to calculate normalized PCT releases of those components.

### 3.2 Density

This section presents and discusses the results of the glass density measurements for the Phase 2 enhanced LAW glasses obtained using the methods discussed in Section 2.4. The prediction of glass density uses a distinctly different process than the other properties. Specifically, specific or molar volumes of the constituent oxides are additive for ideal mixtures. Ionic radii from constituent cations and anions are then used to estimate the partial-specific volumes of glass oxides and halogens. Two constants used to account for non-ideality were fitted to experimental data on waste glasses in the same manner as described in Vienna et al. (2002).

The results of the glass density measurements are shown in Table 3.1. The mode of these 41 density values is 2.64 g/cm<sup>3</sup>, with a minimum of 2.59 g/cm<sup>3</sup> and a maximum of 2.75 g/cm<sup>3</sup>. The density of LAW glasses varies little—60% of the glasses have density values between 2.64 g/cm<sup>3</sup> and 2.70 g/cm<sup>3</sup>.

Figure 3.1 compares these measured density results to predicted density results obtained from the density model

$$\rho = \frac{\sum_{i=1}^N M_i x_i}{V} \quad (3.1)$$

where  $M_i$  is the molecular mass of the  $i$ -th component,  $x_i$  is the mole fraction of the  $i$ -th component, and  $V$  is molar volume (Vienna et al. 2003b). In an ideal mixture, the molar volume of the mixture is given by the sum of partial molar volumes of the mixture constituents. Clearly, glass is not an ideal mixture. However, a model based on volume is more likely to be linear than one based on density. This model tends to overpredict the density for all but two glasses, indicating that the density model is not very accurate in this composition region. This is most likely due to the glass not being an ideal mixture and the molar volume being assumed to be constant irrespective of bonding environment.

However, all density values are well below the contractual limit of 3.7 g/cm<sup>3</sup>. Thus, the available density data for LAW glasses indicate that it is not necessary to develop a property-composition model to comply with the contractual requirement for density of LAW glasses.

Table 3.1. Measured Densities of Phase 2 Enhanced LAW Glasses

Glass ID	Measured Density (g/cm <sup>3</sup> )	Glass ID	Measured Density (g/cm <sup>3</sup> )
LP2-IL-01	2.6864	LP2-OL-05	2.6771
LP2-IL-02	2.6881	LP2-OL-07-1	2.6154
LP2-IL-03	2.6808	LP2-OL-08-MOD	2.6867
LP2-IL-04	2.6986	LP2-OL-09-1	2.5882
LP2-IL-05	2.7014	LP2-OL-10-MOD	2.6326
LP2-IL-06	2.6306	LP2-OL-11	2.6503
LP2-IL-07	2.6329	LP2-OL-12	2.6280
LP2-IL-08	2.7031	LP2-OL-13	2.6591
LP2-IL-09	2.6861	LP2-OL-14	2.5884
LP2-IL-10	2.6625	LP2-OL-15	2.7081
LP2-IL-11	2.7011	LP2-OL-16-MOD	2.5838

LP2-IL-12	2.6508	LP2-OL-17	2.6448
LP2-IL-13	2.6443	LP2-OL-18	2.7360
LP2-IL-14	2.6506	LP2-OL-19	2.6082
LP2-IL-15	2.6422	LP2-OL-20	2.6351
LP2-IL-16	2.6665	LP2-OL-21	2.6409
LP2-IL-17	2.6250	LP2-OL-22	2.7456
LP2-OL-01-3	2.6435	LP2-OL-23	2.7296
LP2-OL-02-1	2.6121	LP2-OL-24	2.6658
LP2-OL-03-MOD2	2.6597	LP2-OL-25	2.7053
LP2-OL-04-1	2.6779		

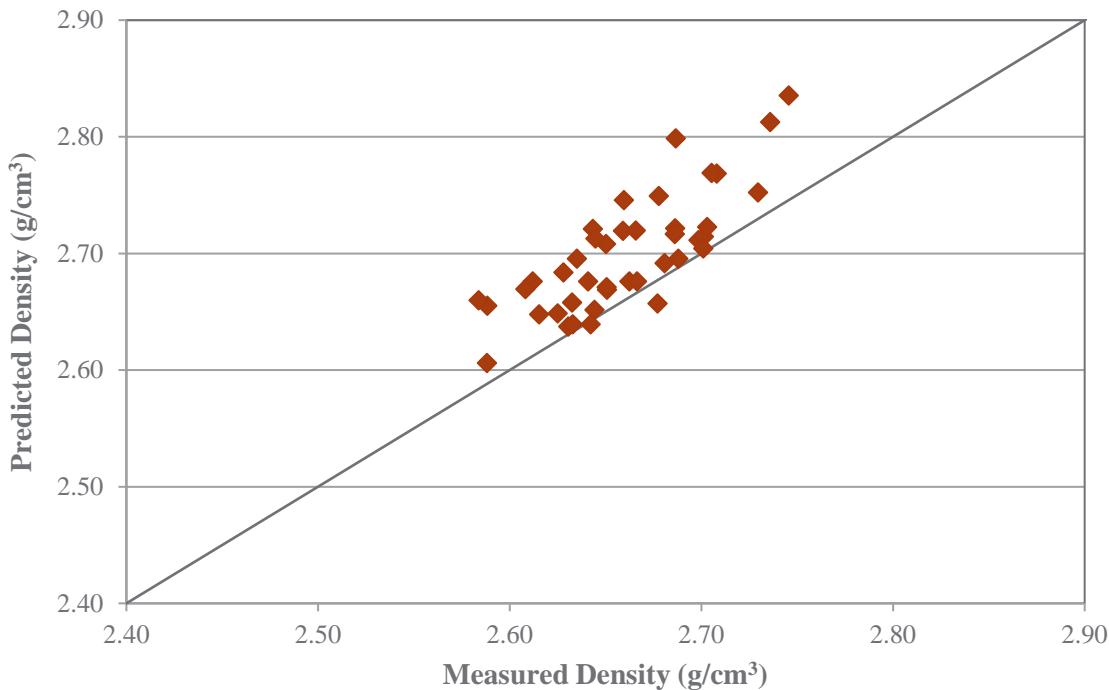


Figure 3.1. Predicted versus Measured Density for Phase 2 Enhanced LAW Glasses. The predicted values were obtained using the model in Equation (3.1).

### 3.3 Viscosity ( $\eta$ )

This section presents and discusses the viscosity results for the Phase 2 enhanced LAW glasses obtained using the methods discussed in Section 2.5. The results of the viscosity measurements are listed in Appendix C and summarized in Table 3.2.

Two model forms are widely used to fit viscosity-temperature data for each waste glass. The first model form is the Arrhenius equation

$$\ln(\eta) = A + \frac{B}{T_K} \quad (3.2)$$

where  $A$  and  $B$  are independent of temperature ( $T_K$ ), which is in K ( $T(^{\circ}\text{C}) + 273.15$ ), and potentially composition dependent. The values for the  $A$  and  $B$  coefficients are shown in Table 3.3 for each glass. The second model is the Vogel-Fulcher-Tamman (VFT) model

$$\ln(\eta) = E + \frac{F}{T_k - T_0} , \quad (3.3)$$

where  $E$ ,  $F$ , and  $T_0$  are temperature independent and potentially composition dependent coefficients and  $T_K$  is the temperature in K. This model can be used to estimate the effect of temperature on viscosity over a wide range of temperatures for silicate-based glasses. Therefore, this model was also applied to the data for each glass; the  $E$ ,  $F$ , and  $T_0$  coefficients for each glass are also shown in Table 3.3. Furthermore, Table 3.3 summarizes the viscosity results at  $1150^{\circ}\text{C}$  ( $\eta_{1150}$ ) calculated using the VFT equation (Equation (3.3)) for the Phase 2 enhanced LAW glasses.

Figure 3.2 displays a plot of the  $\ln$  (predicted viscosity) values against the  $\ln$  (measured viscosity) values based on the latest LAW model from Piepel et al. (2016) given by

$$\begin{aligned} \ln(\eta_{1150}) = & 15.0259(g_{Al_2O_3}) - 5.8836(g_{B_2O_3}) - 5.3224(g_{CaO}) - 0.0395(g_{Fe_2O_3}) \\ & - 0.9015(g_{K_2O}) - 31.5781(g_{Li_2O}) - 3.2548(g_{MgO}) - 7.3212(g_{Na_2O}) \\ & + 11.3813(g_{SiO_2}) + 3.7336(g_{SO_3}) + 5.1123(g_{SnO_2}) - 4.8736(g_{V_2O_5}) \\ & - 2.0498(g_{ZnO}) + 11.5939(g_{ZrO_2}) + 0.4703(g_{Others1}) \end{aligned} \quad (3.4)$$

Although this model produced very good predictions as seen in Figure 3.2, it slightly overpredicts the measured  $\ln(\eta_{1150})$  values for the Phase 2 enhanced LAW glasses. Therefore, it would be useful to re-fit the model to account for the Phase 2 data as well as the entire LAW glass composition region.

**Table 3.2. Measured Viscosity (P) Values Versus Target Temperature (in the sequence of measurement) for the Phase 2 Enhanced LAW Glasses Tested**

Target $T$ , $^{\circ}\text{C}$	1150	1050	950	1150	1250	1150
Glass ID	Viscosity (P)					
LP2-IL-01	25.078	70.056	258.950	25.300	10.900	25.189
LP2-IL-02	62.771	197.680	840.620	62.883	24.668	62.517
LP2-IL-03	56.953	174.980	721.650	57.084	22.522	55.956
LP2-IL-04	24.808	68.137	249.000	25.100	11.100	25.263
LP2-IL-05	24.355	70.386	278.41	24.600	10.600	24.704
LP2-IL-06	46.437	132.000	494.400	47.110	20.212	47.424
LP2-IL-07	25.601	65.778	217.620	25.974	12.200	26.192
LP2-IL-08	35.711	107.000	434.12	36.093	14.997	36.204
LP2-IL-09	24.098	66.425	243.000	24.222	10.795	24.300
LP2-IL-10	46.916	134.580	508.790	47.276	20.114	47.246
LP2-IL-11	58.537	182.920	764.970	59.055	23.859	60.265
LP2-IL-12	62.078	182.830	697.660	62.585	25.958	62.543
LP2-IL-13	56.397	160.500	608.710	55.994	23.912	56.011
LP2-IL-14	27.252	72.645	249.220	27.555	12.555	27.906

Target $T$ , °C	1150	1050	950	1150	1250	1150
Glass ID	Viscosity (P)					
LP2-IL-15	55.414	160.090	613.200	55.377	23.700	55.780
LP2-IL-16	43.301	123.130	461.020	43.809	18.619	43.665
LP2-IL-17	51.172	139.000	500.000	50.442	22.340	51.314
LP2-OL-01-3	85.343	287.000	1390.000	85.906	32.400	86.130
LP2-OL-02-1	54.029	137.750	532.560	52.799	22.929	53.837
LP2-OL-03 MOD2	25.618	73.108	275.070	25.866	11.100	26.043
LP2-OL-04-1	38.693	119.000	490.670	38.804	15.787	39.790
LP2-OL-05	67.671	212.000	1658.687	68.443	27.717	69.974
LP2-OL-07-1	29.977	77.385	268.350	29.646	13.761	30.927
LP2-OL-08 MOD	12.800	33.548	125.190	12.900	5.902	12.806
LP2-OL-09-1	63.768	170.300	630.374	63.776	28.548	64.592
LP2-OL-10 MOD	63.721	197.000	1450.000	65.037	26.566	67.690
LP2-OL-11	11.300	27.304	83.927	11.400	5.592	11.609
LP2-OL-12	7.970	17.577	48.700	8.029	4.240	8.119
LP2-OL-13	13.167	31.861	90.966	13.266	6.420	13.467
LP2-OL-14	9.563	21.329	59.802	9.643	5.042	9.800
LP2-OL-15	12.726	33.842	122.000	12.856	6.003	12.900
LP2-OL-16 MOD	72.672	199.230	742.860	73.708	31.831	73.868
LP2-OL-17	24.736	66.816	229.210	25.350	11.283	25.582
LP2-OL-18	26.037	94.031	408.640	25.782	10.600	26.407
LP2-OL-19	94.658	286.220	1140.300	96.150	38.812	97.627
LP2-OL-20	46.287	122.000	419.930	45.714	20.366	45.952
LP2-OL-21	41.915	116.000	423.520	42.674	18.500	43.189
LP2-OL-22	32.000	106.000	515.778	32.362	12.700	32.200
LP2-OL-23	12.000	31.800	116.000	12.196	5.635	12.200
LP2-OL-24	37.241	103.720	372.040	37.409	16.000	37.457
LP2-OL-25	14.843	39.062	138.000	15.000	6.879	15.050

Table 3.3. Fitted Coefficients of Arrhenius and VFT Models for Viscosity (Poise) as Functions of Temperature, and Predicted Viscosity at 1150°C Using the VFT Model for the Phase 2 Enhanced LAW Glasses

Glass ID	Arrhenius Coefficients		VFT Coefficients			$\eta_{1150}$ (P)
	A (ln P)	B (ln P · K)	E (ln P)	F (ln P · K)	To (K)	
LP2-IL-01	-10.634	19748	-5.560	8378	469.4	25.14
LP2-IL-02	-11.311	22015	-5.854	9698	452.7	62.78
LP2-IL-03	-11.137	21620	-5.962	9856	437.4	56.59
LP2-IL-04	-10.391	19398	-4.997	7520	507.8	25.00
LP2-IL-05	-11.119	20413	-4.906	7032	555.7	24.53
LP2-IL-06	-10.140	19935	-4.851	8152	485.7	46.75
LP2-IL-07	-9.360	17978	-4.396	7011	506.2	25.79
LP2-IL-08	-11.159	21012	-5.236	8010	514.8	35.98

Glass ID	Arrhenius Coefficients		VFT Coefficients			$\eta_{1150}$ (P)
	A (ln P)	B (ln P·K)	E (ln P)	F (ln P·K)	T <sub>0</sub> (K)	
LP2-IL-09	-10.458	19449	-4.856	7212	526.3	24.18
LP2-IL-10	-10.292	20156	-5.122	8566	468.7	47.13
LP2-IL-11	-11.105	21644	-5.391	8912	482.4	59.28
LP2-IL-12	-10.276	20531	-5.542	9691	421.5	62.44
LP2-IL-13	-10.144	20195	-4.939	8538	470.9	56.10
LP2-IL-14	-9.766	18643	-4.891	7760	477.6	27.56
LP2-IL-15	-10.236	20314	-4.795	8229	489.3	55.55
LP2-IL-16	-10.267	20007	-5.256	8717	457.7	43.53
LP2-IL-17	-9.664	19370	-4.803	8422	458.6	50.87
LP2-OL-01-3	-12.005	23456	-5.036	8347	543.0	85.42
LP2-OL-02-1	-9.669	19430	-1.404	3596	755.1	53.41
LP2-OL-03 MOD2	-10.801	20025	-5.562	8330	478.0	25.82
LP2-OL-04-1	-11.376	21434	-5.833	9029	472.5	39.05
LP2-OL-05	-13.579	25414	-0.963	2694	901.1	66.51
LP2-OL-07-1	-9.566	18481	-4.482	7258	502.4	30.01
LP2-OL-08 MOD	-10.807	19043	-4.377	5585	616.4	12.75
LP2-OL-09-1	-9.362	19266	-3.636	6859	542.6	63.66
LP2-OL-10 MOD	-13.213	24816	-1.070	2791	888.4	63.33
LP2-OL-11	-9.409	16878	-4.717	6533	508.8	11.35
LP2-OL-12	-8.594	15216	-4.239	5680	524.0	7.99
LP2-OL-13	-9.008	16514	-7.316	12135	197.1	13.22
LP2-OL-14	-8.545	15408	-3.956	5472	543.2	9.60
LP2-OL-15	-10.658	18837	-4.395	5667	607.1	12.80
LP2-OL-16 MOD	-9.458	19593	-4.186	7896	491.5	72.96
LP2-OL-17	-9.942	18762	-5.476	8599	435.0	25.17
LP2-OL-18	-12.919	23100	-6.192	8449	531.8	26.74
LP2-OL-19	-10.210	21048	-5.053	9368	448.4	95.40
LP2-OL-20	-9.396	18837	-4.381	7737	480.7	46.00
LP2-OL-21	-9.929	19488	-4.313	7248	523.7	42.32
LP2-OL-22	-12.777	23171	-4.972	6829	614.5	32.18
LP2-OL-23	-10.752	18887	-4.469	5682	607.0	12.10
LP2-OL-24	-10.136	19596	-5.530	9111	427.4	37.33
LP2-OL-25	-10.418	18704	-4.836	6621	544.9	14.92

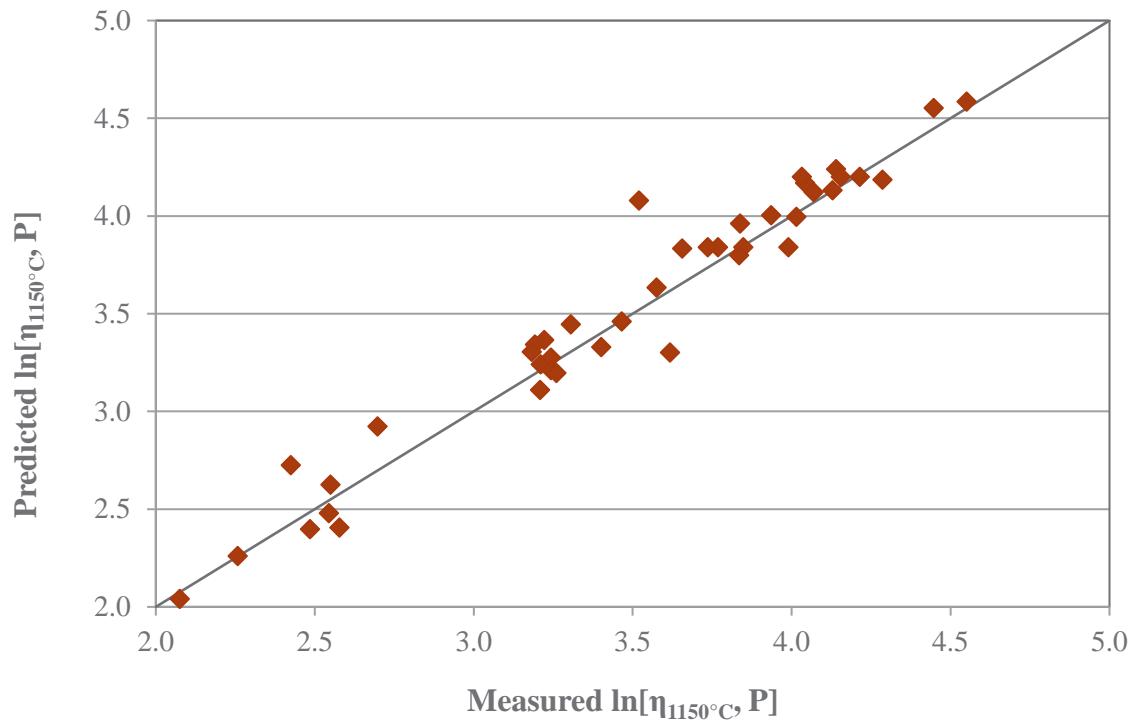


Figure 3.2. Predicted Versus Measured Viscosity at 1150°C Values for Phase 2 Enhanced LAW Glasses. The predicted values were obtained using the model in Equation (3.4).

### 3.4 Electrical Conductivity (EC)

This section presents and discusses the EC results for the Phase 2 enhanced LAW glasses obtained using the methods discussed in Section 2.6. Table 3.4 lists the EC versus temperature data for each of the glasses and Appendix D shows the plots for the EC versus temperature data obtained from the EC experiments.

The Arrhenius equation is widely used to fit EC-temperature data for waste glass. It is

$$\ln(\eta) = A + \frac{B}{T_K} , \quad (3.5)$$

where  $A$  and  $B$  are independent of temperature ( $T_K$ ), which is in K ( $T(^{\circ}\text{C}) + 273.15$ ), and potentially composition dependent. The values for the  $A$  and  $B$  coefficients are shown in Table 3.5 for each glass.

Figure 3.3 shows the  $\ln(\text{EC})$  plot for predicted versus measured EC, where the predicted values were produced by the modified Arrhenius equation parameters expanded as linear mixture models plus three alkali and alkaline earth cross-product terms (Piepel et al. 2007), given by

$$\ln(EC) = \sum_{i=1}^q a_i x_i + a_{CaOLi2O} x_{CaO} x_{Li2O} + a_{CaONa2O} x_{CaO} x_{Na2O} + a_{Li2ONa2O} x_{Li2O} x_{Na2O} + \sum_{i=1}^q b_i \frac{x_i}{\frac{T}{1000}} \quad (3.6)$$

where  $x_i$  is the mass fraction of the  $i^{\text{th}}$  oxide component and  $T$  is the measured temperature in K. The model coefficients are shown in Table 3.6. The measured value at 1 kHz is plotted in Figure 3.3 because this is the frequency used in the model and is closest to the real impedance. This model overpredicted the EC in all but one instance. This could be because of the different glass composition region that the Phase 2 enhanced LAW glass study explored compared to the composition region with lower waste loadings explored for the models in Piepel et al. (2007). Therefore, a new model exploring a wider composition region with higher waste loadings would be useful to account for the Phase 2 data.

Table 3.4. Measured Electrical Conductivity (S/cm) Values versus Temperatures for the Phase 2 Enhanced LAW Glasses

Target $T$ , °C	950	950	1250	1250	1150	1150	1050	1050
Glass ID	Electrical Conductivity (S/cm)							
LP2-IL-01	0.285	0.287	0.715	0.714	0.566	0.567	0.419	0.421
LP2-IL-02	0.290	0.292	0.726	0.725	0.576	0.577	0.425	0.427
LP2-IL-03	0.305	0.307	0.733	--	0.587	0.589	0.439	0.442
LP2-IL-04	0.289	0.291	0.733	0.730	0.580	0.582	0.427	0.428
LP2-IL-05	0.233	0.235	0.646	0.644	0.500	0.502	0.357	0.359
LP2-IL-06	0.272	0.274	0.671	0.667	0.535	0.536	0.398	0.399
LP2-IL-07	0.266	0.268	0.671	--	0.531	0.533	0.393	0.394
LP2-IL-08	0.230	0.231	0.632	0.629	0.488	0.490	0.350	0.352
LP2-IL-09	0.319	0.321	0.775	0.776	0.625	0.627	0.464	0.467
LP2-IL-10	0.258	0.260	0.659	--	0.521	0.522	0.382	0.383
LP2-IL-11	0.261	0.263	0.669	0.667	0.530	0.532	0.390	0.391
LP2-IL-12	0.312	0.314	0.723	0.721	0.583	0.584	0.443	0.445
LP2-IL-13	0.231	0.233	0.594	0.592	0.467	0.467	0.343	0.344
LP2-IL-14	0.332	0.334	0.767	0.766	0.622	0.623	0.472	0.474
LP2-IL-15	0.311	0.313	0.756	0.755	0.608	0.609	0.454	0.455
LP2-IL-16	0.277	0.279	0.708	--	0.559	0.561	0.411	0.413
LP2-IL-17	0.263	0.266	0.630	0.630	0.511	0.513	0.385	0.387
LP2-OL-01-3	0.148	0.150	0.440	0.440	0.334	0.335	0.235	0.236
LP2-OL-02-1	0.235	0.236	0.580	0.578	0.462	0.464	0.344	0.345
LP2-OL-03 MOD2	0.314	0.316	0.751	--	0.609	0.610	0.456	0.458
LP2-OL-04-1	0.192	0.194	0.543	--	0.424	0.425	0.302	0.303
LP2-OL-05	0.163	0.164	0.463	0.461	0.358	0.359	0.254	0.256
LP2-OL-07-1	0.175	0.176	0.487	--	0.378	0.378	0.271	0.272
LP2-OL-08 MOD	0.369	0.371	0.807	--	0.660	0.661	0.512	0.513
LP2-OL-09-1	0.194	0.195	0.496	0.495	0.395	0.396	0.289	0.290
LP2-OL-10 MOD	0.173	0.174	0.475	--	0.370	0.371	0.266	0.267
LP2-OL-11	0.234	0.236	0.616	--	0.486	0.488	0.356	0.357
LP2-OL-12	0.322	0.323	0.749	--	0.604	0.607	0.459	0.461
LP2-OL-13	0.291	0.294	0.670	0.695	0.569	0.570	0.429	0.430
LP2-OL-14	0.255	0.256	0.643	0.641	0.513	--	0.380	0.382

Target $T$ , °C	950	950	1250	1250	1150	1150	1050	1050
Glass ID	Electrical Conductivity (S/cm)							
LP2-OL-15	0.164	0.165	0.531	0.529	0.398	0.399	0.270	0.272
LP2-OL-16 MOD	0.219	0.221	0.525	--	0.421	0.421	0.317	0.318
LP2-OL-17	0.295	0.297	0.702	--	0.565	--	0.426	0.427
LP2-OL-18	0.199	0.200	0.564	--	0.434	0.436	0.307	0.308
LP2-OL-19	0.218	0.219	0.572	0.572	0.451	0.453	0.328	0.329
LP2-OL-20	0.291	0.292	0.662	0.660	0.542	0.543	0.415	0.416
LP2-OL-21	0.251	0.252	0.625	--	0.499	0.500	0.370	0.372
LP2-OL-22	0.176	0.177	0.538	--	0.407	0.408	0.282	0.283
LP2-OL-23	0.184	0.185	0.560	0.558	0.425	0.426	0.295	0.296
LP2-OL-24	0.280	0.281	0.645	0.644	0.526	0.527	0.401	0.402
LP2-OL-25	0.294	0.296	0.688	0.686	0.558	0.559	0.422	0.423

-- = not measured

Table 3.5. Fitted Coefficients of the Arrhenius Equation for Electrical Conductivity as a Function of Temperature, and Predicted Electrical Conductivity at 1150°C Using the Arrhenius Equation for the Phase 2 Enhanced LAW Glasses

Glass ID	Arrhenius Coefficients	
	A (ln P)	B (ln P·K)
LP2-IL-01	8.0308	-5694.1
LP2-IL-02	8.0499	-5698.5
LP2-IL-03	7.9364	-5500.4
LP2-IL-04	8.1048	-5768.3
LP2-IL-05	8.3388	-6314.2
LP2-IL-06	7.8972	-5587.4
LP2-IL-07	8.0433	-5795.2
LP2-IL-08	8.2859	-6269.9
LP2-IL-09	8.0048	-5523.3
LP2-IL-10	8.0872	-5888.4
LP2-IL-11	8.0575	-5830.7
LP2-IL-12	7.7200	-5207.4
LP2-IL-13	7.9411	-5841.8
LP2-IL-14	7.7712	-5191.9
LP2-IL-15	7.9688	-5509.5
LP2-IL-16	8.1560	-5883.6
LP2-IL-17	7.7243	-5409.7
LP2-OL-01-3	8.2301	-6739.5
LP2-OL-02-1	7.7624	-5611.7
LP2-OL-03 MOD2	7.9641	-5503.2
LP2-OL-04-1	8.3389	-6553.4
LP2-OL-05	8.1106	-6477.6
LP2-OL-07-1	8.1412	-6431.9
LP2-OL-08 MOD	7.6300	-4904.2

Glass ID	Arrhenius Coefficients	
	A (ln P)	B (ln P·K)
LP2-OL-09-1	7.7621	-5842.8
LP2-OL-10 MOD	8.0608	-6348.5
LP2-OL-11	8.1500	-6085.1
LP2-OL-12	7.8230	-5305.1
LP2-OL-13	7.8152	-5400.4
LP2-OL-14	7.9294	-5710.6
LP2-OL-15	8.7855	-7292.3
LP2-OL-16 MOD	7.5684	-5459.4
LP2-OL-17	7.8404	-5431.4
LP2-OL-18	8.3738	-6565.6
LP2-OL-19	8.0097	-6003.6
LP2-OL-20	7.5560	-5094.4
LP2-OL-21	7.9400	-5749.0
LP2-OL-22	8.6223	-7013.2
LP2-OL-23	8.5824	-6905.8
LP2-OL-24	7.5888	-5182.2
LP2-OL-25	7.7052	-5264.5

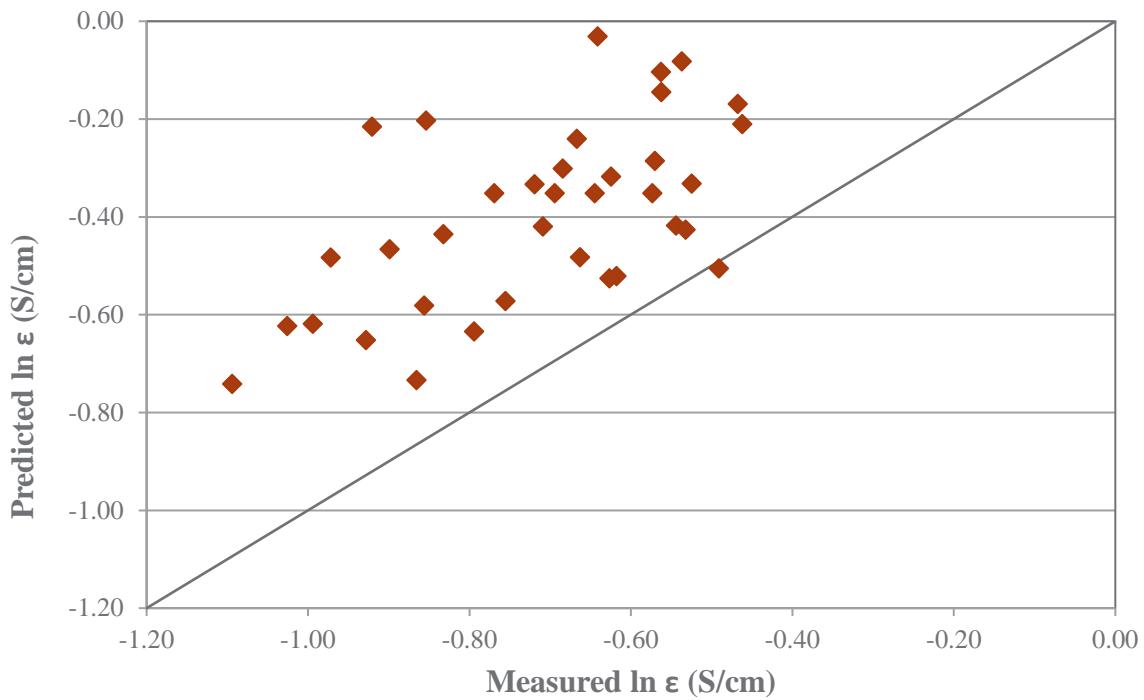


Figure 3.3. Predicted versus Measured Electrical Conductivity at 1150°C Values for Phase 2 Enhanced LAW Glasses. The predicted values were obtained using the model in Equation (3.6) with coefficients in Table 3.6.

The measured value at 1 kHz is plotted in Figure 3.3 because this is the frequency used in the model and is closest to the real impedance. This model overpredicted the EC in all but one instance. This could be because of the different glass composition region that the Phase 2 enhanced LAW glass study explored compared to the composition region with lower waste loadings explored for the models in Piepel et al. (2007). Therefore, a new model exploring a wider composition region with higher waste loadings would be useful to account for the Phase 2 data.

Table 3.6. List of Electrical Conductivity Model Components and Coefficients (Piepel et al. 2007)

Component	Coefficient	Component	Coefficient
Al <sub>2</sub> O <sub>3</sub>	2.3854	Al <sub>2</sub> O <sub>3</sub> /(T/1000)	-9.0593
B <sub>2</sub> O <sub>3</sub>	7.9750	B <sub>2</sub> O <sub>3</sub> /(T/1000)	-11.0983
CaO	5.2093	CaO/(T/1000)	-30.6535
Fe <sub>2</sub> O <sub>3</sub>	4.3935	Fe <sub>2</sub> O <sub>3</sub> /(T/1000)	-9.2407
K <sub>2</sub> O	7.6774	K <sub>2</sub> O/(T/1000)	-11.5299
MgO	15.1675	MgO/(T/1000)	-25.0634
Na <sub>2</sub> O	-2.0291	Na <sub>2</sub> O/(T/1000)	12.3822
SiO <sub>2</sub>	3.6811	SiO <sub>2</sub> /(T/1000)	-10.1563
ZrO <sub>2</sub>	7.8740	ZrO <sub>2</sub> /(T/1000)	-16.5390
Others <sup>(1)</sup>	11.2070	Others <sup>(1)</sup> /(T/1000)	-17.7117
Na <sub>2</sub> O x CaO	79.0190		

(1) Others includes SO<sub>3</sub>, Cl, P<sub>2</sub>O<sub>5</sub>, F, Cr<sub>2</sub>O<sub>3</sub>, SnO<sub>2</sub>, V<sub>2</sub>O<sub>5</sub>, and ZnO

### 3.5 Crystal Fraction of Heat-Treated Glasses

This section presents and discusses the crystal fraction results for the Phase 2 enhanced LAW glasses obtained using the methods discussed in Section 2.7. For each glass composition, specimens were prepared and heat treated at 950°C. Heat-treated specimens were spiked with 5 mass% CeO<sub>2</sub>, milled to powderize and adequately mix the glass, and analyzed using XRD. The CeO<sub>2</sub> spiked into the specimen was used as a standard for semi-quantitative analysis to determine the mass fraction of crystal phase(s) in a specimen. See Appendix E for photos of crystal fraction heat-treated glasses and Appendix F for XRD spectra obtained from them.

All but 14 glasses had insufficient crystals to perform XRD analysis when treated at 950°C for 24 h. Nine glasses contained Nasicon ( $\text{Na}_{1+x}\text{Zr}_2\text{Si}_x\text{P}_{3-x}\text{O}_{12}$ ,  $0 < x < 3$ ) and six glasses contained lazurite,  $(\text{Na},\text{Ca})_8[(\text{S},\text{Cl},\text{SO}_4,\text{OH})_2(\text{Al}_6\text{Si}_6\text{O}_{24})]$ , and/or combeite ( $\text{Na}_2\text{Ca}_2\text{Si}_3\text{O}_9$ ). The wt% total crystallinity ranged from 0 to 17.5 wt%. These results are summarized in Table 3.7.

Table 3.7. Weight Percent Crystallinity and Identification of Crystals by XRD in 24 h Heat-Treated Phase 2 Enhanced LAW Glasses

Glass ID	Heat-Treated Temp. (°C)	Wt% Crystallinity	Crystal Phase Identification
LP2-IL-01	950	0.67 0.29	Nasicon Baddeleyite
LP2-IL-02	950	1.20 0.29	Nasicon Baddeleyite
LP2-IL-03	950	1.96 0.59	Nasicon Baddeleyite
LP2-IL-04	950	0	Amorphous
LP2-IL-05	950	0	Amorphous
LP2-IL-06	950	0	Amorphous
LP2-IL-07	950	0	Amorphous
LP2-IL-08	950	0	Amorphous
LP2-IL-09	950	0	Amorphous
LP2-IL-10	950	0	Amorphous
LP2-IL-11	950	1.96	Nasicon
LP2-IL-12	950	0	Amorphous
LP2-IL-13	950	0	Amorphous
LP2-IL-14	950	0	Amorphous
LP2-IL-15	950	0	Amorphous
LP2-IL-16	950	0	Amorphous
LP2-IL-17	950	0	Amorphous
LP2-OL-01-3	950	~0	Not enough crystals
LP2-OL-02-1	950	0	Amorphous
LP2-OL-03 MOD2	950	2.02 5.29 4.25 0.11	Nasicon Combeite high Lazurite 4A Tin Fluoride
LP2-OL-04-1	950	5.31	Nasicon
LP2-OL-05	950	2.07	Lazurite 1C
LP2-OL-07-1	950	~0	Not enough crystals
LP2-OL-08 MOD	950	6.56 10.90	Nasicon Combeite high
LP2-OL-09-1	950	0	Amorphous with bubbles
LP2-OL-10 MOD	950	10.57	Lazurite 1C
LP2-OL-11	950	0	Amorphous
LP2-OL-12	950	0	Amorphous
LP2-OL-13	950	1.72 0.261	Nasicon Quartz low
LP2-OL-14	950	0	Amorphous
LP2-OL-15	950	0	Amorphous
LP2-OL-16 MOD	950	0	Amorphous
LP2-OL-17	950	~0	Not enough crystals

Glass ID	Heat-Treated Temp. (°C)	Wt% Crystallinity	Crystal Phase Identification
LP2-OL-18	950	0.336	Cassiterite
		0.287	Calcium Sodium Tin
		0.313	Halite
LP2-OL-19	950	~0	Not enough crystals
LP2-OL-20	950	0.544	Mullite (Al, Si, O)
		0.224	Lazurite
		0.131	Zircon
		0.292	Zirconium Aluminum
		1.18	Silicon
LP2-OL-21	950	0	Amorphous
LP2-OL-22	950	2.48	Nasicon
LP2-OL-23	950	0	Amorphous
LP2-OL-24	950	1.22	Hauyne
		0.033	Lazurite 1C
		2.22	Aluminum Phosphate
LP2-OL-25	950	~0	Not enough crystals

### 3.6 Crystal Identification in Canister Centerline Cooling (CCC) Glasses

This section presents and discusses the crystal fraction results from CCC heat treatments of Phase 2 enhanced LAW glasses obtained using the methods discussed in Section 2.8. XRD scans of CCC glass samples identified various crystal types. The crystal types and wt% crystallinity results are summarized in Table 3.8. A total of 28 samples were not analyzed by XRD because there were either no crystals or very few crystals (not enough for XRD to detect) observed by optical microscope. Four glasses had crystal content of less than 5 mass%, while eight glasses had crystal content greater than 10 mass% crystals. Only one glass (LP2-IL-06) had a crystal content between 5 and 10 mass%. The major crystalline phases appearing in the glasses containing crystals were nepheline, sodalite, and combeite, which are all feldspathoids. See Appendix G for photos of CCC-treated glasses and Appendix H for XRD spectra obtained from them.

During cooling, several of the glasses seemed to form a layer of crystals around the Pt crucible walls (see Figure 3.4). When a quartz crucible was used, the glass still formed a layer of crystals around the crucible walls (Figure 3.5). Therefore, this phenomenon did not appear to be due to the Pt.

Table 3.8. Weight Percent Crystallinity and Identification of Crystals by XRD in CCC-Treated Phase 2 Enhanced LAW Glasses

Glass ID	Starting CCC Temp (°C)	Wt% Crystallinity	Crystal Phase Identification
LP2-IL-01	1150	1.22	Lazurite 4A
		2.48	Combeite low
LP2-IL-02	1150	0	Amorphous
LP2-IL-03	1150	0	Amorphous
LP2-IL-04	1150	0	Amorphous
LP2-IL-05	1150	0	Amorphous

Glass ID	Starting CCC Temp (°C)	Wt% Crystallinity	Crystal Phase Identification
LP2-IL-06	1150	8.83 1.07	Lazurite 4A Sodalite
LP2-IL-07	1150	0	Amorphous
LP2-IL-08	1150	0	Amorphous
LP2-IL-09	1150	0	Amorphous
LP2-IL-10	1150	0	Amorphous
LP2-IL-11	1150	0	Amorphous
LP2-IL-12	1150	0	Amorphous
LP2-IL-13	1150	0	Amorphous
LP2-IL-14	1150	0	Amorphous
LP2-IL-15	1150	0	Amorphous
LP2-IL-16	1150	0	Amorphous
LP2-IL-17	1150	0.576	Lazurite 4A
LP2-OL-01-3	1150	0	Amorphous
LP2-OL-02-1	1150	0	Amorphous
LP2-OL-03 MOD2	1150	40.78 6.72 18.87 0.943	Combeite high Nepheline, sodian Sodium Aluminum Silicate Calcium Zinc
LP2-OL-04-1	1150	37.52 18.16 5.17 0.72 1.25 2.98 0.46 3.11	Combeite high Nepheline (Si-rich) Sodium Peroxide Zirconium Oxide 65-9834_AlMg Zeolite Zirconium Oxide Periclase
LP2-OL-05	1150	11.91 8.51 3.00	Hauyne <sup>(b)</sup> Nosean <sup>(a)</sup> Combeite high
LP2-OL-07-1	1150	4.06	Hauyne <sup>(b)</sup>
LP2-OL-08 MOD	1150	6.68 49.56 6.36 7.12	Nasicon Combeite high Sodium Aluminum Silicate nepheline Sodium Iron Aluminum Oxide
LP2-OL-09	1150	0	Amorphous
LP2-OL-10 MOD	1150	11.45 2.04 10.25 4.55	Nepheline, sodian Lazurite 4A Combeite high Nosean <sup>(a)</sup>
LP2-OL-11	1150	0	Amorphous
LP2-OL-12	1150	0	Amorphous
LP2-OL-13	1150	42.36 2.84	Combeite high Nepheline (Si-rich)
LP2-OL-14	1150	0	Amorphous
LP2-OL-15	1150	0	Amorphous
LP2-OL-16 MOD	1150	0	Amorphous
LP2-OL-17	1150	0	Amorphous

Glass ID	Starting CCC Temp (°C)	Wt% Crystallinity	Crystal Phase Identification
LP2-OL-18	1150	3.76	Lazurite 4A
LP2-OL-19	1150	0	Amorphous
LP2-OL-20	1150	16.46	Combeite high
LP2-OL-21	1150	0	Amorphous
LP2-OL-22	1150	0	Amorphous
LP2-OL-23	1150	0	Amorphous
LP2-OL-24	1150	66.22 0.41	SodiumAluminumSiliconOxide SodiumMagnesiumSulfate
LP2-OL-25	1150	0	Amorphous

(a) Nosean is very similar to nepheline except it also contains sulfate.

(b) Hauyne is also similar to nepheline but contains Ca and sulfate.

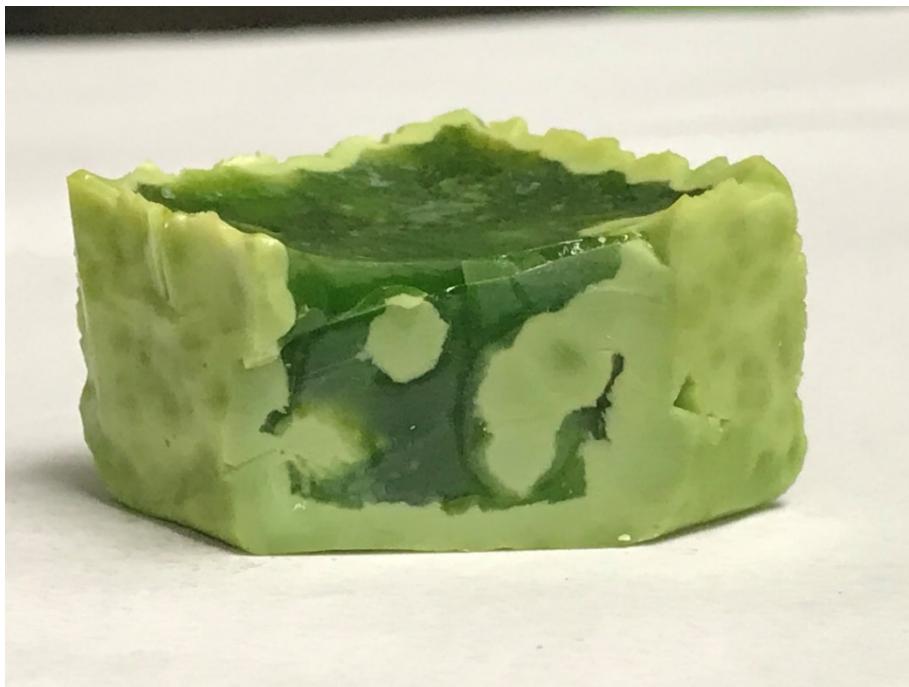


Figure 3.4. Glass LP2-OL-05 Cooled in a Pt Crucible with Crystals along Edge



Figure 3.5. Glass LP2-OL-05 Cooled in a Quartz Crucible with Crystals along Edge

### 3.7 Product Consistency Test (PCT)

This section presents and discusses the PCT results for the Phase 2 enhanced LAW glasses obtained using the methods discussed in Section 2.9. The PCT results are published elsewhere (Fox et al. 2017, 2018), but are summarized here in Table 3.9. The PCT results were normalized to the target values of the glasses. A review of the PCT data shows that none of the inner-layer glasses had normalized releases for boron (NR [B]) and sodium (NR [Na]) that were higher than the WTP contract limit of 4 g/L for either quenched or CCC-treated glasses. However, several of the outer-layer glasses did exceed this limit (which was intended in generating the outer-layer test matrix).

A review of the PCT data resulted in the following observations:

- The CCC heat treatment had little impact on the PCT results as compared to the quenched versions of the study glasses for the inner-layer glasses. For the outer-layer glasses, the CCC heat treatment increased PCT normalized releases for most glasses that formed crystals.
- Glass LP2-OL-18 showed a decrease in PCT normalized releases after CCC heat treatment.
- The quenched and CCC glass LP2-OL-12 had the highest  $NR_B$  and  $NR_{Na}$  values based on normalization to the targeted composition.

Table 3.9. PCT Normalized Releases (g/L) from Fox et al. (2017 and 2018)

Glass ID	Type	B (g/L)	Na (g/L)	Si (g/L)
LP2-IL-01	Quenched	1.375	0.927	0.235
	CCC	1.045	1.363	0.275
LP2-IL-02	Quenched	0.570	0.670	0.192
	CCC	0.562	0.683	0.204
LP2-IL-03	Quenched	0.384	0.556	0.169
	CCC	0.373	0.546	0.176
LP2-IL-04	Quenched	0.680	0.954	0.257
	CCC	0.743	1.068	0.287
LP2-IL-05	Quenched	0.502	0.569	0.141
	CCC	0.583	0.679	0.163
LP2-IL-06	Quenched	1.261	0.934	0.126
	CCC	1.124	0.865	0.129
LP2-IL-07	Quenched	1.474	1.281	0.312
	CCC	1.320	1.268	0.307
LP2-IL-08	Quenched	0.659	0.786	0.204
	CCC	0.594	0.737	0.205
LP2-IL-09	Quenched	1.734	1.347	0.222
	CCC	1.646	1.275	0.236
LP2-IL-10	Quenched	0.441	0.573	0.159
	CCC	0.473	0.601	0.180
LP2-IL-11	Quenched	0.291	0.480	0.143
	CCC	0.308	0.472	0.155
LP2-IL-12	Quenched	0.692	0.749	0.229
	CCC	0.541	0.681	0.213
LP2-IL-13	Quenched	1.011	0.816	0.165
	CCC	0.756	0.679	0.161
LP2-IL-14	Quenched	1.456	1.178	0.184
	CCC	1.357	1.116	0.198
LP2-IL-15	Quenched	0.890	0.681	0.172
	CCC	0.461	0.451	0.158
LP2-IL-16	Quenched	0.486	0.599	0.163
	CCC	0.453	0.572	0.167
LP2-IL-17	Quenched	0.889	0.706	0.152
	CCC	0.807	0.670	0.168
LP2-OL-01-3	Quenched	0.665	1.140	0.337
	CCC	0.625	0.955	0.292
LP2-OL-02-1	Quenched	0.937	1.045	0.334
	CCC	0.959	0.983	0.314

Glass ID	Type	B (g/L)	Na (g/L)	Si (g/L)
LP2-OL-03MOD2	Quenched	0.741	2.552	0.398
	CCC	1.642	14.511	1.693
LP2-OL-04-1	Quenched	1.531	2.115	0.444
	CCC	9.449	20.573	2.304
LP2-OL-05	Quenched	0.319	0.725	0.184
	CCC	0.862	0.990	0.190
LP2-OL-07-1	Quenched	0.874	1.001	0.271
	CCC	0.813	0.845	0.224
LP2-OL-08MOD	Quenched	2.535	4.522	0.872
	CCC	18.526	22.386	1.979
LP2-OL-09-1	Quenched	3.117	1.843	0.250
	CCC	2.309	1.453	0.246
LP2-OL-10MOD	Quenched	0.339	0.809	0.187
	CCC	9.581	5.007	0.408
LP2-OL-11	Quenched	7.737	7.210	1.214
	CCC	7.129	6.675	1.235
LP2-OL-12	Quenched	34.223	26.813	4.068
	CCC	35.740	28.587	4.489
LP2-OL-13	Quenched	1.031	3.885	0.640
	CCC	11.643	14.231	1.560
LP2-OL-14	Quenched	14.466	12.760	2.076
	CCC	9.921	9.293	1.788
LP2-OL-15	Quenched	0.552	0.875	0.243
	CCC	0.477	0.840	0.221
LP2-OL-16MOD	Quenched	2.608	2.612	0.904
	CCC	2.179	2.153	0.753
LP2-OL-17	Quenched	11.233	9.488	2.306
	CCC	12.632	10.825	2.582
LP2-OL-18	Quenched	2.366	2.371	0.581
	CCC	0.350	0.968	0.259
LP2-OL-19	Quenched	0.777	1.825	0.533
	CCC	0.739	1.743	0.483
LP2-OL-20	Quenched	0.540	2.182	0.331
	CCC	1.848	4.560	0.886
LP2-OL-21	Quenched	0.901	1.041	0.354
	CCC	0.985	1.003	0.328
LP2-OL-22	Quenched	0.395	1.078	0.222
	CCC	0.459	1.051	0.215
LP2-OL-23	Quenched	0.961	1.194	0.323

Glass ID	Type	B (g/L)	Na (g/L)	Si (g/L)
LP2-OL-24	CCC	0.753	1.077	0.266
	Quenched	0.914	1.746	0.448
LP2-OL-25	CCC	3.242	4.030	0.718
	Quenched	5.148	3.864	0.624
	CCC	5.697	4.138	0642

Figure 3.6 compares the PCT normalized releases of B with the normalized releases of Na for the quenched glass samples. Figure 3.6 shows that B values tend to be lower than Na values below approximately the natural log of 0.7 g/m<sup>2</sup>. Above approximately the natural log of 1 g/m<sup>2</sup>, the B values tend to be at or slightly above the Na values. Figure 3.7 compares the PCT normalized releases of B with the normalized releases of Na for the CCC glass samples. Figure 3.7 shows that the PCT normalized releases of B are typically lower than those of Na for CCC glass samples.

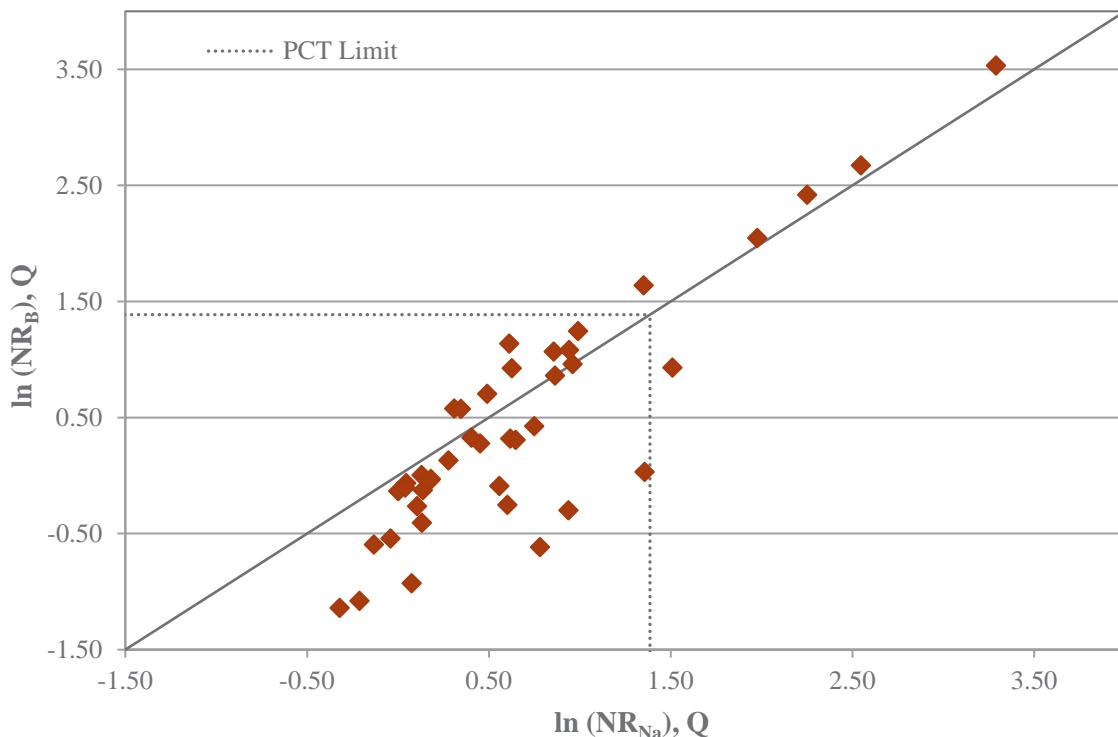


Figure 3.6. Comparison of Natural Logarithms of PCT Normalized Releases of B and Na (both g/L) for Quenched Samples of Phase 2 Enhanced LAW Glasses

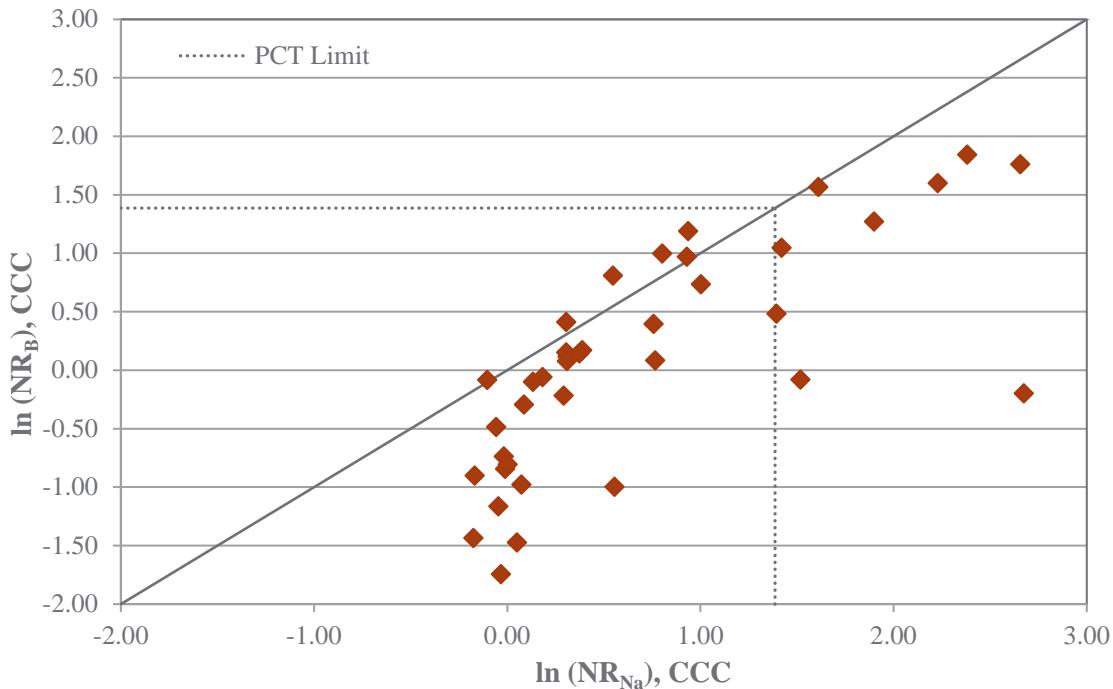


Figure 3.7. Comparison of Natural Logarithms of PCT Normalized Releases of B and Na (g/L) for CCC Samples of Phase 2 Enhanced LAW Glasses

Figure 3.8 shows the measured Na and B normalized releases compared to the predictions using previous models for Na and B normalized releases of LAW glasses from Piepel et al. (2007). These models were partial quadratic mixture (PQM) models (Piepel et al. 2002) of the form

$$\ln(NR) = \sum_{i=1}^q b_i x_i + \text{selected} \left\{ \sum_{i=1}^q b_{ii} x_i^2 + \sum_{j=1}^{q-1} \sum_{k=j+1}^q b_{jk} x_j x_k \right\} \quad (3.7)$$

where

$NR$	ormalized release of B or Na (g/L)
$q$	number of components in the waste glass
$x_i$	mass fraction of the $i$ th component
$b_i$	coefficient of the $i$ th component
$b_{ii}$	coefficient for the $i$ th component squared
$b_{jk}$	coefficient for the crossproduct of the $j$ th and $k$ th components

However, the models from that report were for a different LAW glass composition region that did not include enhanced waste glasses. The coefficients for the B model are listed in Table 3.10 and for the Na model are listed in Table 3.11. It appears that the B releases are generally overpredicted, and the Na releases are generally underpredicted using these models. These prediction differences in PCT releases for the Phase 2 LAW glasses are likely a result of the Piepel et al. (2007) models being developed from data over a composition region that did not include enhanced waste glasses. Also, it was noted in Piepel et al. (2007) that the recommend partial quadratic mixture models were not as accurate with higher waste loadings and higher Na and B releases. Since the current effort is to increase waste loading, new PCT models are needed to ensure that the LAW glasses meet the release limit of 2 g/m<sup>2</sup> (4 g/L).

Figure 3.9 compares the normalized releases (g/L) of the quenched and CCC glasses. When significant crystals containing Al and Si (>10 wt%) are present in the glass, CCC-treated samples can have notably higher releases than quenched samples. This may be because the crystals remove the glass formers (Si and Al) from the bulk glass structure and composition, making it less durable.

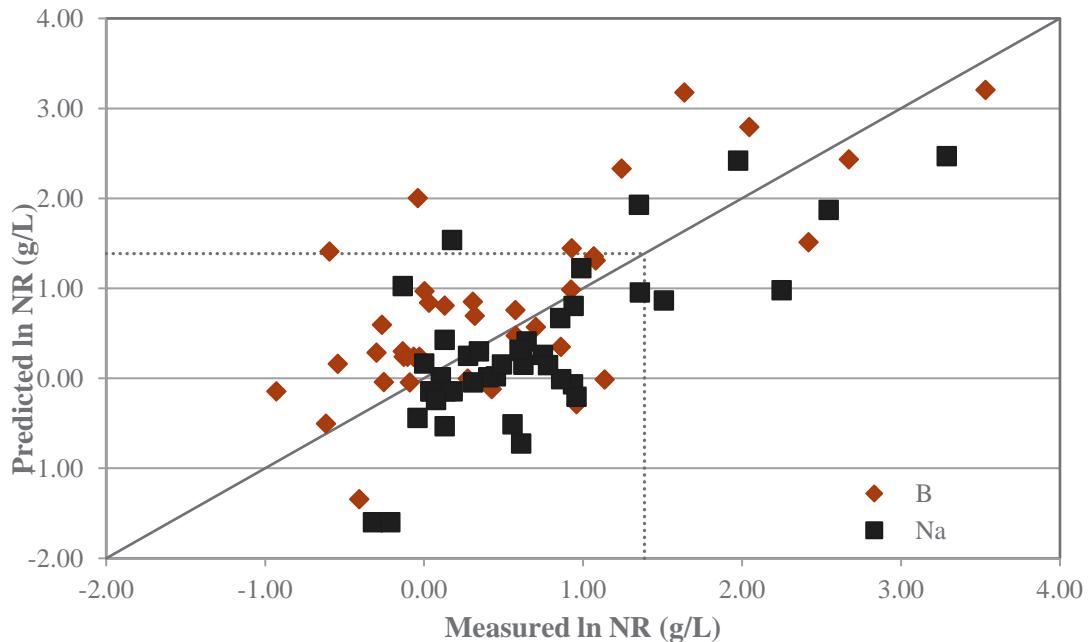


Figure 3.8. Predicted Versus Measured Natural Logarithms of Normalized Releases (g/L) of Boron and Sodium for Phase 2 Enhanced LAW Glasses. The predicted values were obtained using the model form in Equation (3.7) with coefficients listed in Tables 3.10 and 3.11.

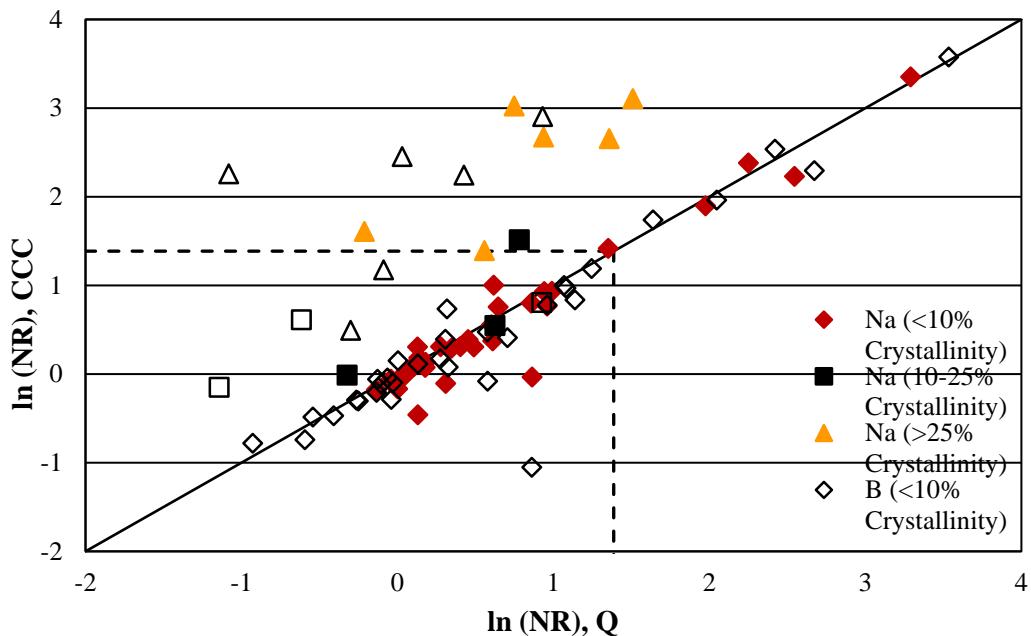


Figure 3.9. Comparison of Natural Logarithm of PCT Normalized Release (g/L) of B and Na for Quenched and CCC-Treated Samples of Phase 2 Enhanced LAW Glasses that Contain Aluminosilicates

Table 3.10. Coefficients for PCT Boron (g/L) Model (Piepel 2007)

Component	Coefficient	Component	Coefficient
Al <sub>2</sub> O <sub>3</sub>	-31.3612	P <sub>2</sub> O <sub>5</sub>	-19.254
B <sub>2</sub> O <sub>3</sub>	11.8101	SiO <sub>2</sub>	-1.6161
CaO	-13.8404	ZrO <sub>2</sub>	-6.6289
Fe <sub>2</sub> O <sub>3</sub>	-16.5948	Others <sup>(1)</sup>	-5.169
K <sub>2</sub> O	7.9687	B <sub>2</sub> O <sub>3</sub> x MgO	488.8612
MgO	-21.2343	Na <sub>2</sub> O x SiO <sub>2</sub>	-74.3462
Na <sub>2</sub> O	46.1599	CaO x Fe <sub>2</sub> O <sub>3</sub>	212.0947

(1) The data Piepel et al. (2007) used to fit this model contained many minor components in Others. However, in the Phase 2 LAW glasses for which the model was used to predict, Others included only SO<sub>3</sub>, Cl, F, Cr<sub>2</sub>O<sub>3</sub> and ZnO.

Table 3.5. Coefficients for PCT Sodium (g/L) Model (Piepel 2007)

Component	Coefficient	Component	Coefficient
Al <sub>2</sub> O <sub>3</sub>	-20.7142	P <sub>2</sub> O <sub>5</sub>	-14.5324
B <sub>2</sub> O <sub>3</sub>	-6.5489	SiO <sub>2</sub>	-4.8834
CaO	0.0151	ZrO <sub>2</sub>	-0.62
Fe <sub>2</sub> O <sub>3</sub>	-8.4617	Others <sup>(1)</sup>	3.345
K <sub>2</sub> O	-0.8724	B <sub>2</sub> O <sub>3</sub> x MgO	437.4267
MgO	-13.8667	Na <sub>2</sub> O x B <sub>2</sub> O <sub>3</sub>	87.6716

Na <sub>2</sub> O	9.9942	CaO x Fe <sub>2</sub> O <sub>3</sub>	182.6191
		K <sub>2</sub> O x K <sub>2</sub> O	315.6867

(1) The data Piepel et al. (2007) used to fit this model contained many minor components in Others. However, in the Phase 2 LAW glasses for which the model was used to predict, Others included only SO<sub>3</sub>, Cl, F, Cr<sub>2</sub>O<sub>3</sub> and ZnO.

### 3.8 Vapor Hydration Test (VHT)

This section presents and discusses the VHT results obtained using the methods discussed in Section 2.10. Table 3.12 shows the corrosion rate (g/m<sup>2</sup>/d) of each glass based on the VHT. See Appendix I for photos of the glass samples after the VHT. A total of 14 of the 41 quenched glasses failed the VHT, with a corrosion rate of >50 g/m<sup>2</sup>/d (Table 3.12). A total of 11 of the 41 CCC glasses failed the VHT, with a corrosion rate of >50 g/m<sup>2</sup>/d (Table 3.13). The glasses tested performed either extremely well or extremely poor, with only two quenched glasses and one CCC glass near the corrosion rate limit. Ideally there would have been a better distribution of VHT corrosion rates for the Phase 2 LAW glasses. Still, glasses with corrosion rates above and below the limit are necessary for developing property-composition models that can predict glasses that meet or fail the limit.

Table 3.6. VHT Results from the Quenched Phase 2 Enhanced LAW Glasses

Glass ID	Density (g/cm <sup>3</sup> )	Temp. (°C)	Days	Alteration Depth (μm)	Rate (g/m <sup>2</sup> /d)	Comparison to Limit of 50 g/m <sup>2</sup> /d
LP2-IL-01-Q	2.6864	200	7	263	52.1	104%
LP2-IL-02-Q	2.6881	200	7	172	34.1	68%
LP2-IL-03-Q	2.6808	200	24	14.2	0.78	1.6%
LP2-IL-04-Q	2.6986	200	7	895	176	351%
			24	42.3	8.39	17%
			24	18.0	1.01	2.0%
LP2-IL-05-Q	2.7014	200	7	2.0	0.40	0.8%
LP2-IL-06-Q	2.6306	200	24	93.4	5.15	10%
LP2-IL-07-Q	2.6329	200	7	702	132	264%
LP2-IL-08-Q	2.7031	200	7	598	118	235%
			24	1.2	0.23	0.5%
			24	222	12.4	25%
LP2-IL-09-Q	2.6861	200	7	187	36.7	73%
			24	573	30.5	61%
LP2-IL-10-Q	2.6625	200	7	563	108	215%
LP2-IL-11-Q	2.7011	200	7	29.6	5.76	12%
			24	492	27.2	54%
LP2-IL-12-Q	2.6508	200	7	191	36.1	72%

Glass ID	Density (g/cm <sup>3</sup> )	Temp. (°C)	Days	Alteration Depth (μm)	Rate (g/m <sup>2</sup> /d)	Comparison to Limit of 50 g/m <sup>2</sup> /d
			24	832	44.8	90%
LP2-IL-13-Q	2.6443	200	7	15.2	2.92	5.8%
			24	38.7	2.08	4.2%
LP2-IL-14-Q	2.6506	200	7	193	35.3	71%
			24	711	35.8	72%
LP2-IL-15-Q	2.6422	200	7	6.4	1.20	2.4%
			24	114	6.03	12%
LP2-IL-16-Q	2.6665	200	7	176	32.6	65%
			24	862	46.7	93%
LP2-IL-17-Q	2.6250	200	7	331	61.9	124%
LP2-OL-01-3-Q	2.6435	200	11	133	15.8	32%
			24	9.7	0.53	1.1%
LP2-OL-02-1-Q	2.6121	200	11	209	24.7	49%
			24	22.6	1.24	2.5%
LP2-OL-03-MOD2-Q	2.6597	200	24	420	22.5	45%
LP2-OL-04-1-Q	2.6779	200	11	0.0	0.0	0.0%
			24	48.4	2.68	5.4%
LP2-OL-05-Q	2.6771	200	11	234	27.7	55%
			24	94.5	5.15	10%
LP2-OL-07-1-Q	2.6154	200	11	136	15.8	32%
			24	286	15.4	31%
LP2-OL-08-MOD-Q	2.6867	200	7	578	113	226%
			24	>1360	>75.4	>151%
LP2-OL-09-1-Q	2.5882	200	11	251	28.3	57%
			24	185	9.67	19%
LP2-OL-10-MOD-Q	2.6326	200	24	157	8.50	17%
LP2-OL-11-Q	2.6503	200	11	966	115	231%
			24	1003	50.6	101%
LP2-OL-12-Q	2.6280	200	11	1333	151	302%
			24	>1550	>77.1	>154%
LP2-OL-13-Q	2.6591	200	11	>1350	>161	>322%
			24	920	49.4	99%
LP2-OL-14-Q	2.5884	200	7	>960	>190	>381%
			24	>1110	>59.8	>120%

Glass ID	Density (g/cm <sup>3</sup> )	Temp. (°C)	Days	Alteration Depth (μm)	Rate (g/m <sup>2</sup> /d)	Comparison to Limit of 50 g/m <sup>2</sup> /d
LP2-OL-15-Q	2.7081	200	24	22.6	1.30	2.6%
LP2-OL-16-MOD-Q	2.5838	200	24	69.3	3.71	7.4%
LP2-OL-17-Q	2.6448	200	7	>1460	>272	>544%
LP2-OL-18-Q	2.7360	200	24	172	9.36	19%
LP2-OL-19-Q	2.6082	200	7	640	121	242%
LP2-OL-20-Q	2.6351	200	24	>1540	>79.1	>158%
LP2-OL-21-Q	2.6409	200	24	445	22.9	46%
LP2-OL-22-Q	2.7456	200	24	25.1	1.44	2.9%
LP2-OL-23-Q	2.7296	200	24	38.8	2.18	4.4%
LP2-OL-24-Q	2.6658	200	24	252	13.8	28%
LP2-OL-25-Q	2.7053	200	24	502	27.3	55%

Table 3.7. VHT Results from the CCC Phase 2 Enhanced LAW Glasses

Glass ID	Density (g/cm <sup>3</sup> )	Temp. (°C)	Days	Alteration Depth (μm)	Rate (g/m <sup>2</sup> /d)	Comparison to Limit of 50 g/m <sup>2</sup> /d
LP2-IL-01-CCC	2.6864	200	7	222	41.3	83%
			24	821	44.9	90%
LP2-IL-02-CCC	2.6881	200	7	110	18.9	38%
			24	755	35.1	70%
LP2-IL-03-CCC	2.6808	200	7	5.7	1.09	2.2%
			24	366	19.8	40%
LP2-IL-04-CCC	2.6986	200	7	956	174	348%
			7	21.7	4.04	8.1%
LP2-IL-05-CCC	2.7014	200	24	233	13.0	26%
LP2-IL-06-CCC	2.6306	200	7	559	104	207%
LP2-IL-07-CCC	2.6329	200	7	408	76.2	152%
LP2-IL-08-CCC	2.7031	200	7	69.1	13.0	26%
			24	480	24.1	48%
LP2-IL-09-CCC	2.6861	200	7	48.0	8.87	18%
			24	285	16.3	32%
LP2-IL-10-CCC	2.6625	200	7	43.2	8.10	16%

Glass ID	Density (g/cm <sup>3</sup> )	Temp. (°C)	Days	Alteration Depth (μm)	Rate (g/m <sup>2</sup> /d)	Comparison to Limit of 50 g/m <sup>2</sup> /d
LP2-IL-11-CCC	2.7011	200	24	662	32.7	65%
			7	55.1	10.5	21%
LP2-IL-12-CCC	2.6508	200	24	320	17.6	35%
			7	7.8	1.37	2.8%
LP2-IL-13-CCC	2.6443	200	24	74.6	3.93	7.9%
LP2-IL-14-CCC	2.6506	200	7	345	61.1	122%
LP2-IL-15-CCC	2.6422	200	7	74.8	3.98	8.0%
			24	231	12.7	25%
LP2-IL-16-CCC	2.6665	200	24	175	9.18	18%
LP2-IL-17-CCC	2.6250	200	7	20.6	3.85	7.7%
			24	567	30.1	60%
LP2-OL-01-3-CCC	2.6435	200	11	181	21.6	43%
LP2-OL-02-1-CCC	2.6121	200	24	70.6	3.76	7.5%
LP2-OL-03-MOD2-CCC	2.6597	200	7	11.5	0.05	0.1%
LP2-OL-04-1-CCC	2.6779	200	24	530	24.9	50%
			11	588	68.0	136%
LP2-OL-05-CCC	2.6771	200	7	11.5	1.98	4.0%
			24	82.1	4.30	8.6%
LP2-OL-07-1-CCC	2.6154	200	24	36.3	1.97	3.9%
LP2-OL-08-MOD-CCC	2.6867	200	7	36.5	6.92	14%
			24	745	39.2	78%
LP2-OL-09-1-CCC	2.5882	200	24	92.9	4.94	9.9%
LP2-OL-10-MOD-CCC	2.6326	200	7	132	24.1	48%
			24	67.8	3.65	7.3%
LP2-OL-11-CCC	2.6503	200	24	52.9	2.92	5.8%
LP2-OL-12-CCC	2.6280	200	7	228	37.8	76%
			24	>1140	>61.9	>124%
LP2-OL-13-CCC	2.6591	200	7	1510	316	631%
			24	1225	64.6	129%
LP2-OL-14-CCC	2.5884	200	7	>1250	>201	>401%
LP2-OL-15-CCC	2.7081	200	24	38.7	2.19	4.4%
LP2-OL-16-MOD-CCC	2.5838	200	24	16.2	0.88	1.8%

Glass ID	Density (g/cm <sup>3</sup> )	Temp. (°C)	Days	Alteration Depth (μm)	Rate (g/m <sup>2</sup> /d)	Comparison to Limit of 50 g/m <sup>2</sup> /d
LP2-OL-17-CCC	2.6448	200	7	>1540	>262	>524%
			24	>1450	>74.8	>150%
LP2-OL-18- CCC	2.7360	200	7	113	21.3	43%
			24	106	5.76	12%
LP2-OL-19-CCC	2.6082	200	24	0.0	0.0	0.0%
LP2-OL-20-CCC	2.6351	200	7	1430	256	511%
			24	>1790	>96.2	>193%
LP2-OL-21-CCC	2.6409	200	24	395	20.3	41%
LP2-OL-22-CCC	2.7456	200	24	56.6	3.26	6.5%
LP2-OL-23-CCC	2.7296	200	24	253	13.3	27%
LP2-OL-24-CCC	2.6658	200	7	678	129	257%
			24	>1470	>78.7	>157%
LP2-OL-25-CCC	2.7053	200	24	481	23.8	48%

Figure 3.10 shows how much the total normalized alkali [Nalk = Na<sub>2</sub>O + 0.66(K<sub>2</sub>O) + 2(Li<sub>2</sub>O)] decreases the durability of the LAW glasses by plotting the VHT results against the total normalized alkali values. Basically, all the glasses up to 23 wt% alkali passed the VHT. Above 23 wt% alkali, the glasses began failing; at about 26 wt%, all but one of the current glasses failed the VHT.

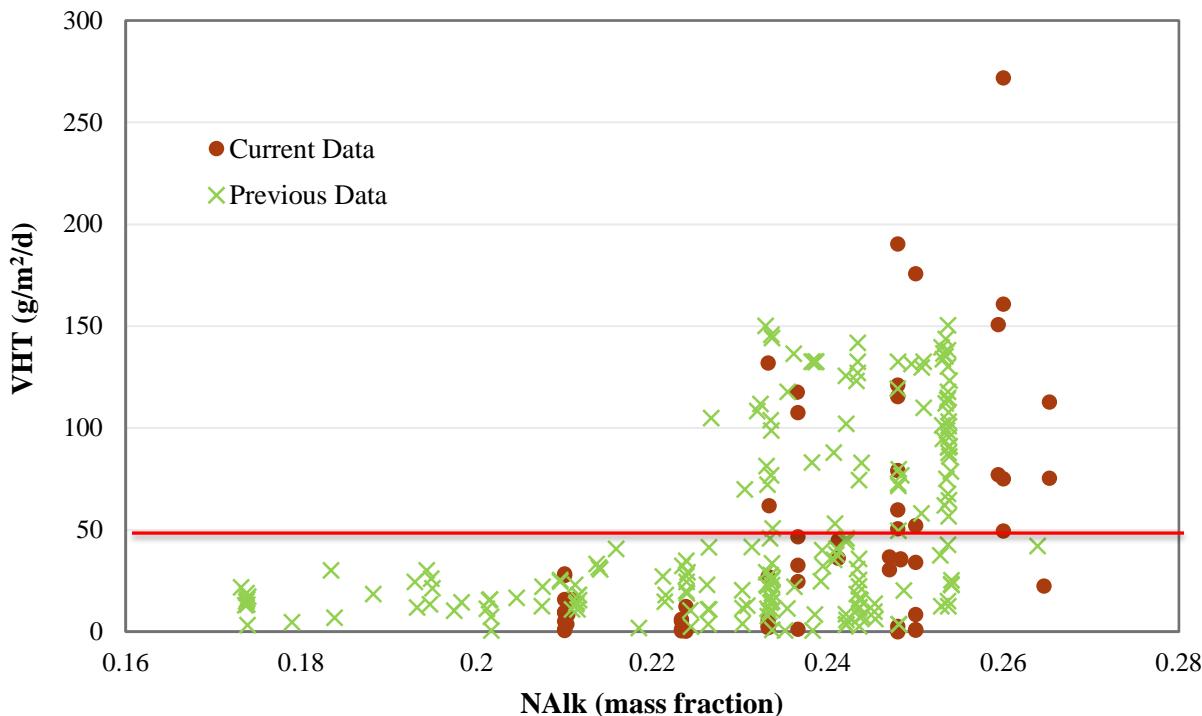


Figure 3.10. VHT Response Compared to the Total Normalized Alkali [Nalk =  $\text{Na}_2\text{O} + 0.66(\text{K}_2\text{O}) + 2(\text{Li}_2\text{O})$ ] Content of the Glass

Figure 3.11 shows the quenched glass alteration depth versus the CCC glass alteration depth results depending on amount of crystallinity in the glass. There does not appear to be any correlation between amount of crystallinity in the glass and the depth of glass alteration. The corrosion rate per day was also looked at and did not appear to have a direct correlation.

The VHT data were also compared to predictions from a VHT model (Piepel et al. 2007), which is a 15-term reduced partial cubic mixture model based on alteration depth (Figure 3.12), with the coefficients shown in Table 3.14. The VHT data were also compared to predictions from another VHT model (Piepel et al. 2007), a 16-term reduced partial quadratic mixture model based on alteration depth (Figure 3.13), with the coefficients shown in Table 3.15. There was relatively large scatter in data points using the models from Piepel et al. (2007). There are likely several reasons for this. First, the VHT is known to produce large variability in VHT results, even for the same glass composition. Second, Piepel et al. (2007) noted that their models had large, and statistically significant lack-of-fits, possibly due to the large variability in VHT results. Third, the Phase 2 LAW glasses have higher waste loadings than the glasses used to develop the Piepel et al. (2007) models. Hence, models developed using glasses with higher waste loadings and other approaches should be tried to produce a model that would fit the data closer.

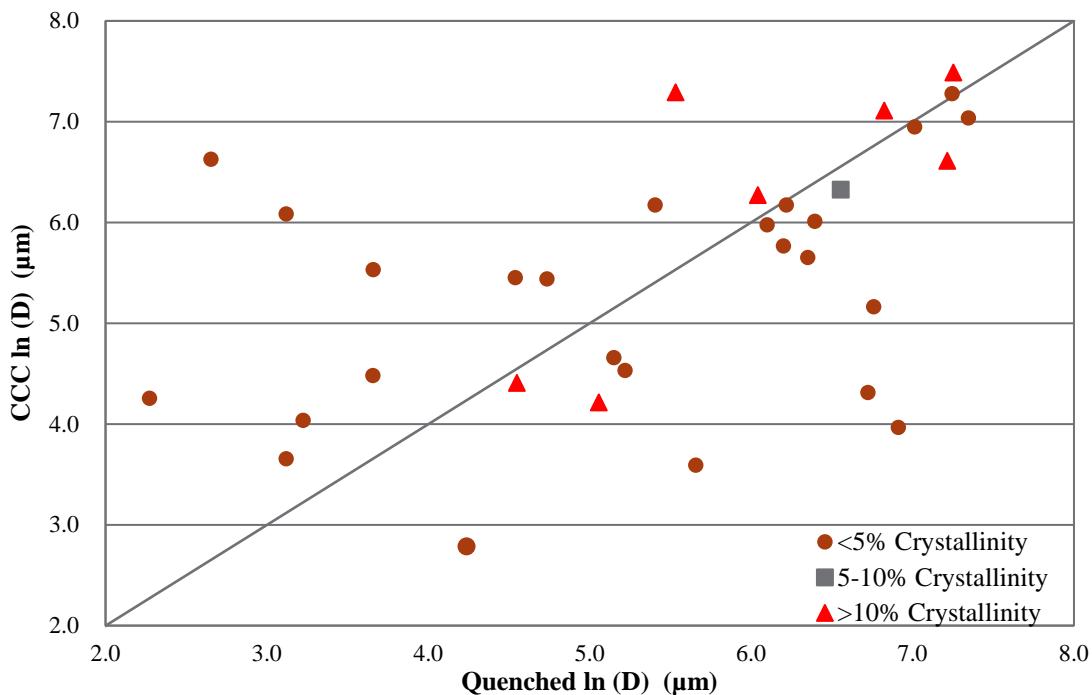


Figure 3.11 Natural Logarithm of VHT Alteration Depth Results for CCC versus Quenched Versions of Phase 2 Enhanced LAW Glasses

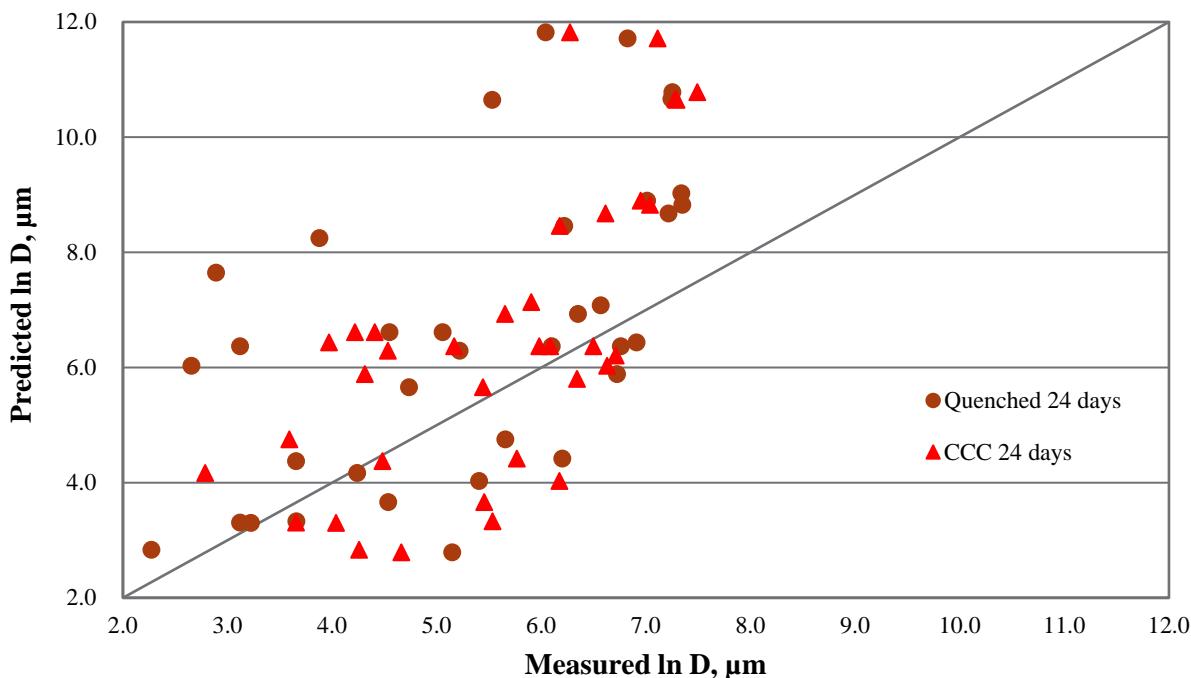


Figure 3.12. Natural Logarithm of VHT Alteration Depth Results Predicted using 15-Term Reduced Partial Cubic Mixture Model Versus Measured Values for Phase 2 Enhanced LAW Glasses

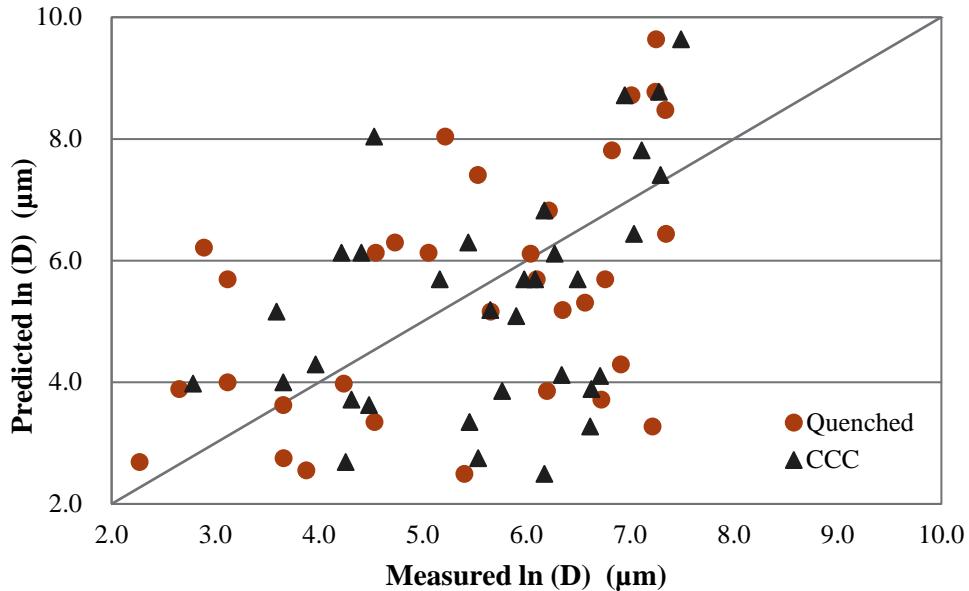


Figure 3.13. Natural Logarithm of VHT Alteration Depth Results Predicted using 16-Term Reduced Partial Quadratic Mixture Model Versus Measured VHT Values for Phase 2 Enhanced LAW Glasses

Table 3.8. Coefficients for 15-Term Reduced Partial Cubic Mixture Model Based on Alteration Depth for VHT Data (Piepel 2007)

Component	Coefficient	Component	Coefficient
Al <sub>2</sub> O <sub>3</sub>	19.5685	SiO <sub>2</sub>	-0.5137
B <sub>2</sub> O <sub>3</sub>	18.5336	ZrO <sub>2</sub>	-62.8457
CaO	38.2412	Others <sup>(1)</sup>	-0.4293
Fe <sub>2</sub> O <sub>3</sub>	-8.4126	K <sub>2</sub> O x K <sub>2</sub> O x Na <sub>2</sub> O	10138.2817
K <sub>2</sub> O	-39.3124	(Na <sub>2</sub> O) <sup>3</sup>	872.6563
MgO	-8.3068	Na <sub>2</sub> O x CaO x B <sub>2</sub> O <sub>3</sub>	-1943.0687
Na <sub>2</sub> O	-20.6518		

(1) The data Piepel et al. (2007) used to fit this model contained many minor components in Others. However, in the Phase 2 LAW glasses for which the model was used to predict, Others included only SO<sub>3</sub>, Cl, F, Cr<sub>2</sub>O<sub>3</sub> and ZnO.

Table 3.9. Coefficients for 16-Term Reduced Partial Quadratic Mixture Model on Natural Logarithm of VHT Alteration Depth (Piepel 2007)

Component	Coefficient	Component	Coefficient
Al <sub>2</sub> O <sub>3</sub>	66.1577	SiO <sub>2</sub>	-29.0882
B <sub>2</sub> O <sub>3</sub>	5.2229	ZrO <sub>2</sub>	77.6908
CaO	-233.0861	Others <sup>(1)</sup>	1.7371
Fe <sub>2</sub> O <sub>3</sub>	-5.2172	Al <sub>2</sub> O <sub>3</sub> x ZrO <sub>2</sub>	-1479.4599
K <sub>2</sub> O	-33.5013	Na <sub>2</sub> O x MgO	-920.4672
MgO	111.5235	CaO x SiO <sub>2</sub>	556.6025
Na <sub>2</sub> O	75.4548	K <sub>2</sub> O x K <sub>2</sub> O	1605.6605
		Na <sub>2</sub> O x ZrO <sub>2</sub>	-336.1985

(1) The data Piepel et al. (2007) used to fit this model contained many minor components in Others. However, in the Phase 2 LAW glasses for which the model was used to predict, Others included only SO<sub>3</sub>, Cl, F, Cr<sub>2</sub>O<sub>3</sub> and ZnO.

### 3.9 Sulfur Solubility Results

This section presents and discusses the sulfur solubility results of test glasses obtained using the methods discussed in Section 2.11. For each glass, the as melted sample (called baseline in this subsection) and the “sulfur-saturated” (SSM) sample were analyzed by ICP-AES and IC. The chemical analysis results of the baseline glasses have been presented and discussed in Section 3.1. More detailed chemical analysis results have been reported by Fox et al. (2017, 2018).

Note that 41 glass samples were prepared based on the glasses listed in Table 1.3. The measured Na<sub>2</sub>O concentrations were slightly below the targeted values for both baseline (0.011 mf) and SSM samples. There were no indications of errors in glass preparation or measurement that had to be addressed in using the data. Therefore, the entire set of measurement data was used in determining representative, measured compositions for the SSM versions of the glasses.

Table 3.16 and Figure 3.14 summarize the analyzed SO<sub>3</sub> concentrations in the baseline and the sulfur-saturated glasses. The SO<sub>3</sub> concentrations in the baseline glasses were mostly below 0.015 mass fraction (including several glasses with low SO<sub>3</sub> at 0.001 mass fraction). After sulfur-saturation, there was a significant increase of SO<sub>3</sub> in the Phase 2 LAW glasses, which is considered the experimentally determined SO<sub>3</sub> solubility of the glass. In most glasses, the SO<sub>3</sub> solubilities (i.e., the saturated SO<sub>3</sub> concentrations) were between 1.2 wt% and 1.5 wt%. Two glasses had a SO<sub>3</sub> solubility slightly above 2.0 wt%, with the highest SO<sub>3</sub> solubility being 2.62 wt% in glass LP2-OL-14.

Appendix J shows the analyzed glass compositions after normalization of the baseline and sulfur-saturated glass samples. Comparisons of the compositions showed that after the sulfur-saturation, other major glass components only have negligible changes except when the SO<sub>3</sub> reaches a sulfur-saturation mass fraction greater than about 0.015. For the minor components, K<sub>2</sub>O decreases, which may be due to ion-exchange, and the losses of the Cl, F, and P<sub>2</sub>O<sub>5</sub> may be due to volatilization during multiple times of melting and/or extraction into the salt.

The compositions of the sulfur-saturated glasses based on chemical analyses and normalization have been used to evaluate a preliminary SO<sub>3</sub> solubility model (Vienna et al. 2014). The empirical model produces the predicted SO<sub>3</sub> solubility using a PQM model of the form

$$w_{\text{SO}_3}^{\text{Pred}} = \sum_{i=1}^q s_i n_i + \text{selected} \left\{ \sum_{i=1}^q s_{ii} n_i^2 + \sum_{j=1}^{q-1} \sum_{k=j+1}^q s_{jk} n_j n_k \right\} \quad (3.8)$$

where

$w_{\text{SO}_3}^{\text{Pred}}$	the predicted SO <sub>3</sub> solubility (in wt%)
$q$	the number of components in the waste glass except for SO <sub>3</sub>
$n_i$	normalized (after removing SO <sub>3</sub> ) mass fraction of the $i$ th component
$s_i$	coefficient of the $i$ th component
$s_{ii}$	coefficient for the $i$ th component squared
$s_{jk}$	coefficient for the crossproduct of the $j$ th and $k$ th components

The model coefficients are listed in Table 3.17. In this preliminary model, only Li<sub>2</sub>O has a squared term ( $s_{ii}$ ) and there are no crossproduct terms ( $s_{jk}$ ).

The model predicted and measured SO<sub>3</sub> solubility values are compared in Figure 3.15. The data points are below the equal line, indicating the SO<sub>3</sub> solubility values for the Phase 2 LAW glasses are underpredicted

by the model. The underprediction is expected because a large portion of data used to develop the preliminary model were not fully saturated with SO<sub>3</sub>. The previous samples were prepared by one-time mixing and melting of the baseline glasses with Na<sub>2</sub>SO<sub>4</sub>, which could not fully saturate the glass and achieve the true SO<sub>3</sub> solubility. On the other hand, the three-times-mixing-and-melting sulfur-saturation method developed in this work (see Section 2.10) can fabricate glasses fully saturated by SO<sub>3</sub> and determine the true SO<sub>3</sub> solubility of the glass (Jin et al. 2019; Skidmore et al. 2019). Future work will help modify the preliminary model using this new experimentally determined SO<sub>3</sub> solubility data to improve the empirical model.

Table 3.10. Target and Measured Baseline Values of SO<sub>3</sub> (mass fraction) and SO<sub>3</sub> Solubility (wt%) Values for Phase 2 Enhanced LAW Glasses

Sample ID	SO <sub>3</sub> , Mass Fraction		SO <sub>3</sub> Solubility (wt%)
	Target Baseline	Measured Baseline	
LP2-IL-01	0.00800	0.00817	1.558
LP2-IL-02	0.00800	0.00799	1.195
LP2-IL-03	0.00200	0.00216	1.232
LP2-IL-04	0.00200	0.00231	1.542
LP2-IL-05	0.00200	0.00215	1.520
LP2-IL-06	0.00800	0.00771	1.076
LP2-IL-07	0.00800	0.00789	1.694
LP2-IL-08	0.00800	0.00771	1.445
LP2-IL-09	0.00200	0.00215	1.501
LP2-IL-10	0.00500	0.00481	1.396
LP2-IL-11	0.00200	0.00201	1.236
LP2-IL-12	0.00200	0.00210	1.536
LP2-IL-13	0.00200	0.00202	1.265
LP2-IL-14	0.00800	0.00783	1.524
LP2-IL-15	0.00800	0.00753	1.276
LP2-IL-16	0.00500	0.00493	1.366
LP2-IL-17	0.01000	0.00964	1.354
LP2-OL-01-3	0.00100	0.00158	1.472
LP2-OL-02-1	0.00500	0.00475	1.110
LP2-OL-03-MOD2	0.00754	0.00743	1.478
LP2-OL-04-1	0.00100	0.00158	1.091
LP2-OL-05	0.00980	0.00948	1.416
LP2-OL-07-1	0.01060	0.01033	1.620
LP2-OL-08-MOD	0.00816	0.00646	1.885
LP2-OL-09-1	0.00100	0.00110	1.081
LP2-OL-10-MOD	0.00800	0.00734	1.116
LP2-OL-11	0.00100	0.00149	1.485
LP2-OL-12	0.00100	0.00139	2.354
LP2-OL-13	0.00100	0.00104	1.555
LP2-OL-14	0.01519	0.01581	2.619
LP2-OL-15	0.00100	0.00122	1.975
LP2-OL-16-MOD	0.00992	0.00883	1.195
LP2-OL-17	0.00100	0.00141	1.789
LP2-OL-18	0.01137	0.01036	1.249
LP2-OL-19	0.00796	0.00653	1.018
LP2-OL-20	0.00100	0.00123	1.915
LP2-OL-21	0.00500	0.00495	1.128
LP2-OL-22	0.00100	0.00108	1.180
LP2-OL-23	0.01315	0.01167	1.737

Sample ID	SO <sub>3</sub> , Mass Fraction		SO <sub>3</sub> Solubility (wt%)
	Target Baseline	Measured Baseline	
LP2-OL-24	0.00100	0.00130	1.421
LP2-OL-25	0.01012	0.00809	1.293

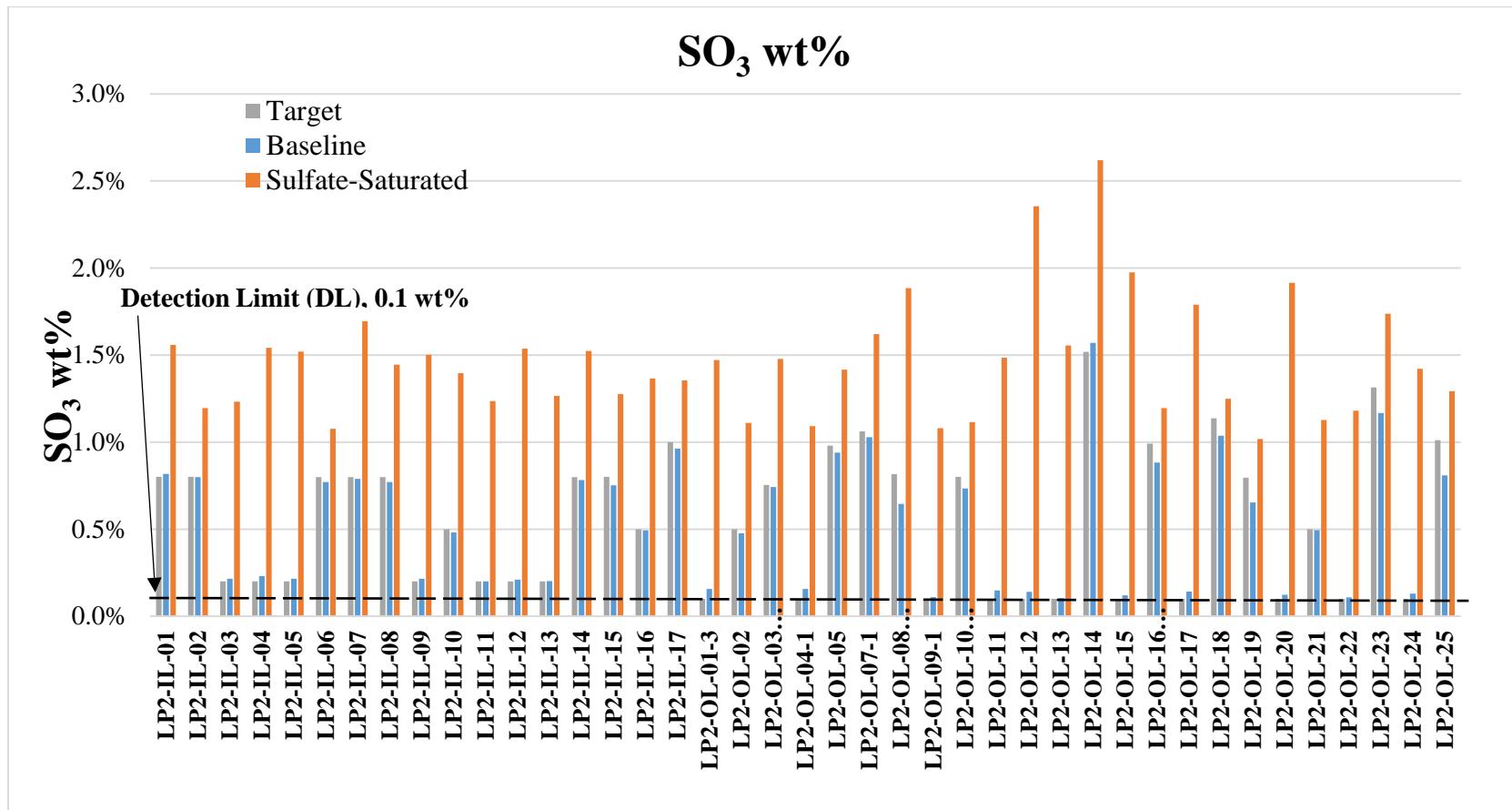


Figure 3.14. Analyzed Sulfur Concentration (wt%) in the Baseline and the Sulfate-Saturated Glasses

Table 3.11. List of SO<sub>3</sub> Solubility Model Components and Coefficients (Vienna et al. 2016)

Model Term	s <sub>i</sub> Coefficient
Al <sub>2</sub> O <sub>3</sub>	-2.091901
B <sub>2</sub> O <sub>3</sub>	3.0440748
CaO	4.4422886
Cl	-22.65353
Cr <sub>2</sub> O <sub>3</sub>	-13.14139
K <sub>2</sub> O	0.615785
Li <sub>2</sub> O	2.473926
Na <sub>2</sub> O	2.8972089
P <sub>2</sub> O <sub>5</sub>	4.606083
SiO <sub>2</sub>	0.2407285
SnO <sub>2</sub>	-1.775325
V <sub>2</sub> O <sub>5</sub>	7.5345478
ZrO <sub>2</sub>	-1.871916
Others *	-0.280272
(Li <sub>2</sub> O) <sup>2</sup>	260.203

\* Others is the sum of all components not specifically listed as model terms (i.e., those not anticipated to have a significant effect).

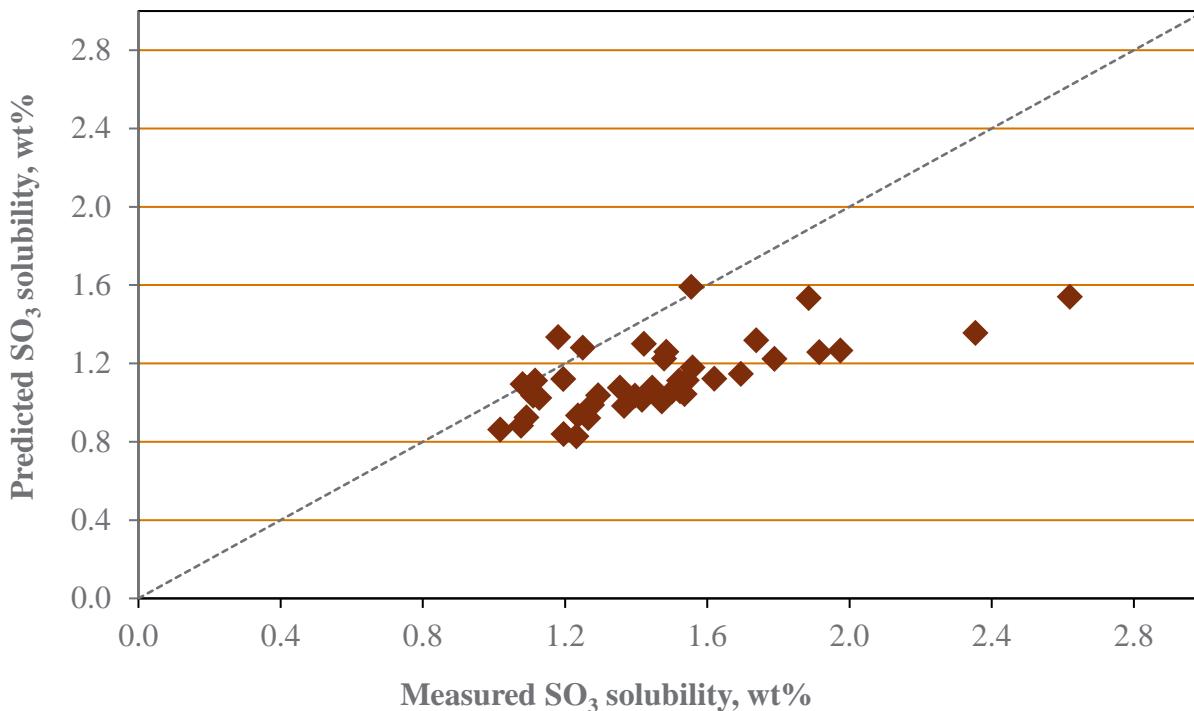


Figure 3.15. Predicted versus Measured SO<sub>3</sub> Solubility (wt%) for Phase 2 Enhanced LAW Glasses. The predicted values were obtained using the model in Equation (3.6) with coefficients as listed in Table 3.16.

## Results and Discussion

## 4.0 Summary

The objective of the task in this report was to generate data on enhanced LAW glass compositions to ultimately support the development, validation, and implementation of glass property models that can achieve high waste loading for the full region of Hanford LAW compositions. To extend the models beyond our current knowledge space, a new enhanced LAW EGCR was developed. Fifteen LAW glass components were selected for variation in the experimental work, including an Others component mix. Certain components were chosen for variation in the experimental work for specific reasons. The components SnO<sub>2</sub> and ZrO<sub>2</sub> were included because they can decrease the VHT response. The components V<sub>2</sub>O<sub>5</sub> and Li<sub>2</sub>O were included because they can increase the SO<sub>3</sub> tolerance in the melter. Finally, the components ZnO and Cr<sub>2</sub>O<sub>3</sub> were included because they can decrease refractory corrosion.

A statistical layered experimental design approach (Piepel et al. 1993; Cooley et al. 2003; Piepel et al. 2005) was used to generate a test matrix of 42 Phase 2 enhanced LAW glass compositions. The test matrix consisted of 21 outer-layer glasses, 15 inner-layer glasses, a center glass (three replicates), and two glasses previously tested at another laboratory. Five of the outer-layer matrix glasses needed some modification to their composition and/or melt temperature to form homogeneous glasses. However, one of the outer-layer matrix glasses (LP2-OL-06) was not able to be modified to produce a homogenous glass and was dropped from testing.

The purpose of the chemical composition analysis was to identify whether (i) any Phase 2 enhanced LAW glass(es) was(were) mis-batched, (ii) there was non-negligible volatility in any component(s) during glass melting, or (iii) whether there were any component(s) that was(were) not completely incorporated into the glass melts. All the measured sums of oxides for the study glasses fell within the interval of 97.8 to 101.7 wt% for the inner-layer glasses and 94.7 to 101.9 wt% for the outer-layer glasses, indicating excellent recovery of the glass components.

XRD scans of CCC glass samples identified several crystal types. The major crystalline phases appearing (in the glasses containing crystals) were nepheline, sodalite, and combeite, which are all feldspathoids. A total of 28 samples were not analyzed by XRD because there were either no crystals or very few crystals (not enough for XRD to detect) observed by optical microscope. Four glasses had crystal content of less than 5 mass%, while eight glasses had crystal content greater than 10 mass% crystals. Only one glass (LP2-IL-06) had a crystal content between 5 and 10 mass%.

During the CCC heat-treatment, several of the Phase 2 enhanced LAW glasses seemed to form a layer of crystals around the Pt crucible walls. When a quartz crucible was used, the glass still formed a layer of crystals around the crucible walls. Therefore, this crystal formation did not appear to be due to the Pt.

The mode of the 41 measured density values was 2.64 g/cm<sup>3</sup>, with a minimum of 2.59 g/cm<sup>3</sup> and a maximum of 2.75 g/cm<sup>3</sup>. The density of LAW glasses varied little—60% of the glasses had density values between 2.64 g/cm<sup>3</sup> and 2.70 g/cm<sup>3</sup>. The predicted glass density based on the model discussed in Section 3.2 was higher than the measured density for all but one of the Phase 2 enhanced LAW glass compositions. However, all density values were well below the contractual limit of 3.7 g/cm<sup>3</sup>. Thus, the available density data for LAW glasses indicated that it is not necessary to develop a property-composition model to comply with the contractual requirement for LAW density.

Although a previous model (Piepel et al. 2016) produced very good predictions of  $\eta_{1150}$  for the Phase 2 enhanced LAW glasses, the model slightly overpredicted the measured values. Therefore, it would be useful to re-fit the model to account for the Phase 2 data, as well as the entire LAW glass composition region.

A previous model expressed as a function of glass composition and melt temperature (Piepel et al. 2007), overpredicted electrical conductivity at 1150°C ( $\epsilon_{1150}$ ) for all but one of the Phase 2 LAW glasses. This could be because of the different glass composition region that the Phase 2 enhanced LAW glass study explored compared to the composition region explored for the models in Piepel et al. (2007). Therefore, a new model exploring a wider composition region would be useful to account for the Phase 2 data.

In measuring the crystal fraction of the glasses by holding them at 950°C for 24 ± 2 h, all but 14 glasses had insufficient crystals to perform XRD analysis. Nine glasses contained Nasicon ( $\text{Na}_{1+x}\text{Zr}_2\text{Si}_x\text{P}_{3-x}\text{O}_{12}$ ,  $0 < x < 3$ ) and six glasses contained lazurite,  $(\text{Na},\text{Ca})_8[(\text{S},\text{Cl},\text{SO}_4,\text{OH})_2](\text{Al}_6\text{Si}_6\text{O}_{24})$ , and/or combeite ( $\text{Na}_2\text{Ca}_2\text{Si}_3\text{O}_9$ ). The wt% total crystallinity ranged from 0 to 17.46 wt%.

A review of the PCT data shows that none of the inner-layer glasses had normalized release values for boron (NR [B]) and sodium (NR [Na]) that are higher than the WTP contract limit of 2 g/m<sup>2</sup> for both quenched and CCC-treated glasses. However, several of the outer-layer glasses did exceed this limit. The test matrix was developed in this way so that PCT-composition models would be able to predict whether a given glass meets the PCT limits. It appeared that the CCC heat treatment had little impact on the PCT results as compared to the quenched versions of the study glasses for the inner-layer glasses. For the outer-layer glasses, the CCC heat treatment resulted in increased normalized release values of glasses with crystals. It appears that the B release is generally overpredicted, and the Na release is generally underpredicted using the PCT models from Piepel et al. (2007). It was noted in Piepel et al. (2007) that the given partial quadratic mixture models were not as accurate with higher waste loadings and higher Na and B releases. Since the current effort is to increase waste loading, new PCT models are needed to ensure that the glasses meet the release limit of 2 g/m<sup>2</sup> (4 g/L).

A total of 14 of the 41 quenched glasses and 11 of the 41 CCC glasses failed the VHT with a corrosion rate of >50 g/m<sup>2</sup>/d. The glasses tested performed either extremely well or extremely poor, with only two quenched and one CCC glasses near the corrosion rate limit. Ideally the VHT results for the Phase 2 LAW glasses would have been better distributed, but the goal of having some VHT results above the limit for modeling purposes was achieved.

The VHT data were also predicted using two VHT models (Piepel et al. 2007) based on alteration depth (see Section 3.8). The data in predicted versus measured plots are quite scattered, with the models generally overpredicting the VHT response. There are likely several reasons for this. First, the VHT is known to produce large variability in VHT results, even for the same glass composition. Second, Piepel et al. (2007) noted that their models had large, and statistically significant lack-of-fits, possibly due to the large variability in VHT results. Third, the Phase 2 LAW glasses have higher waste loadings than the glasses used to develop the Piepel et al. (2007) models. Hence, models developed using glasses with higher waste loadings and other approaches should be tried to produce a model that would fit the data closer.

The SO<sub>3</sub> concentrations (mass fractions) in the baseline glasses were mostly below 0.015 (including several glasses with low SO<sub>3</sub> at 0.001). After sulfur-saturation, there was a significant increase of SO<sub>3</sub> mass fraction, which is considered the experimentally determined SO<sub>3</sub> solubility of the glass. In most glasses, the SO<sub>3</sub> solubility (i.e., the saturated SO<sub>3</sub> concentrations) was between 1.2 wt% and 1.5 wt%. Two glasses had a SO<sub>3</sub> solubility slightly above 2.0 wt%, with the highest SO<sub>3</sub> being 2.62 wt% in glass LP2-OL-14.

## 5.0 References

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## Appendix A – Morphology/Color of Each Quenched Glass

The photos in this appendix show quenched samples of each Phase 2 enhanced LAW glass after melting in a Pt/Rh crucible twice at the specified melt temperature.



Figure A.1. Photo of Glass LP2-IL-01 Morphology of Second Melt at 1150°C for 1.5 h

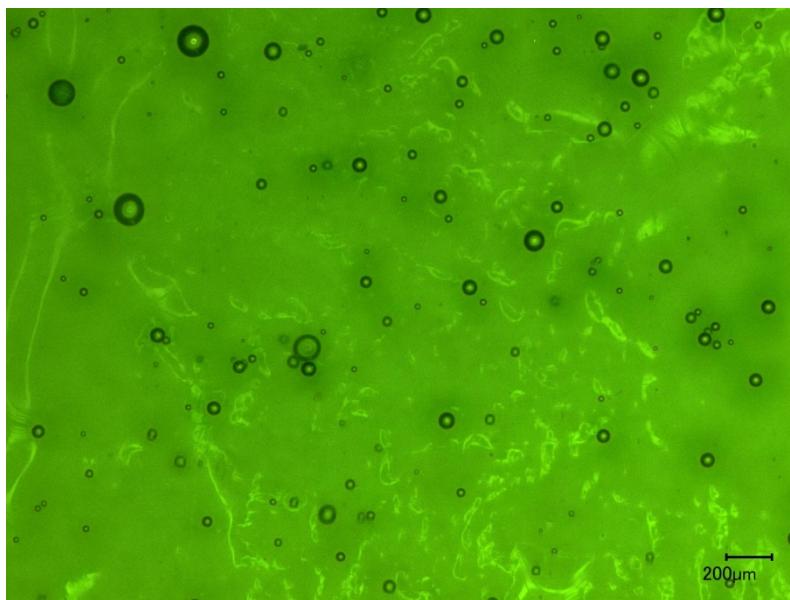


Figure A.2. Photo of Glass LP2-IL-02 Morphology of Fourth Melt at 1150°C for 0.5 h



Figure A.3. Photo of Glass LP2-IL-03 Morphology of Second Melt at 1150°C for 1.5 h

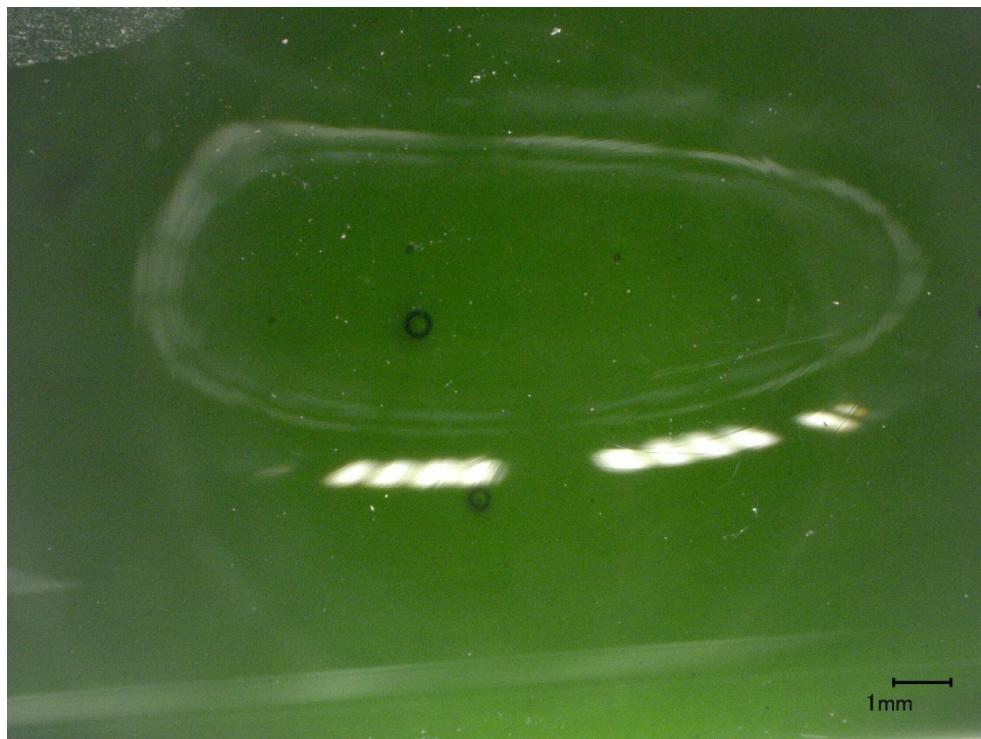


Figure A.4. Photo of Glass LP2-IL-04 Morphology of Second Melt at 1150°C for 2.3 h

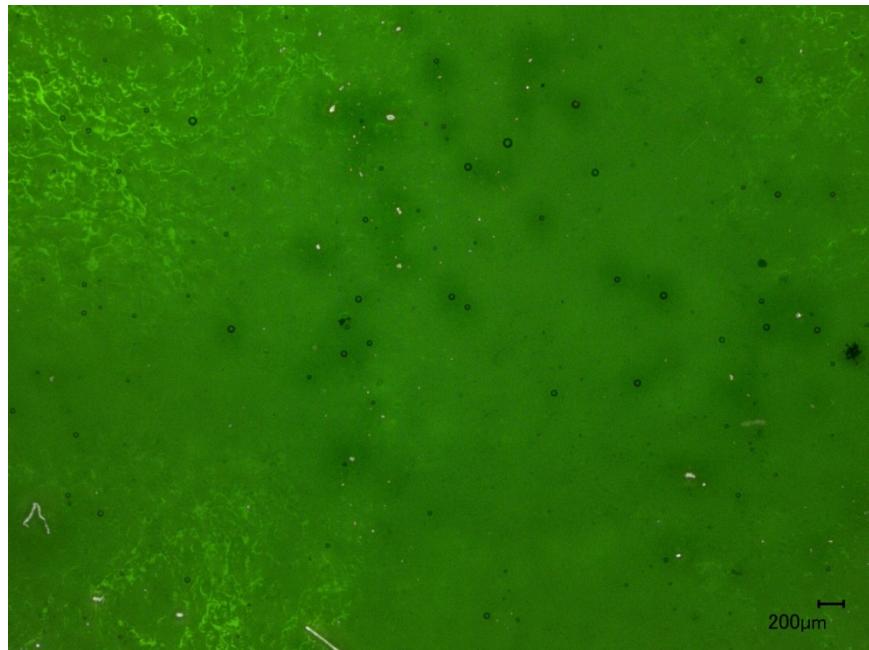


Figure A.5. Photo of Glass LP2-IL-05 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.6. Photo of Glass LP2-IL-06 Morphology of Fourth Melt at 1175°C for 1 h

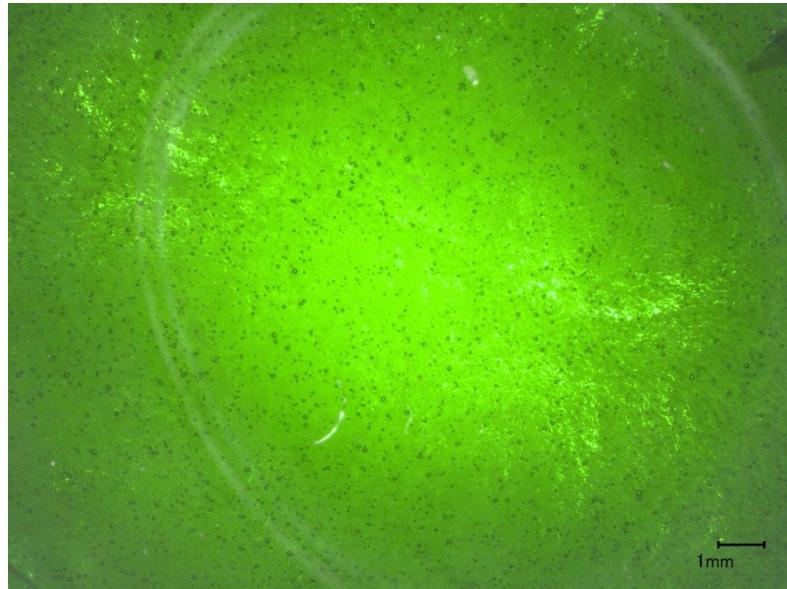


Figure A.7. Photo of Glass LP2-IL-07 Morphology of Second Melt at 1150°C for 1 h



Figure A.8. Photo of Glass LP2-IL-08 Morphology of Third Melt at 1175°C for 1.1 h

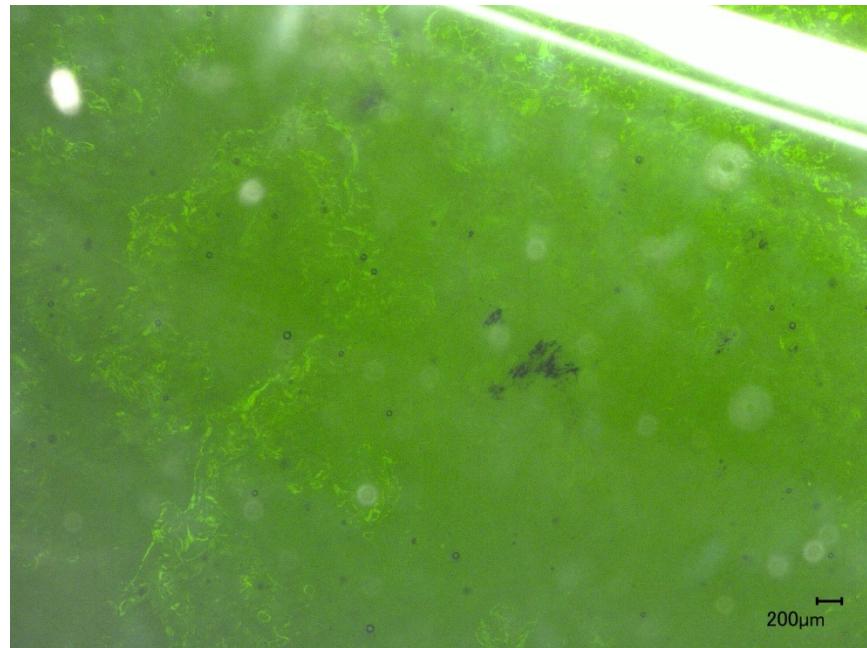


Figure A.9. Photo of Glass LP2-IL-09 Morphology of Third Melt at 1175°C for 1 h



Figure A.10. Photo of Glass LP2-IL-10 Morphology of Third Melt at 1175°C for 1.5 h

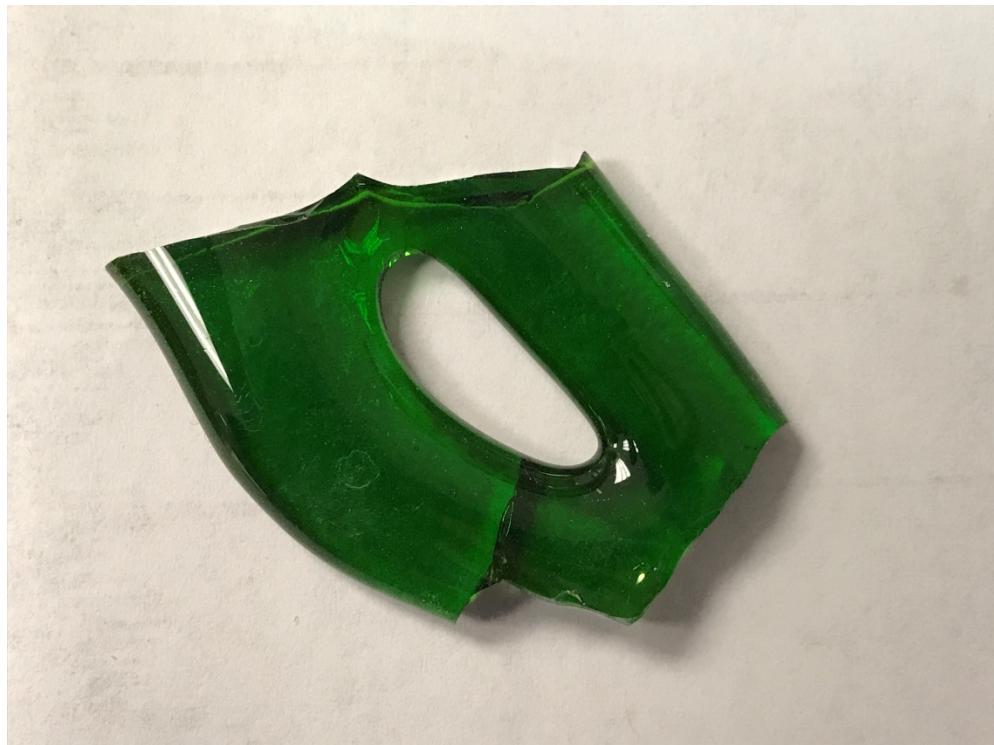


Figure A.11. Photo of Glass LP2-IL-11 Morphology of Third Melt at 1175°C for 1 h



Figure A.12. Photo of Glass LP2-IL-12 Morphology of Third Melt at 1175°C for 1 h



Figure A.13. Photo of Glass LP2-IL-13 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.14. Photo of Glass LP2-IL-14 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.15. Photo of Glass LP2-IL-15 Morphology of Third Melt at 1150°C for 1 h



Figure A.16. Photo of Glass LP2-IL-16 Morphology of Second Melt at 1175°C for 0.75 h



Figure A.17. Photo of Glass LP2-IL-17 Morphology of Second Melt at 1150°C for 1.5 h

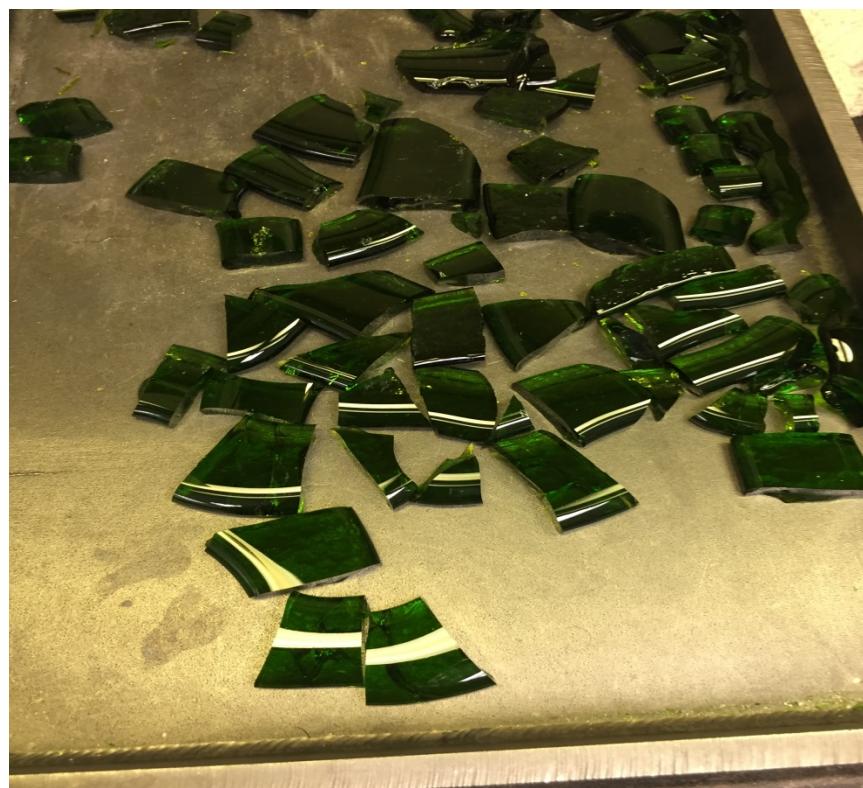


Figure A.18. Photo of Glass LP2-OL-01-3 Morphology of Second Melt at 1150°C for 1.5 h

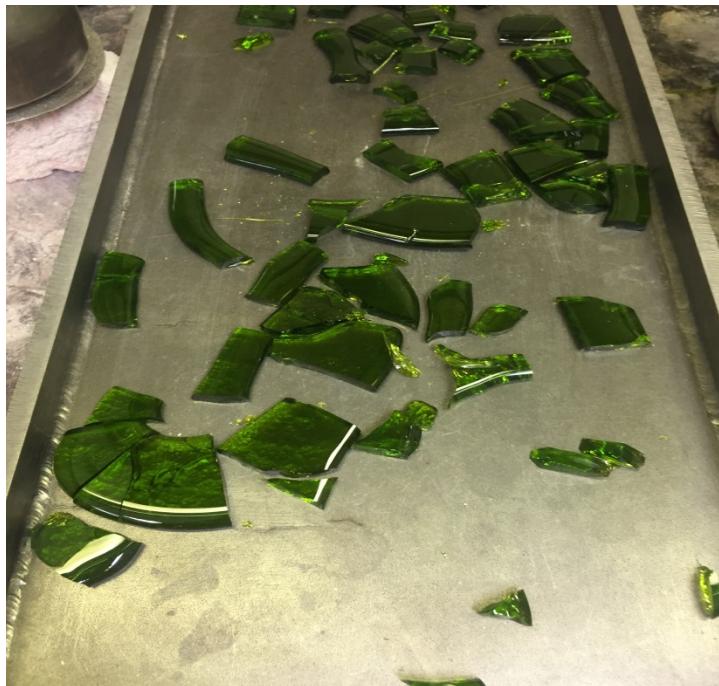


Figure A.19. Photo of Glass LP2-OL-02-1 Morphology of Second Melt at 1150°C for 1.3 h

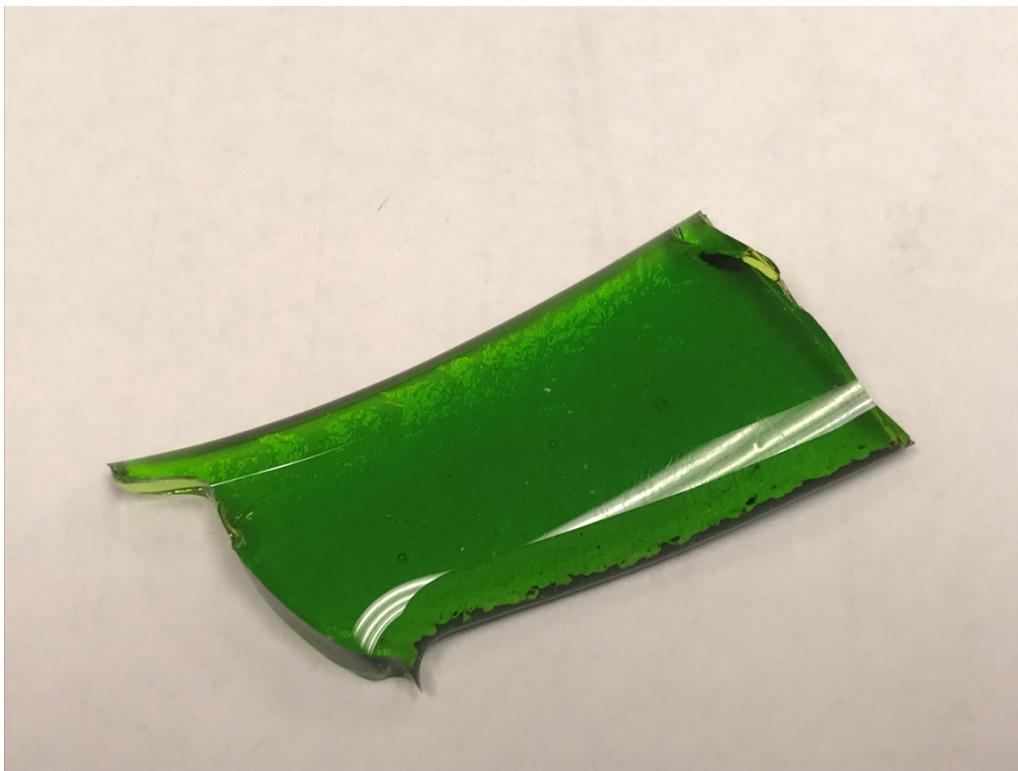


Figure A.20. Photo of Glass LP2-OL-03MOD2 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.21. Photo of Glass LP2-OL-04-1 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.22. Photo of Glass LP2-OL-05 Morphology of Third Melt at 1150°C for 1.5 h



Figure A.23. Photo of Glass LP2-OL-07-1 Morphology of Second Melt at 1150°C for 1.5 h

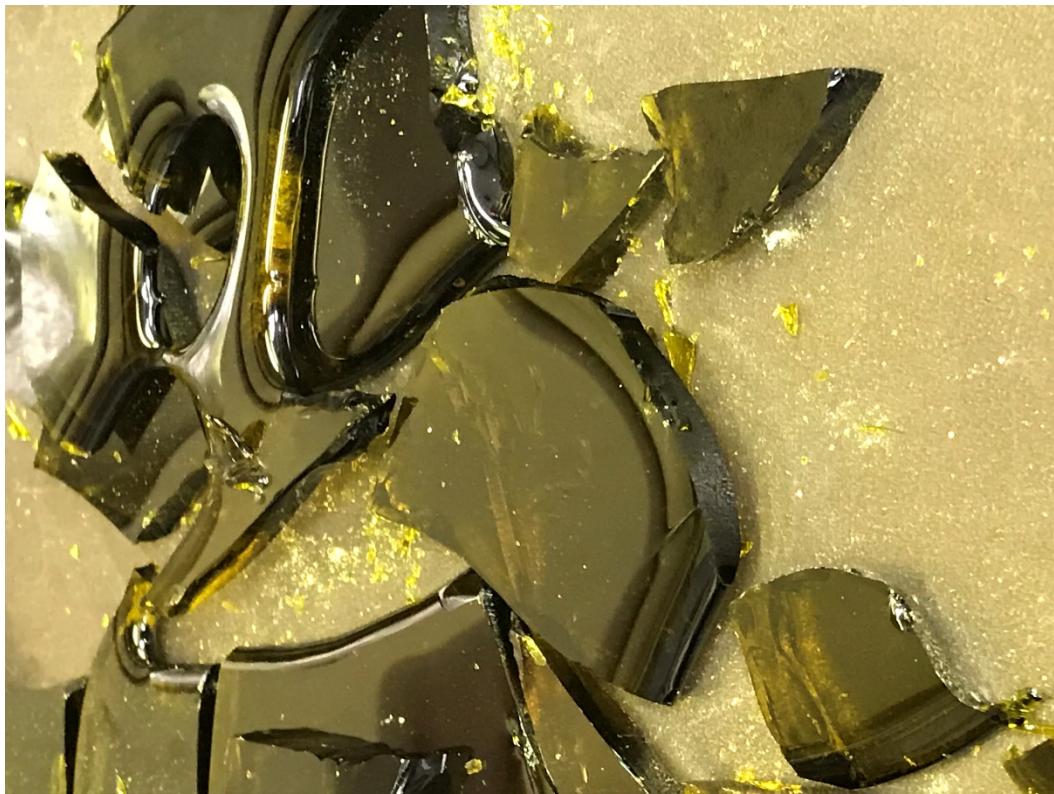


Figure A.24. Photo of Glass LP2-OL-08MOD Morphology of Second Melt at 1200°C for 1.3 h



Figure A.25. Photo of Glass LP2-OL-09-1 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.26. Photo of Glass LP2-OL-10 MOD Morphology of Second Melt at 1150°C for 1.5 h



Figure A.27. Photo of Glass LP2-OL-11 Morphology of Second Melt at 1150°C for 1.6 h



Figure A.28. Photo of Glass LP2-OL-12 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.29. Photo of Glass LP2-OL-13 of Morphology Third Melt at 1150°C for 1.7 h



Figure A.30. Photo of Glass LP2-OL-14 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.31. Photo of Glass LP2-OL-15 Morphology of Third Melt at 1150°C for 1 h



Figure A.32. Photo of Glass LP2-OL-16 MOD of Third Melt at 1200°C for 2 h



Figure A.33. Photo of Glass LP2-OL-17 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.34. Photo of Glass LP2-OL-18 Morphology of Second Melt at 1250°C for 1.6 h



Figure A.35. Photo of Glass LP2-OL-19 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.36. Photo of Glass LP2-OL-20 Morphology of First Melt at 1150°C for 1.5 h



Figure A.37. Photo of Glass LP2-OL-21 Morphology of Second Melt at 1150°C for 1.4 h



Figure A.38. Photo of Glass LP2-OL-22 Morphology of Third Melt at 1150°C for 1.5 h



Figure A.39. Photo of Glass LP2-OL-23 Morphology of Second Melt at 1150°C for 1.5 h



Figure A.40. Photo of Glass LP2-OL-24 Morphology of Third Melt at 1200°C for 1.5 h



Figure A.41. Photo of Glass LP2-OL-25 Morphology of Second Melt at 1150°C for 1.6 h

## Appendix B – Analyzed Glass Compositions

The tables in this appendix compare the targeted glass compositions with the analyzed glass compositions and their percent differences for the Phase 2 enhanced LAW glasses. There were two main purposes for analyzing the compositions of these glasses. First, the analyzed SO<sub>3</sub> values estimate the concentrations of that component incorporated into the glass melts. Second, comparing target and analyzed values of components provides for detecting glasses that were mis-batched, or components subject to volatilization during melting.

There appeared to be overall agreement between targeted and analyzed components for all Phase 2 LAW glasses. Hence, renormalized versions of the targeted compositions, with use of the measured instead of targeted SO<sub>3</sub> values, will be used in future work to develop property-composition models.

Table B.1. Comparison of Targeted and Analyzed LAW Phase 2 Enhanced Glass Compositions

Glass ID	LP2-IL-01			LP2-IL-02			LP2-IL-03			LP2-IL-04		
	Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)
Al <sub>2</sub> O <sub>3</sub>	7.500	6.906	-7.92	7.500	7.275	-3.00	8.730	8.073	-7.53	7.500	7.213	-3.83
B <sub>2</sub> O <sub>3</sub>	8.000	7.631	-4.61	8.130	8.138	0.10	8.730	8.549	-2.07	8.000	8.227	2.84
CaO	7.620	7.877	3.37	2.000	2.305	15.25	2.000	2.337	16.85	7.490	7.615	1.67
Cl	0.170	0.124	-27.06	0.170	0.115	-32.35	0.350	0.262	-25.14	0.350	0.226	-35.43
Cr <sub>2</sub> O <sub>3</sub>	0.530	0.520	-1.89	0.380	0.372	-2.11	0.530	0.520	-1.89	0.530	0.520	-1.89
F	0.260	0.225	-13.46	0.260	0.219	-15.77	0.530	0.462	-12.83	0.530	0.462	-12.83
Fe <sub>2</sub> O <sub>3</sub>	0.200	0.217	8.50	0.580	0.603	3.97	0.200	0.221	10.50	1.000	1.069	6.90
K <sub>2</sub> O	2.000	1.985	-0.75	2.000	1.985	-0.75	0.760	0.813	6.97	2.000	1.945	-2.75
MgO	0.300	0.315	5.00	1.000	0.979	-2.10	0.300	0.313	4.33	1.000	0.985	-1.50
Na <sub>2</sub> O	23.680	22.242	-6.07	23.680	22.410	-5.36	24.500	22.107	-9.77	23.680	22.411	-5.36
P <sub>2</sub> O <sub>5</sub>	0.560	0.661	18.04	0.560	0.517	-7.68	1.130	0.828	-26.73	1.130	0.835	-26.11
SiO <sub>2</sub>	37.980	39.096	2.94	41.810	42.572	1.82	40.360	42.305	4.82	38.200	39.737	4.02
SO <sub>3</sub>	0.800	0.806	0.75	0.800	0.792	-1.00	0.200	0.211	5.50	0.200	0.229	14.50
SnO <sub>2</sub>	0.500	0.504	0.80	2.500	2.517	0.68	2.500	2.571	2.84	2.500	2.634	5.36
V <sub>2</sub> O <sub>5</sub>	2.000	2.008	0.40	0.500	0.491	-1.80	0.500	0.481	-3.80	0.500	0.488	-2.40
ZnO	2.400	2.427	1.13	2.630	2.627	-0.11	3.200	3.165	-1.09	2.400	2.409	0.38
ZrO <sub>2</sub>	5.500	5.096	-7.35	5.500	5.174	-5.93	5.500	4.498	-18.22	3.000	2.313	-22.90
Total	100.000	98.856	-1.14	100.000	99.305	-0.70	100.020	97.930	-2.09	100.010	99.534	-0.48

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID		LP2-IL-05			LP2-IL-06			LP2-IL-07			LP2-IL-08		
Component		Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Al <sub>2</sub> O <sub>3</sub>		7.500	7.048	-6.03	10.680	10.397	-2.65	7.500	6.986	-6.85	7.500	7.227	-3.64
B <sub>2</sub> O <sub>3</sub>		12.000	11.423	-4.81	12.000	12.107	0.89	12.000	11.938	-0.52	8.000	8.501	6.26
CaO		7.030	7.227	2.80	2.000	2.295	14.75	5.150	5.369	4.25	8.000	8.108	1.35
Cl		0.350	0.244	-30.29	0.350	0.218	-37.71	0.350	0.270	-22.86	0.350	0.206	-41.14
Cr <sub>2</sub> O <sub>3</sub>		0.380	0.369	-2.89	0.530	0.524	-1.13	0.380	0.368	-3.16	0.530	0.508	-4.15
F		0.530	0.441	-16.79	0.530	0.424	-20.00	0.530	0.466	-12.08	0.530	0.443	-16.42
Fe <sub>2</sub> O <sub>3</sub>		0.200	0.225	12.50	0.200	0.218	9.00	0.200	0.123	-38.50	1.000	0.988	-1.20
K <sub>2</sub> O		0.500	0.527	5.40	2.000	2.003	0.15	2.000	1.985	-0.75	0.500	0.537	7.40
MgO		0.300	0.305	1.67	1.000	0.988	-1.20	1.000	0.963	-3.70	1.000	0.973	-2.70
Na <sub>2</sub> O		22.000	20.658	-6.10	22.000	22.276	1.25	22.330	22.040	-1.30	22.000	20.928	-4.87
P <sub>2</sub> O <sub>5</sub>		1.130	0.749	-33.72	1.130	0.872	-22.83	1.130	0.745	-34.07	1.130	0.866	-23.36
SiO <sub>2</sub>		37.000	38.721	4.65	37.000	39.203	5.95	39.450	40.433	2.49	38.980	39.898	2.36
SO <sub>3</sub>		0.200	0.212	6.00	0.800	0.782	-2.25	0.800	0.782	-2.25	0.800	0.763	-4.63
SnO <sub>2</sub>		2.500	2.606	4.24	0.820	0.831	1.34	0.500	0.379	-24.20	0.500	0.401	-19.80
V <sub>2</sub> O <sub>5</sub>		0.500	0.484	-3.20	1.080	1.023	-5.28	0.500	0.486	-2.80	0.500	0.483	-3.40
ZnO		2.400	2.402	0.08	2.400	2.353	-1.96	3.200	3.124	-2.38	3.200	3.109	-2.84
ZrO <sub>2</sub>		5.500	5.140	-6.55	5.500	4.978	-9.49	3.000	2.678	-10.73	5.500	5.022	-8.69
Total		100.020	98.996	-1.02	100.020	101.705	1.68	100.020	99.351	-0.67	100.020	99.176	-0.84

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID		LP2-IL-09			LP2-IL-10			LP2-IL-11			LP2-IL-12		
Component		Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Al <sub>2</sub> O <sub>3</sub>		7.500	7.076	-5.65	10.000	9.060	-9.40	9.000	8.663	-3.74	7.500	6.878	-8.29
B <sub>2</sub> O <sub>3</sub>		12.000	12.155	1.29	9.500	10.054	5.83	8.000	8.460	5.75	8.000	7.921	-0.99
CaO		2.000	2.281	14.05	5.000	5.216	4.32	3.080	3.337	8.34	3.120	3.400	8.97
Cl		0.170	0.120	-29.41	0.210	0.137	-34.76	0.350	0.206	-41.14	0.350	0.256	-26.86
Cr <sub>2</sub> O <sub>3</sub>		0.530	0.511	-3.58	0.450	0.434	-3.56	0.380	0.367	-3.42	0.380	0.366	-3.68
F		0.260	0.223	-14.23	0.320	0.269	-15.94	0.530	0.438	-17.36	0.530	0.454	-14.34
Fe <sub>2</sub> O <sub>3</sub>		1.000	0.938	-6.20	0.600	0.552	-8.00	1.000	0.970	-3.00	0.200	0.119	-40.50
K <sub>2</sub> O		0.500	0.545	9.00	1.000	1.080	8.00	2.000	1.930	-3.50	0.500	0.528	5.60
MgO		1.000	0.975	-2.50	0.650	0.627	-3.54	0.300	0.294	-2.00	1.000	0.966	-3.40
Na <sub>2</sub> O		24.370	23.489	-3.62	23.000	21.871	-4.91	22.000	21.332	-3.04	23.790	22.545	-5.23
P <sub>2</sub> O <sub>5</sub>		0.560	0.625	11.61	0.680	0.603	-11.32	1.130	0.770	-31.86	1.130	0.754	-33.27
SiO <sub>2</sub>		37.000	37.224	0.61	38.800	38.668	-0.34	38.850	39.042	0.49	42.920	43.695	1.81
SO <sub>3</sub>		0.200	0.212	6.00	0.500	0.469	-6.20	0.200	0.199	-0.50	0.200	0.206	3.00
SnO <sub>2</sub>		2.200	2.123	-3.50	1.500	1.495	-0.33	2.500	2.549	1.96	0.500	0.408	-18.40
V <sub>2</sub> O <sub>5</sub>		2.000	1.999	-0.05	1.000	0.939	-6.10	2.000	1.986	-0.70	2.000	1.999	-0.05
ZnO		3.200	3.128	-2.25	2.800	2.739	-2.18	3.200	3.090	-3.44	2.400	2.365	-1.46
ZrO <sub>2</sub>		5.500	5.049	-8.20	4.000	3.377	-15.58	5.500	5.532	0.58	5.500	5.035	-8.45
Total		99.990	98.887	-1.10	100.010	97.804	-2.21	100.020	99.382	-0.64	100.020	98.112	-1.91

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-IL-13			LP2-IL-14			LP2-IL-15			LP2-IL-16		
Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Al <sub>2</sub> O <sub>3</sub>	7.500	7.237	-3.51	8.800	8.106	-7.89	7.500	7.062	-5.84	10.000	9.452	-5.48
B <sub>2</sub> O <sub>3</sub>	11.260	10.964	-2.63	12.000	11.302	-5.82	10.750	10.328	-3.93	9.500	9.136	-3.83
CaO	2.320	2.575	10.99	3.830	4.117	7.49	2.000	2.176	8.80	5.000	5.271	5.42
Cl	0.170	0.127	-25.29	0.350	0.243	-30.57	0.350	0.254	-27.43	0.210	0.139	-33.81
Cr <sub>2</sub> O <sub>3</sub>	0.530	0.509	-3.96	0.380	0.365	-3.95	0.530	0.519	2.08	0.450	0.439	2.44
F	0.260	0.202	-22.31	0.530	0.422	-20.38	0.530	0.416	-21.51	0.320	0.263	-17.81
Fe <sub>2</sub> O <sub>3</sub>	1.000	0.954	-4.60	1.000	0.914	-8.60	1.000	0.941	-5.90	0.600	0.558	-7.00
K <sub>2</sub> O	2.000	1.927	-3.65	0.500	0.541	8.20	0.500	0.542	8.40	1.000	1.087	8.70
MgO	0.300	0.291	-3.00	0.300	0.297	-1.00	0.300	0.299	-0.33	0.650	0.641	-1.38
Na <sub>2</sub> O	22.000	21.433	-2.58	24.500	23.489	-4.13	22.000	21.130	-3.95	23.000	22.478	-2.27
P <sub>2</sub> O <sub>5</sub>	0.560	0.600	7.14	1.130	0.777	-31.24	1.130	0.923	-18.32	0.680	0.617	-9.26
SiO <sub>2</sub>	43.000	43.374	0.87	37.000	38.240	3.35	42.720	43.535	1.91	38.800	39.149	0.90
SO <sub>3</sub>	0.200	0.199	-0.50	0.800	0.767	-4.13	0.800	0.741	-7.38	0.500	0.486	-2.80
SnO <sub>2</sub>	0.500	0.430	-14.00	0.500	0.471	-5.80	2.500	2.409	-3.64	1.500	1.441	-3.93
V <sub>2</sub> O <sub>5</sub>	0.500	0.480	-4.00	0.500	0.487	-2.60	2.000	2.022	1.10	1.000	0.959	-4.10
ZnO	2.400	2.365	-1.46	2.400	2.365	-1.46	2.400	2.390	-0.42	2.800	2.760	-1.43
ZrO <sub>2</sub>	5.500	4.735	-13.91	5.500	5.045	-8.27	3.000	2.749	-8.37	4.000	3.681	-7.98
Total	100.000	98.618	-1.38	100.020	98.164	-1.86	100.010	98.650	-1.36	100.010	98.774	-1.24

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-IL-17			LP2-OL-01-3			LP2-OL-02-1			LP2-OL-03 MOD2		
Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Al <sub>2</sub> O <sub>3</sub>	9.230	8.678	-5.98	6.000	5.697	-5.05	10.000	9.122	-8.78	10.738	9.773	-8.99
B <sub>2</sub> O <sub>3</sub>	11.000	10.408	-5.38	6.000	6.037	0.62	9.500	9.225	-2.89	6.107	5.691	-6.81
CaO	2.500	2.753	10.12	9.090	8.500	-6.49	5.000	5.069	1.38	10.905	10.802	-0.94
Cl	0.070	0.062	-11.43	0.062	<0.050	--	0.208	0.146	-29.81	0.063	0.067	6.35
Cr <sub>2</sub> O <sub>3</sub>	0.080	0.087	8.75	0.600	0.717	19.50	0.450	0.559	24.22	0.611	0.685	12.11
F	0.110	0.087	-20.91	0.095	0.072	-24.21	0.316	0.260	-17.72	0.097	0.102	5.15
Fe <sub>2</sub> O <sub>3</sub>	0.200	0.165	-17.50	0.000	0.418	--	0.600	1.011	68.50	0.000	0.471	--
K <sub>2</sub> O	0.500	0.558	11.60	0.000	<0.120	--	1.000	0.977	-2.30	0.000	<0.120	--
MgO	1.000	0.970	-3.00	1.350	1.282	-5.04	0.650	0.654	0.62	1.374	1.347	-1.97
Na <sub>2</sub> O	23.000	22.714	-1.24	21.000	19.580	-6.76	23.000	22.748	-1.10	26.464	26.185	-1.05
P <sub>2</sub> O <sub>5</sub>	0.240	0.176	-26.67	0.203	<0.243	--	0.676	0.577	-14.65	0.207	0.180	-13.04
SiO <sub>2</sub>	40.940	41.609	1.63	47.000	47.947	2.01	38.800	41.117	5.97	35.523	34.122	-3.94
SO <sub>3</sub>	1.000	0.954	-4.60	0.1000	0.154	54.00	0.500	0.479	-4.20	0.754	0.725	-3.85
SnO <sub>2</sub>	0.000	<0.127	---	0.000	<0.127	--	1.500	1.717	14.47	2.779	2.965	6.69
V <sub>2</sub> O <sub>5</sub>	2.100	2.089	-0.52	0.000	<0.179	--	1.000	0.952	-4.80	0.000	<0.179	--
ZnO	3.000	2.947	-1.77	2.000	1.923	-3.85	2.800	2.692	-3.86	2.036	2.088	2.55
ZrO <sub>2</sub>	5.030	4.620	-8.15	6.500	5.194	-20.09	4.000	3.451	-13.73	2.342	2.431	3.80
Total	100.000	99.219	-0.78	100.000	98.683	-1.32	100.000	101.099	1.099	100.000	98.276	-1.72

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-OL-04-1			LP2-OL-05			LP2-OL-07-1		
Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Al <sub>2</sub> O <sub>3</sub>	10.500	10.147	-3.36	12.500	11.814	-5.49	10.150	9.523	-6.18
B <sub>2</sub> O <sub>3</sub>	6.000	6.263	4.38	6.000	5.989	-0.18	12.040	12.332	2.43
CaO	7.840	7.283	-7.10	11.000	10.798	-1.84	8.010	8.063	0.66
Cl	0.062	<0.050	--	0.467	0.292	-37.47	0.330	0.204	-38.18
Cr <sub>2</sub> O <sub>3</sub>	0.600	0.628	4.67	0.300	0.385	28.33	0.500	0.584	16.80
Cs <sub>2</sub> O	0.000	--	--	0.000	--	--	0.130	--	--
F	0.095	0.079	-16.84	0.708	0.595	-15.96	0.170	0.122	-28.24
Fe <sub>2</sub> O <sub>3</sub>	1.500	1.855	23.67	1.500	1.916	27.73	1.000	1.339	33.90
K <sub>2</sub> O	5.750	5.267	-8.40	0.000	<0.120	--	0.160	0.211	31.88
MgO	1.350	1.251	-7.33	0.000	<0.166	--	1.000	0.983	-1.70
Na <sub>2</sub> O	21.000	19.748	-5.96	21.000	19.007	-9.49	20.980	19.344	-7.80
NiO	0.000	<0.127	--	0.000	<0.127	--	0.040	<0.127	--
P <sub>2</sub> O <sub>5</sub>	0.203	<0.241	--	1.515	1.461	-3.56	0.290	0.261	-10.00
SiO <sub>2</sub>	34.900	36.037	3.26	39.080	40.641	3.99	37.140	37.502	0.97
SO <sub>3</sub>	0.100	0.154	54.00	0.980	0.929	-5.20	1.060	1.011	-4.62
SnO <sub>2</sub>	0.000	<0.127	--	0.000	<0.127	--	0.000	<0.127	--
V <sub>2</sub> O <sub>5</sub>	0.000	<0.179	--	0.000	<0.179	--	1.000	0.929	-7.10
ZnO	3.600	3.457	-3.97	2.000	1.998	-0.10	3.000	3.053	1.77
ZrO <sub>2</sub>	6.500	5.545	-14.69	2.950	2.161	-26.75	3.000	2.452	-18.27
Total	100.000	98.652	-1.35	100.000	98.922	-1.08	100.000	98.382	-1.62

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-OL-08 MOD			LP2-OL-09-1			LP2-OL-10 MOD			LP2-OL-11		
	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Component												
Al <sub>2</sub> O <sub>3</sub>	6.121	5.763	-5.85	12.500	11.876	-4.99	12.523	11.441	-8.64	6.000	5.508	-8.20
B <sub>2</sub> O <sub>3</sub>	6.121	6.037	-1.37	13.750	13.805	0.40	6.011	5.627	-6.39	13.750	13.242	-3.69
CaO	10.879	10.532	-3.19	2.000	1.948	-2.60	11.020	10.721	-2.71	7.990	7.832	-1.98
Cl	0.060	0.063	-5.00	0.062	<0.050	--	0.468	0.378	-19.23	0.062	0.051	-17.74
Cr <sub>2</sub> O <sub>3</sub>	0.612	0.694	13.40	0.600	0.691	15.17	0.301	0.404	34.22	0.300	0.402	34.00
F	0.097	0.077	-20.62	0.095	0.067	-29.47	0.709	0.648	-8.60	0.095	0.077	-18.95
Fe <sub>2</sub> O <sub>3</sub>	1.530	1.891	23.60	0.000	0.570	--	1.503	1.919	27.68	0.000	0.330	--
K <sub>2</sub> O	0.000	<0.120	--	0.000	<0.120	--	0.000	<0.120	--	5.750	5.336	-7.20
MgO	0.000	<0.166	--	0.000	<0.166	--	0.000	<0.166	--	1.350	1.332	-1.33
Na <sub>2</sub> O	26.524	24.904	-6.11	21.000	19.175	-8.69	21.038	20.523	-2.45	21.000	20.153	-4.03
P <sub>2</sub> O <sub>5</sub>	0.207	0.227	9.66	0.203	<0.241	--	1.518	1.723	13.5	0.203	0.234	15.3
SiO <sub>2</sub>	35.604	35.486	-0.33	39.190	39.978	2.01	39.151	38.454	-1.78	34.900	36.646	5.00
SO <sub>3</sub>	0.816	0.633	-22.43	0.100	0.108	8.00	0.800	0.718	-10.25	0.100	0.147	47.00
SnO <sub>2</sub>	0.000	0.472	--	1.550	1.536	-0.90	0.000	0.262	--	0.000	0.265	--
V <sub>2</sub> O <sub>5</sub>	4.081	3.945	-3.33	4.000	3.776	-5.60	0.000	<0.179	--	0.000	<0.179	--
ZnO	2.040	2.020	-0.98	2.000	1.945	-2.75	2.004	2.013	0.45	2.000	1.957	-2.15
ZrO <sub>2</sub>	5.305	5.268	-0.70	2.950	2.060	-30.17	2.955	3.033	2.64	6.500	5.187	-20.20
Total	100.000	98.637	-1.36	100.000	98.455	-1.55	100.000	98.673	-1.33	100.000	99.220	-0.78

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID		LP2-OL-12			LP2-OL-13			LP2-OL-14			LP2-OL-15		
Component		Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff
Al <sub>2</sub> O <sub>3</sub>		6.000	5.768	-3.87	6.000	5.621	-6.32	6.000	5.541	-7.65	6.000	5.796	-3.40
B <sub>2</sub> O <sub>3</sub>		13.750	13.741	-0.07	6.000	5.933	-1.12	13.750	13.717	-0.24	13.750	13.894	1.05
CaO		7.991	7.930	-0.76	11.000	10.886	-1.04	7.171	7.125	-0.64	11.000	10.662	-3.07
Cl		0.467	0.348	-25.48	0.467	0.299	-35.97	0.062	<0.053	--	0.062	<0.054	--
Cr <sub>2</sub> O <sub>3</sub>		0.600	0.688	14.67	0.300	0.374	24.67	0.600	0.671	11.83	0.600	0.692	15.33
F		0.708	0.586	-17.23	0.708	0.595	-15.96	0.095	0.070	-26.32	0.095	0.070	-26.32
Fe <sub>2</sub> O <sub>3</sub>		1.500	1.862	24.13	0.000	0.365	--	0.000	0.286	--	1.500	2.009	33.93
K <sub>2</sub> O		0.000	<0.120	--	5.750	5.562	-3.27	5.750	5.580	-2.96	0.000	<0.120	--
MgO		1.350	1.324	-1.93	0.000	<0.166	--	0.000	<0.166	--	0.000	<0.166	--
Na <sub>2</sub> O		25.941	24.331	-6.21	22.205	20.523	-7.58	21.000	18.939	-9.81	21.000	19.142	-8.85
P <sub>2</sub> O <sub>5</sub>		1.515	1.431	-5.55	1.515	1.760	16.17	0.203	<0.233	--	0.203	<0.232	--
SiO <sub>2</sub>		35.128	36.336	3.44	35.405	35.208	-0.56	34.900	33.737	-3.33	35.640	36.459	2.30
SO <sub>3</sub>		0.100	0.137	37.00	0.100	0.102	2.00	1.519	1.503	-1.05	0.100	0.119	19.00
SnO <sub>2</sub>		0.000	<0.127	--	0.000	0.277	--	0.000	<0.127	--	3.500	3.463	-1.06
V <sub>2</sub> O <sub>5</sub>		0.000	<0.179	--	4.000	3.963	-0.93	4.000	3.974	-0.65	0.000	<0.179	--
ZnO		2.000	2.013	0.65	3.600	3.675	2.08	2.000	2.017	0.85	3.600	3.551	-1.36
ZrO <sub>2</sub>		2.950	2.148	-27.19	2.950	2.499	-15.29	2.950	1.898	-35.66	2.950	2.080	-29.49
Total		100.000	98.437	-1.56	100.000	98.149	-1.85	100.000	95.977	-4.02	100.000	99.028	-0.97

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-OL-16 MOD			LP2-OL-17			LP2-OL-18			LP2-OL-19		
	Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)
Al <sub>2</sub> O <sub>3</sub>	6.008	5.475	-8.87	6.000	5.720	-4.67	6.000	5.772	-3.80	6.000	5.692	-5.13
B <sub>2</sub> O <sub>3</sub>	7.483	7.309	-2.33	6.000	6.182	3.03	6.000	5.925	-1.25	6.000	6.037	0.62
CaO	3.054	3.064	0.33	4.550	4.345	-4.51	8.720	8.626	-1.08	3.345	3.505	4.78
Cl	0.062	0.052	-16.13	0.467	0.329	-29.55	0.470	0.318	-32.34	0.062	0.055	-11.29
Cr <sub>2</sub> O <sub>3</sub>	0.601	0.710	18.14	0.300	0.378	26.00	0.600	0.657	9.50	0.300	0.424	41.33
F	0.095	0.075	-21.05	0.708	0.603	-14.83	0.710	0.630	-11.27	0.095	0.081	-14.74
Fe <sub>2</sub> O <sub>3</sub>	1.502	1.880	25.17	1.500	1.769	17.93	0.000	0.462	--	1.500	1.969	31.27
K <sub>2</sub> O	0.000	<0.120	--	5.750	5.388	-6.30	0.000	<0.120	--	5.750	5.641	-1.90
MgO	1.352	1.301	-3.77	1.350	1.288	-4.59	1.350	1.281	-5.11	0.000	<0.166	--
Na <sub>2</sub> O	21.026	20.490	-2.55	22.205	20.523	-7.58	21.000	20.287	-3.40	21.000	19.175	-8.69
P <sub>2</sub> O <sub>5</sub>	0.203	0.204	0.49	1.515	1.463	-3.43	1.520	1.277	-15.99	0.203	0.242	19.21
SiO <sub>2</sub>	47.059	49.894	6.02	37.105	38.037	2.51	34.900	34.111	-2.26	46.499	43.150	-7.20
SO <sub>3</sub>	0.992	0.896	-9.68	0.100	0.138	38.0	1.140	1.003	-12.02	0.796	0.620	-22.11
SnO <sub>2</sub>	0.000	0.440	--	3.500	3.399	-2.89	3.500	3.847	9.91	3.500	3.625	3.57
V <sub>2</sub> O <sub>5</sub>	4.005	3.771	-5.84	4.000	3.834	-4.15	4.000	3.972	-0.70	0.000	<0.179	--
ZnO	3.605	3.439	-4.61	2.000	1.967	-1.65	3.600	3.706	2.94	2.000	2.010	0.50
ZrO <sub>2</sub>	2.954	2.465	-16.55	2.950	2.242	-24.00	6.500	4.903	-24.57	2.950	2.668	-9.56
Total	100.000	101.928	1.93	100.000	97.949	-2.05	100.000	97.242	-2.76	100.000	95.582	-4.42

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-OL-20			LP2-OL-21			LP2-OL-22			LP2-OL-23		
	Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)
Al <sub>2</sub> O <sub>3</sub>	6.000	5.560	-7.33	10.000	9.358	-6.42	7.000	6.514	-6.94	6.000	5.513	-8.12
B <sub>2</sub> O <sub>3</sub>	6.000	5.796	-3.40	9.500	9.434	-0.70	6.000	5.884	-1.93	13.725	13.266	-3.34
CaO	8.050	8.063	0.16	5.000	5.128	2.56	11.000	10.714	-2.60	11.000	10.438	-5.11
Cl	0.062	0.064	3.23	0.208	0.162	-22.12	0.062	<0.050	--	0.062	0.056	-9.68
Cr <sub>2</sub> O <sub>3</sub>	0.300	0.433	44.33	0.450	0.553	22.89	0.300	0.376	25.33	0.300	0.423	41.00
F	0.095	0.081	-14.74	0.316	0.278	-12.03	0.095	0.075	-21.05	0.095	0.072	-24.21
Fe <sub>2</sub> O <sub>3</sub>	0.000	0.535	--	0.600	0.953	58.83	1.500	1.898	26.53	0.000	0.599	--
K <sub>2</sub> O	0.000	<0.120	--	1.000	1.056	5.60	0.000	<0.120	--	0.000	<0.120	--
MgO	0.000	<0.166	--	0.650	0.643	-1.08	0.000	<0.166	--	1.350	1.306	-3.26
Na <sub>2</sub> O	26.000	25.545	-1.75	23.000	21.972	-4.47	21.000	19.243	-8.37	21.000	20.456	-2.59
P <sub>2</sub> O <sub>5</sub>	0.203	0.214	5.42	0.676	0.632	-6.51	0.203	0.275	35.47	0.203	0.195	-3.94
SiO <sub>2</sub>	46.640	44.540	-4.50	38.800	42.096	8.50	36.740	36.320	-1.14	34.900	36.411	4.33
SO <sub>3</sub>	0.100	0.120	20.00	0.500	0.502	0.40	0.100	0.104	4.00	1.315	1.160	-11.79
SnO <sub>2</sub>	0.000	0.258	--	1.500	1.796	19.73	3.500	3.571	2.03	3.500	3.545	1.29
V <sub>2</sub> O <sub>5</sub>	0.000	<0.179	--	1.000	0.951	-4.90	4.000	3.905	-2.38	0.000	<0.179	--
ZnO	3.600	3.716	3.22	2.800	2.742	-2.07	2.000	2.001	0.05	3.600	3.417	-5.08
ZrO <sub>2</sub>	2.950	2.533	14.14	4.000	3.228	-19.30	6.500	5.214	-19.79	2.950	2.573	-12.78
Total	100.000	98.263	-1.74	100.000	101.825	1.83	100.000	96.773	-3.23	100.000	100.072	0.07

Table B.1. Comparison of Targeted and Analyzed LAW Phase 1 Enhanced Glass Compositions (cont.)

Glass ID	LP2-OL-24			LP2-OL-25		
	Component	Targeted (wt%)	Analyzed (wt%)	% Diff	Targeted (wt%)	Analyzed (wt%)
Al <sub>2</sub> O <sub>3</sub>	12.500	11.403	-8.78	6.000	5.782	-3.63
B <sub>2</sub> O <sub>3</sub>	6.000	5.804	-3.27	13.750	13.419	-2.41
CaO	7.245	7.423	2.5	2.578	2.624	1.8
Cl	0.062	0.061	-1.61	0.062	0.058	-6.45
Cr <sub>2</sub> O <sub>3</sub>	0.300	0.421	40.33	0.300	0.402	34.00
F	0.095	0.095	0.00	0.095	0.076	-20.00
Fe <sub>2</sub> O <sub>3</sub>	1.500	1.916	27.73	1.500	1.991	32.73
K <sub>2</sub> O	0.000	<0.120	--	0.000	<0.120	--
MgO	1.350	1.351	0.07	0.000	<0.166	--
Na <sub>2</sub> O	25.195	25.241	0.18	26.000	23.860	-8.23
P <sub>2</sub> O <sub>5</sub>	0.203	0.192	-5.42	0.203	0.279	37.44
SiO <sub>2</sub>	34.900	33.956	-2.71	34.900	35.823	2.65
SO <sub>3</sub>	0.100	0.128	28.00	1.012	0.790	-21.9
SnO <sub>2</sub>	0.000	0.250	--	3.500	3.710	6.00
V <sub>2</sub> O <sub>5</sub>	4.000	4.084	2.10	0.000	<0.179	--
ZnO	3.600	3.809	5.81	3.600	3.535	-1.81
ZrO <sub>2</sub>	2.950	2.627	-10.95	6.500	5.356	-17.60
Total	100.000	99.225	-0.78	100.000	98.511	-1.49

## Appendix C – Viscosity Data

This appendix contains the measured viscosity data for each of the Phase 2 enhanced LAW glasses. The plots shown in this appendix were fitted to the Arrhenius equation

$$\ln(\eta) = A + \frac{B}{T_K} \quad (\text{C.1})$$

where  $A$  and  $B$  are independent of temperature and possibly composition dependent, and temperature ( $T_K$ ) is in K ( $T(^{\circ}\text{C}) + 273.15$ ). If the plots showed curvature, the data would be better fit to the Vogel- Fulcher-Tamman (VFT) model

$$\ln(\eta) = E + \frac{F}{T_k - T_0} \quad (\text{C.2})$$

where  $E$ ,  $F$ , and  $T_0$  are temperature independent and possibly composition dependent coefficients, and  $T_K$  is the temperature in K ( $T(^{\circ}\text{C}) + 273.15$ ). The intent of the figures and Arrhenius equation fits shown in this appendix is mainly to assess trends of the data and provide some observations about whether there may be sufficient curvature in the data to consider VFT fits in the subsequent work that will decide between fitting the viscosity-temperature data to the Arrhenius or VFT equations.

## C.1 Glass LP2-IL-01 Viscosity Data

Table C.1. Viscosity Data for Glass LP2-IL-01

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	25.08	7.027	3.22
1050	70.06	7.559	4.25
950	258.95	8.177	5.56
1150	25.30	7.027	3.23
1250	10.90	6.566	2.39
1150	25.19	7.027	3.23

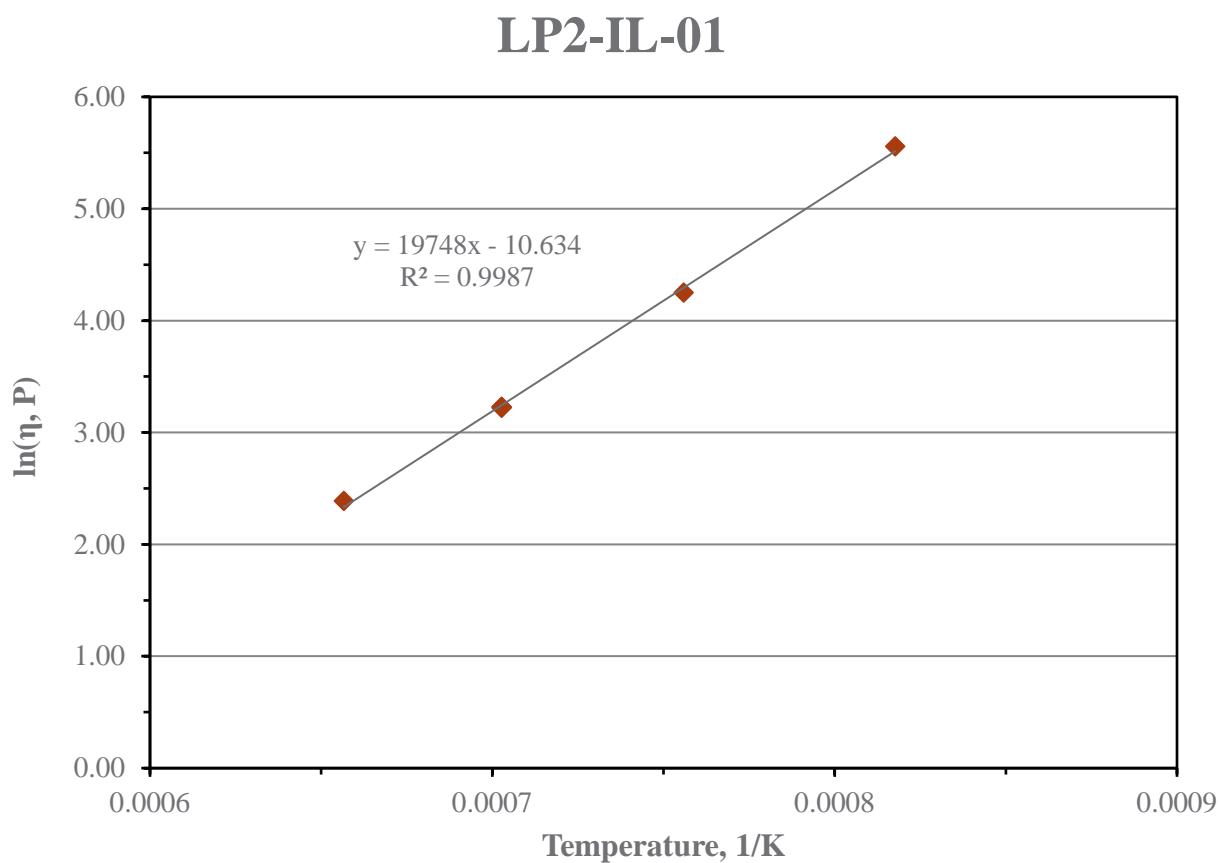


Figure C.1. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-01

## C.2 Glass LP2-IL-02 Viscosity Data

Table C.2. Viscosity Data for Glass LP2-IL-02

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	62.77	7.027	4.14
1050	197.68	7.559	5.29
950	840.62	8.177	6.73
1150	62.88	7.027	4.14
1250	24.67	6.566	3.21
1150	62.52	7.027	4.14

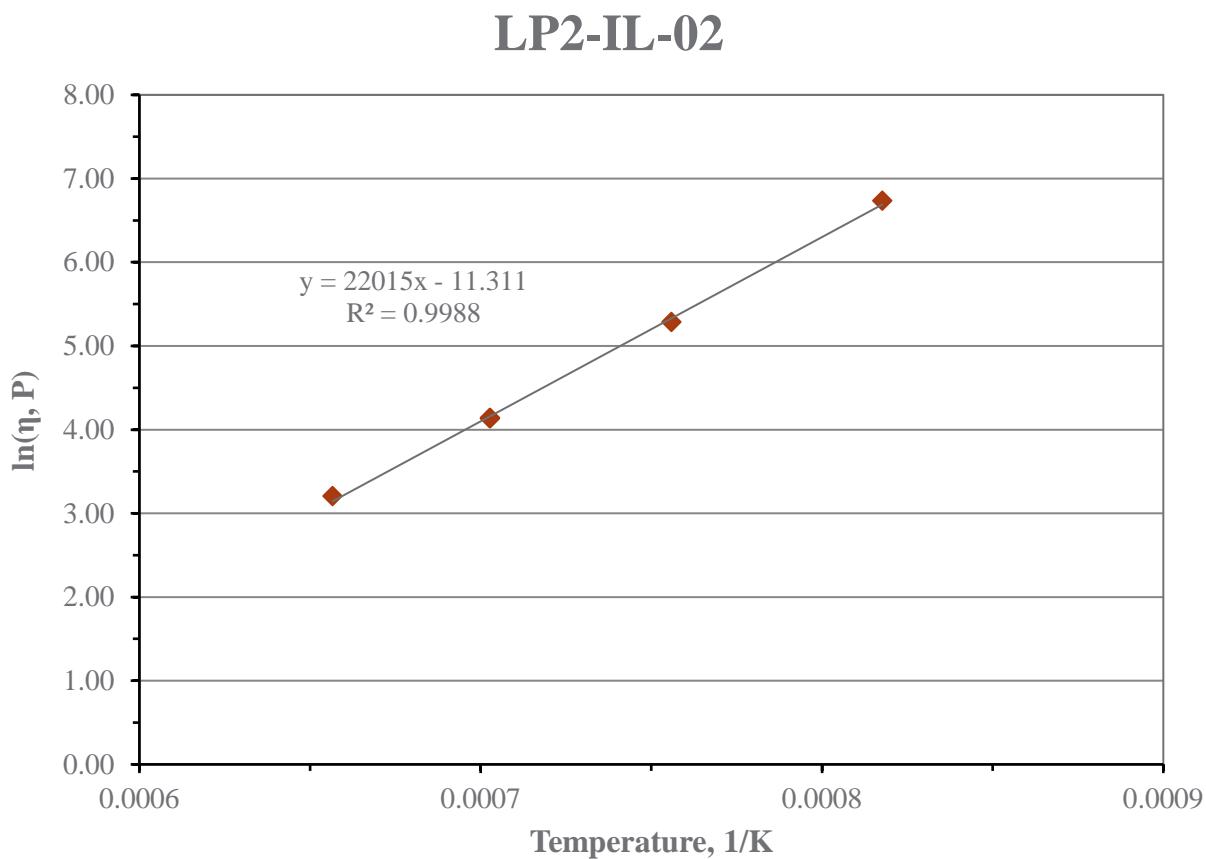


Figure C.2. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-02

### C.3 Glass LP2-IL-03 Viscosity Data

Table C.3. Viscosity Data for Glass LP2-IL-03

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	56.95	7.027	4.04
1050	174.98	7.559	5.17
950	721.65	8.177	6.58
1150	57.08	7.027	4.05
1250	22.52	6.566	3.11
1150	55.96	7.027	4.03

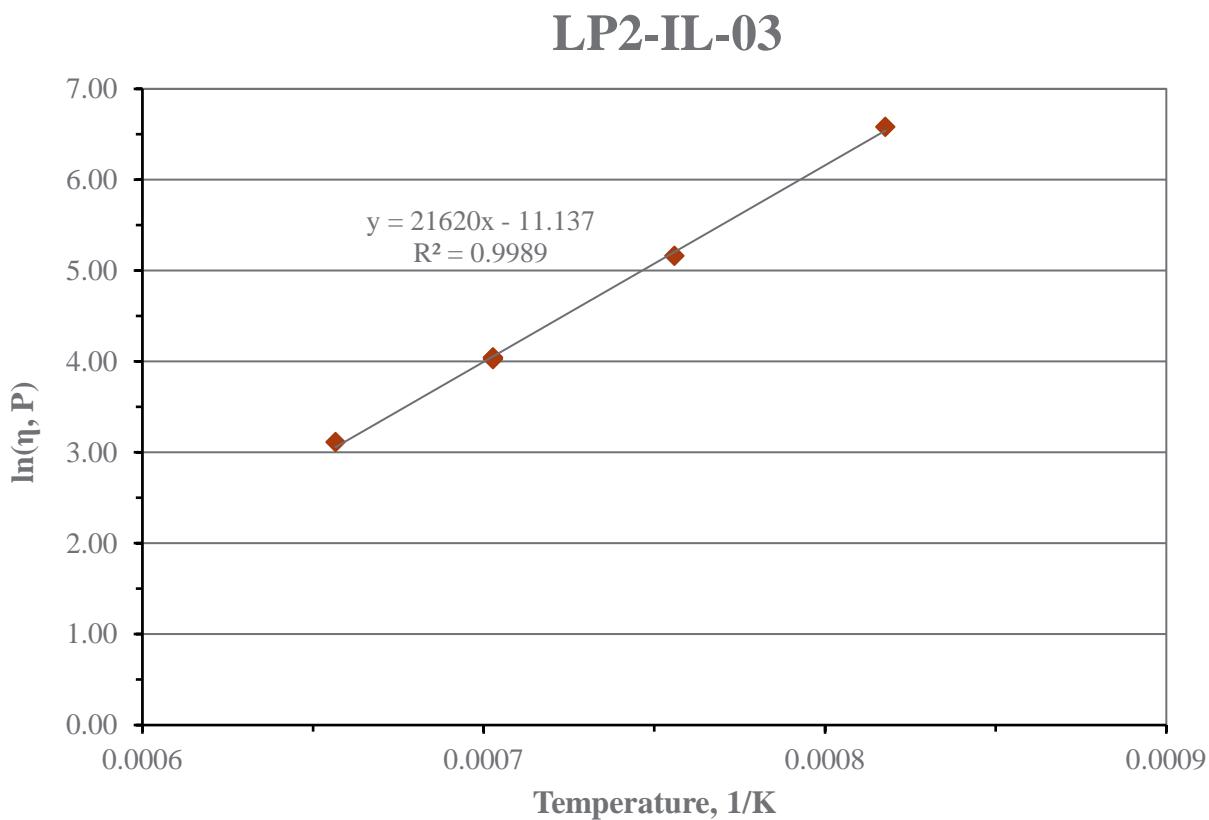


Figure C.3. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-03

## C.4 Glass LP2-IL-04 Viscosity Data

Table C.4. Viscosity Data for Glass LP2-IL-04

Measured Temp., °C	Viscosity, P	1/T x10000, K-1	ln η, P
1150	24.81	7.027	3.21
1050	68.14	7.559	4.22
950	249.00	8.177	5.52
1150	25.10	7.027	3.22
1250	11.10	6.566	2.41
1150	25.26	7.027	3.23

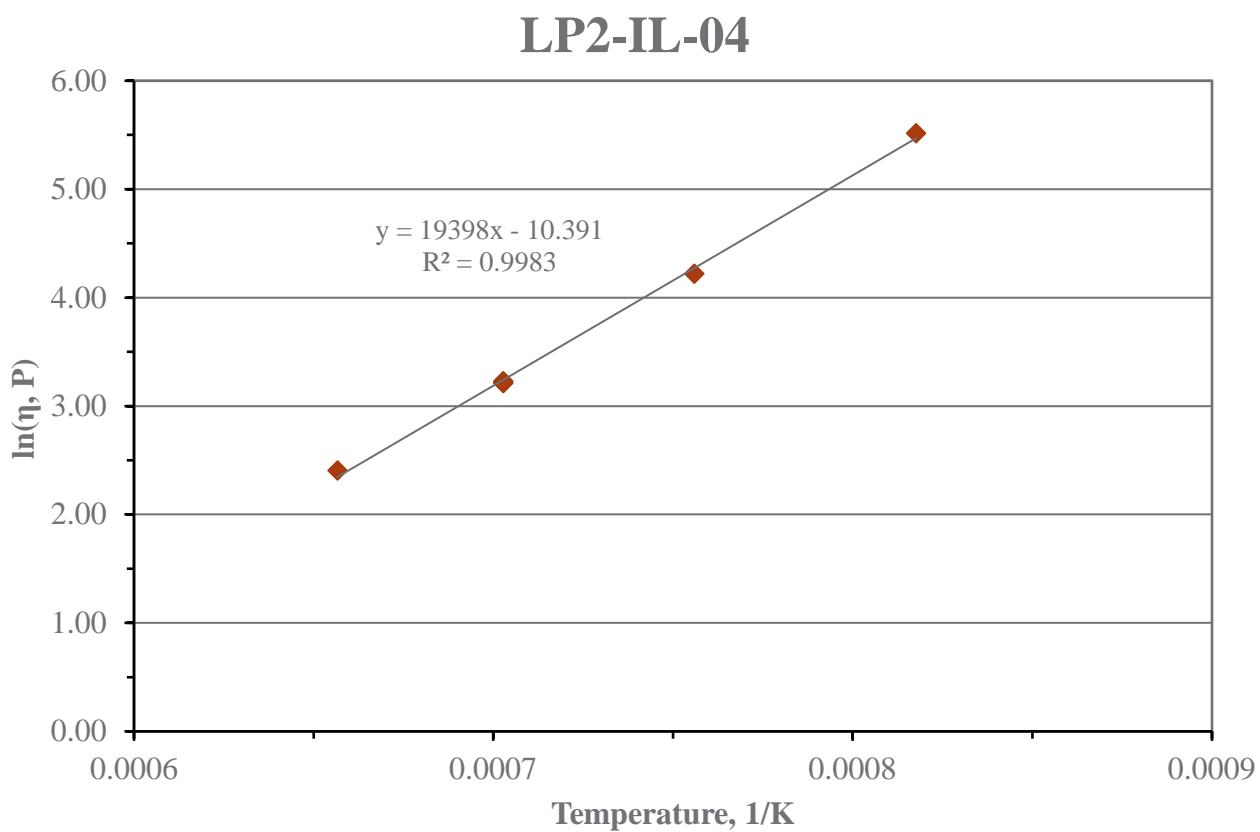


Figure C.4. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-04

## C.5 Glass LP2-IL-05 Viscosity Data

Table C.5. Viscosity Data for Glass LP2-IL-05

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	24.36	7.027	3.19
1050	70.39	7.559	4.25
950	278.41	8.177	5.63
1150	24.60	7.027	3.20
1250	10.60	6.566	2.36
1150	24.70	7.027	3.21

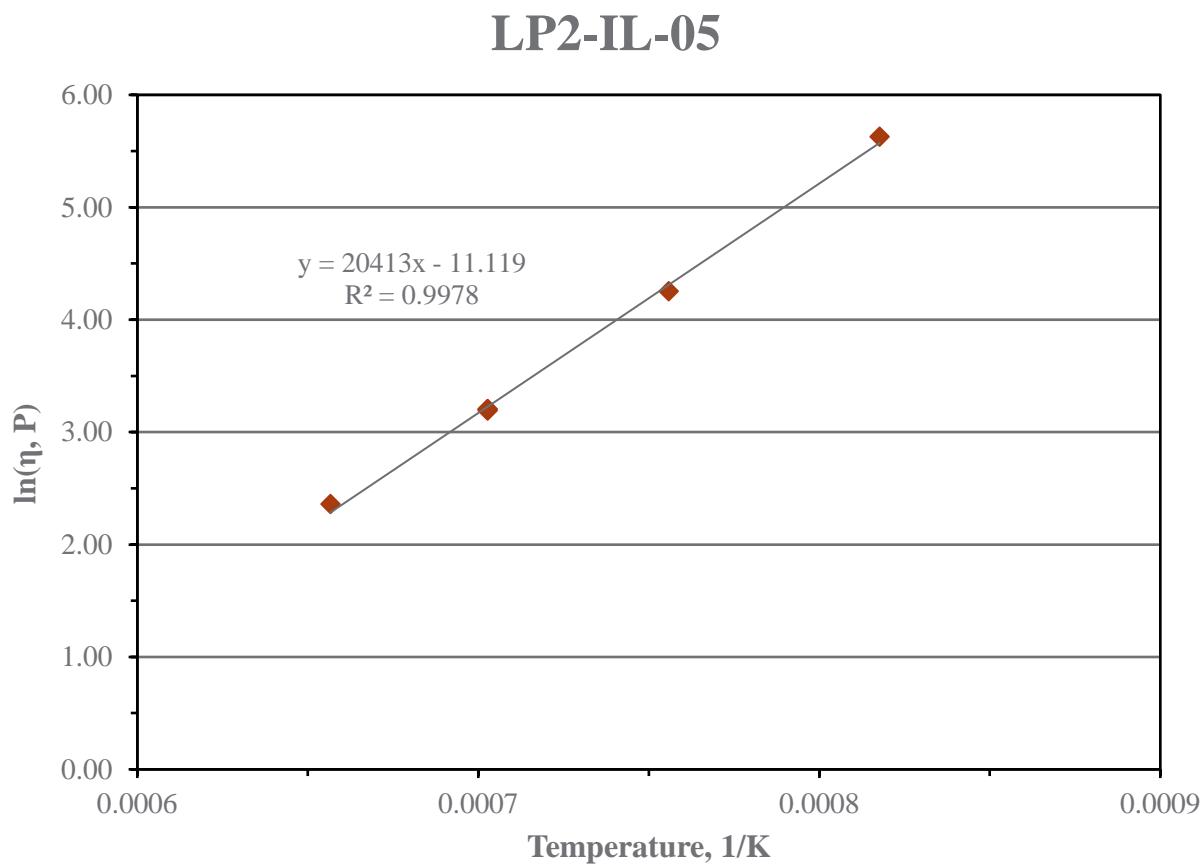


Figure C.5. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-05

## C.6 Glass LP2-IL-06 Viscosity Data

Table C.6. Viscosity Data for Glass LP2-IL-06

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	46.44	7.027	3.84
1050	132.00	7.559	4.88
950	494.40	8.177	6.20
1150	47.11	7.027	3.85
1250	20.21	6.566	3.01
1150	47.42	7.027	3.86

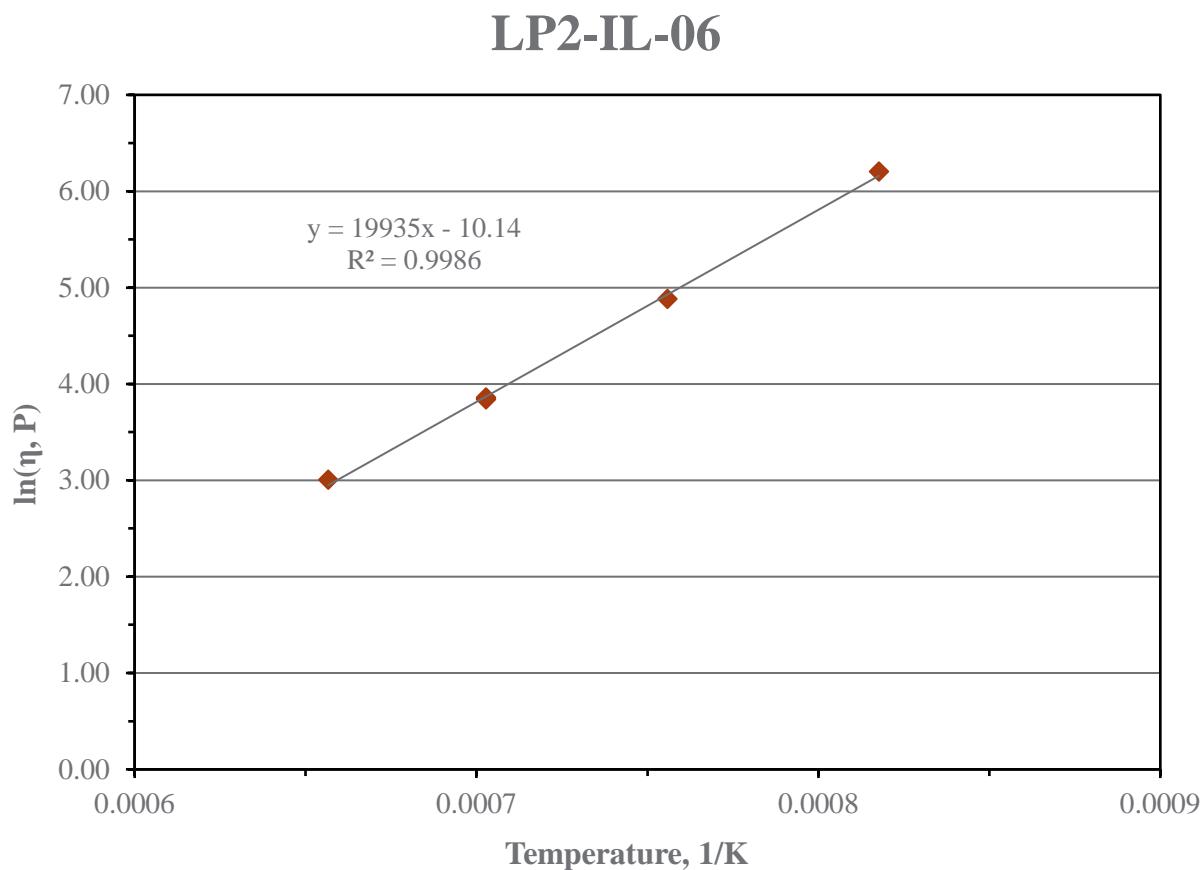


Figure C.6. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-06

## C.7 Glass LP2-IL-07 Viscosity Data

Table C.7. Viscosity Data for Glass LP2-IL-07

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	25.60	7.027	3.24
1050	65.78	7.559	4.19
950	217.62	8.177	5.38
1150	25.97	7.027	3.26
1250	12.20	6.566	2.50
1150	26.19	7.027	3.27

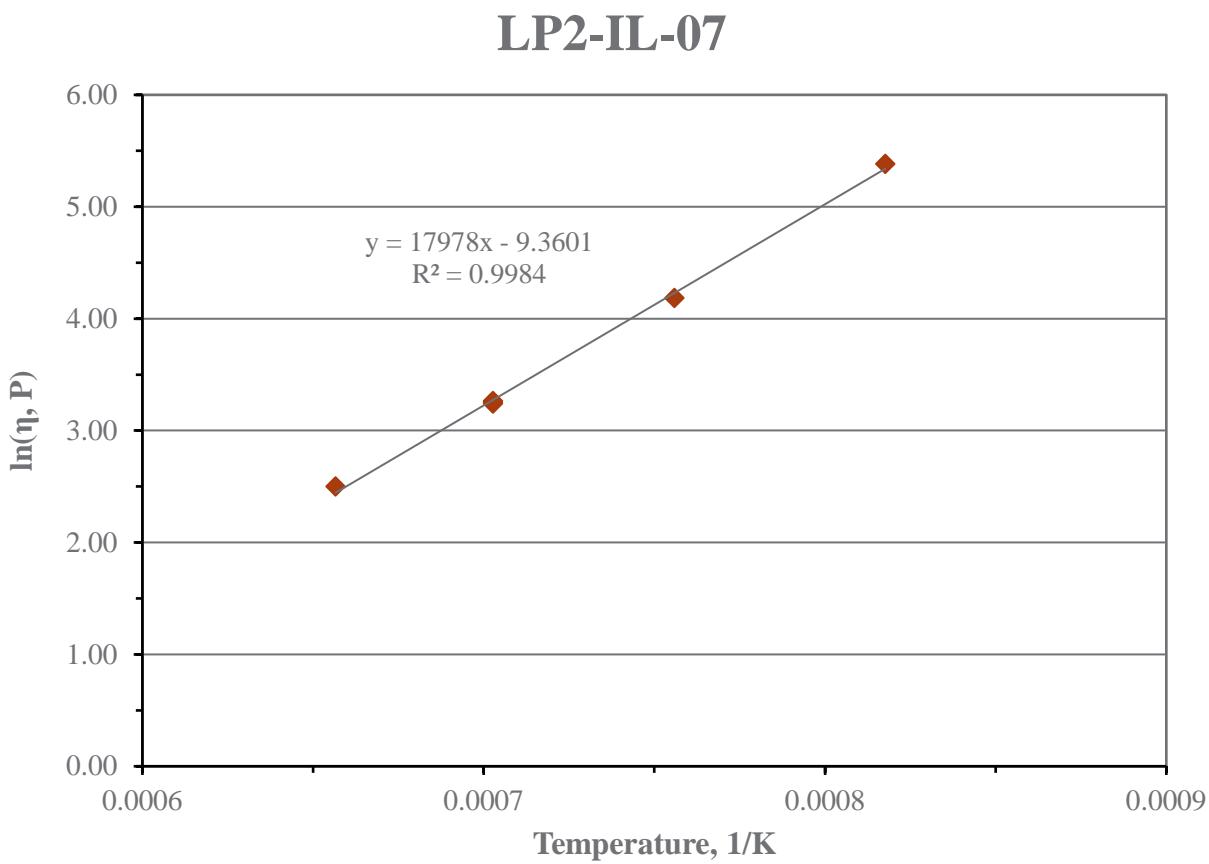


Figure C.7. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-07

## C.8 Glass LP2-IL-08 Viscosity Data

Table C.8. Viscosity Data for Glass LP2-IL-08

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	35.71	7.027	3.58
1050	107.00	7.559	4.67
950	434.12	8.177	6.07
1150	36.09	7.027	3.59
1250	15.00	6.566	2.71
1150	36.20	7.027	3.59

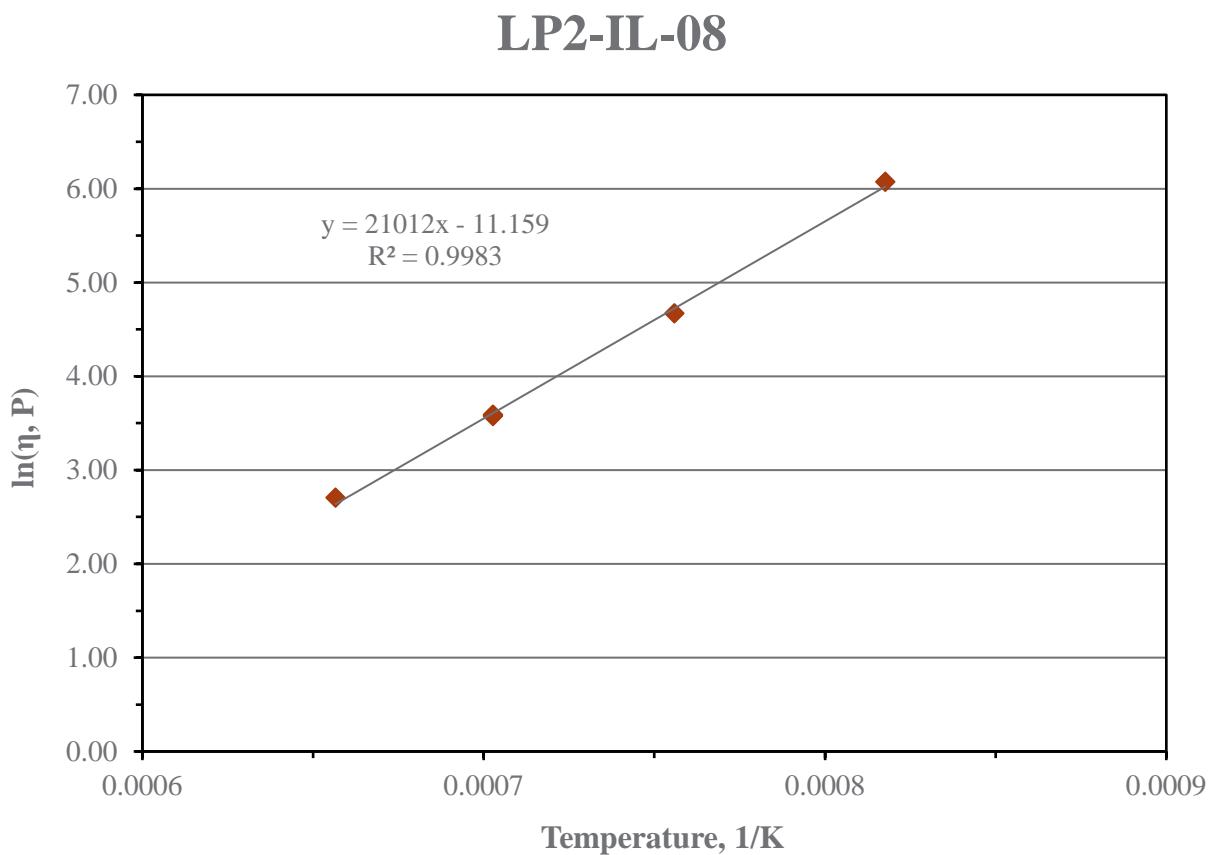


Figure C.8. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-08

## C.9 Glass LP2-IL-09 Viscosity Data

Table C.9. Viscosity Data for Glass LP2-IL-09

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	24.10	7.027	3.18
1050	66.42	7.559	4.20
950	243.00	8.177	5.49
1150	24.22	7.027	3.19
1250	10.80	6.566	2.38
1150	24.30	7.027	3.19

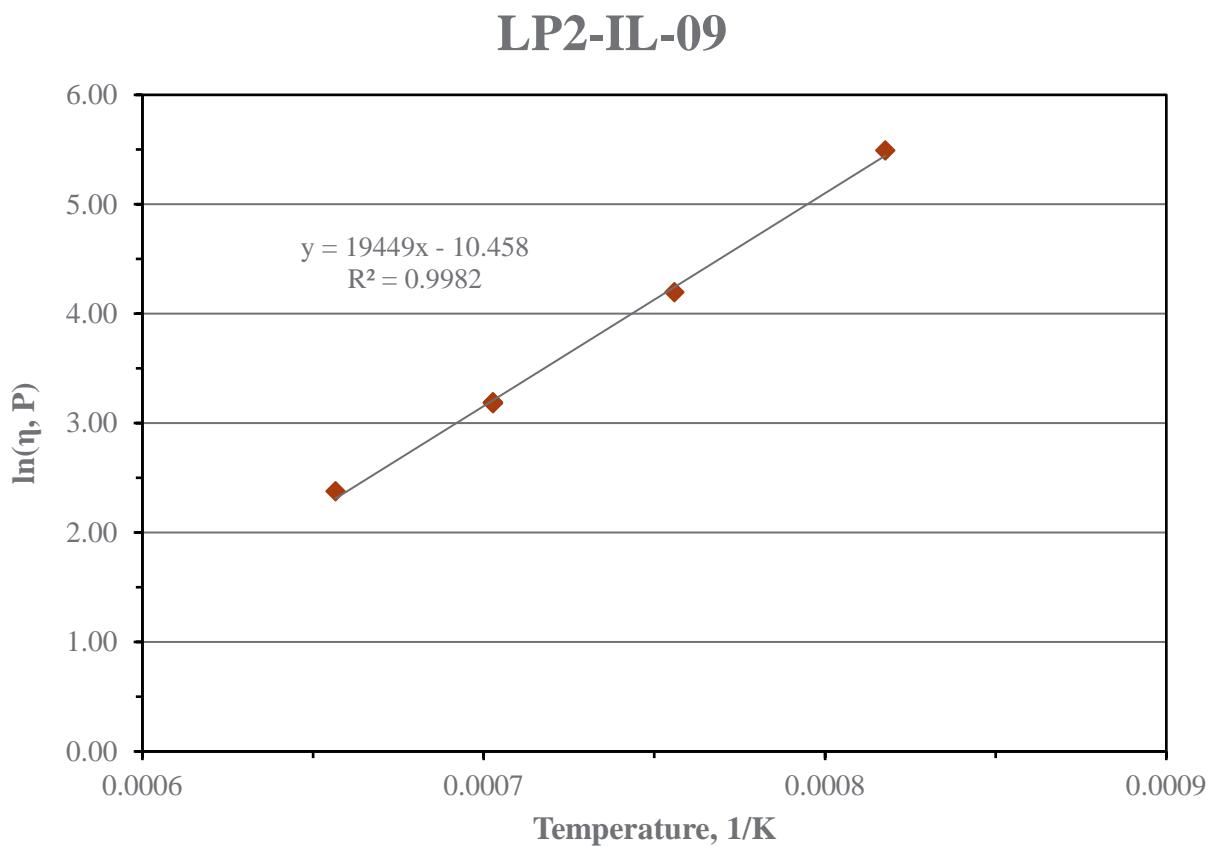


Figure C.9. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-09

## C.10 Glass LP2-IL-10 Viscosity Data

Table C.10. Viscosity Data for Glass LP2-IL-10

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	46.92	7.027	3.85
1050	134.58	7.559	4.90
950	508.79	8.177	6.23
1150	47.28	7.027	3.86
1250	20.11	6.566	3.00
1150	47.25	7.027	3.86

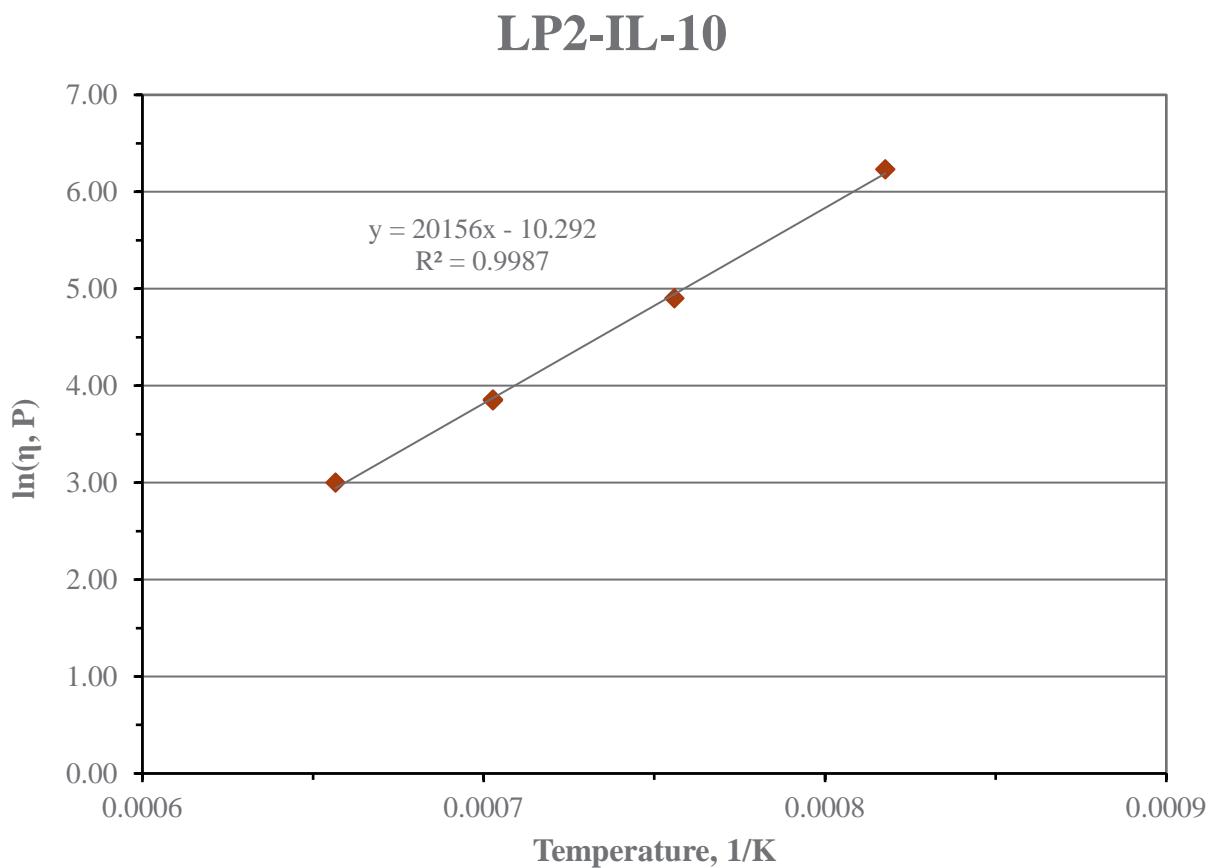


Figure C.10. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-10

## C.11 Glass LP2-IL-11 Viscosity Data

Table C.11. Viscosity Data for Glass LP2-IL-11

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	58.54	7.027	4.07
1050	182.92	7.559	5.21
950	764.97	8.177	6.64
1150	59.06	7.027	4.08
1250	23.86	6.566	3.17
1150	60.26	7.027	4.10

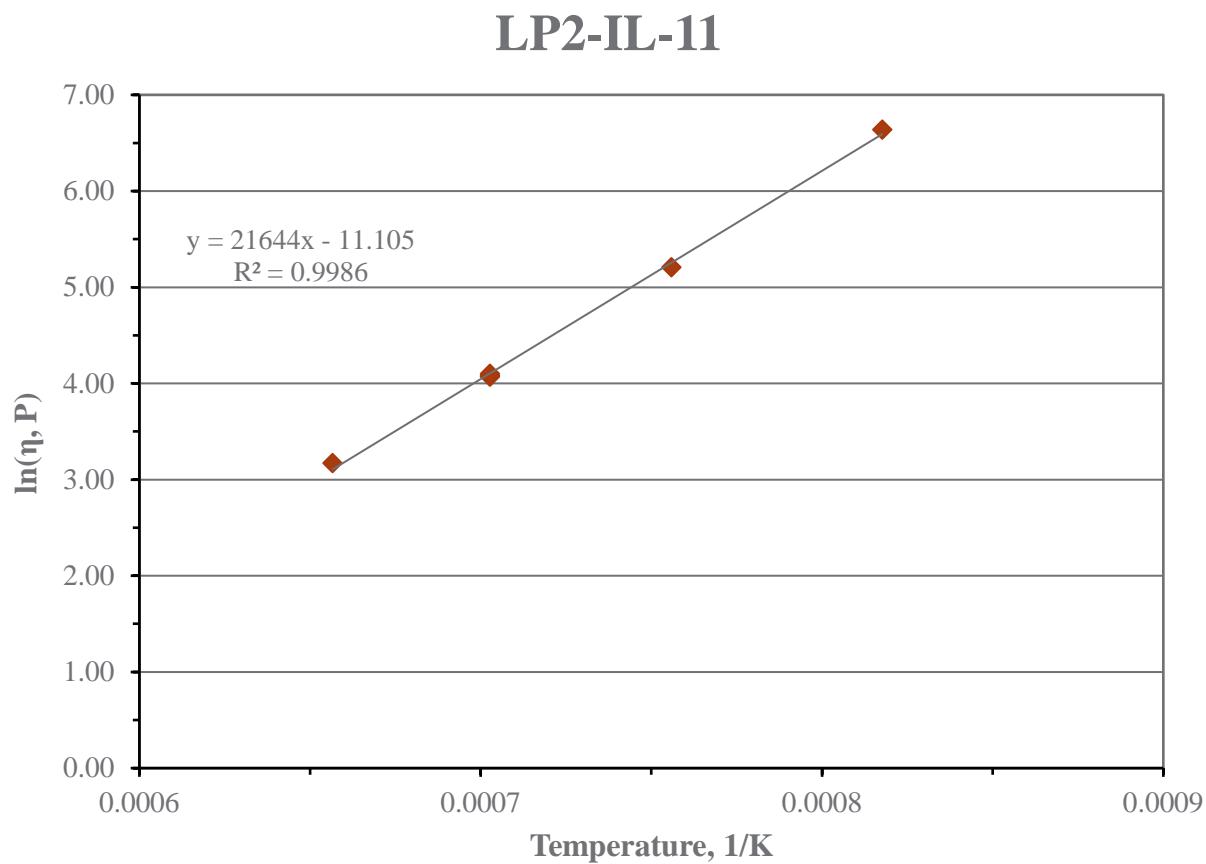


Figure C.11. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-11

## C.12 Glass LP2-IL-12 Viscosity Data

Table C.12. Viscosity Data for Glass LP2-IL-12

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	62.08	7.027	4.13
1050	182.83	7.559	5.21
950	697.66	8.177	6.55
1150	62.59	7.027	4.14
1250	25.96	6.566	3.26
1150	62.54	7.027	4.14

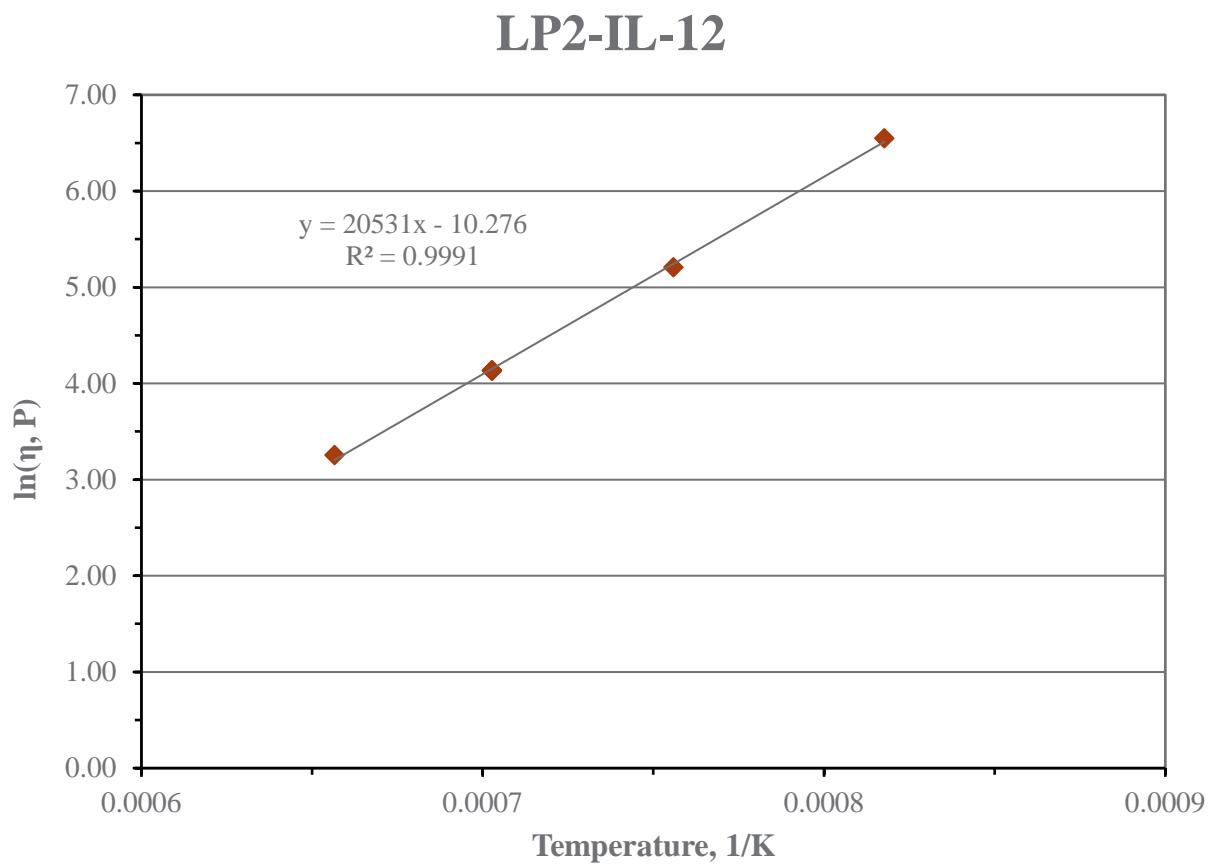


Figure C.12. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-12

## C.13 Glass LP2-IL-13 Viscosity Data

Table C.13. Viscosity Data for Glass LP2-IL-13

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	56.40	7.027	4.03
1050	160.50	7.559	5.08
950	608.71	8.177	6.41
1150	55.99	7.027	4.03
1250	23.91	6.566	3.17
1150	56.01	7.027	4.03

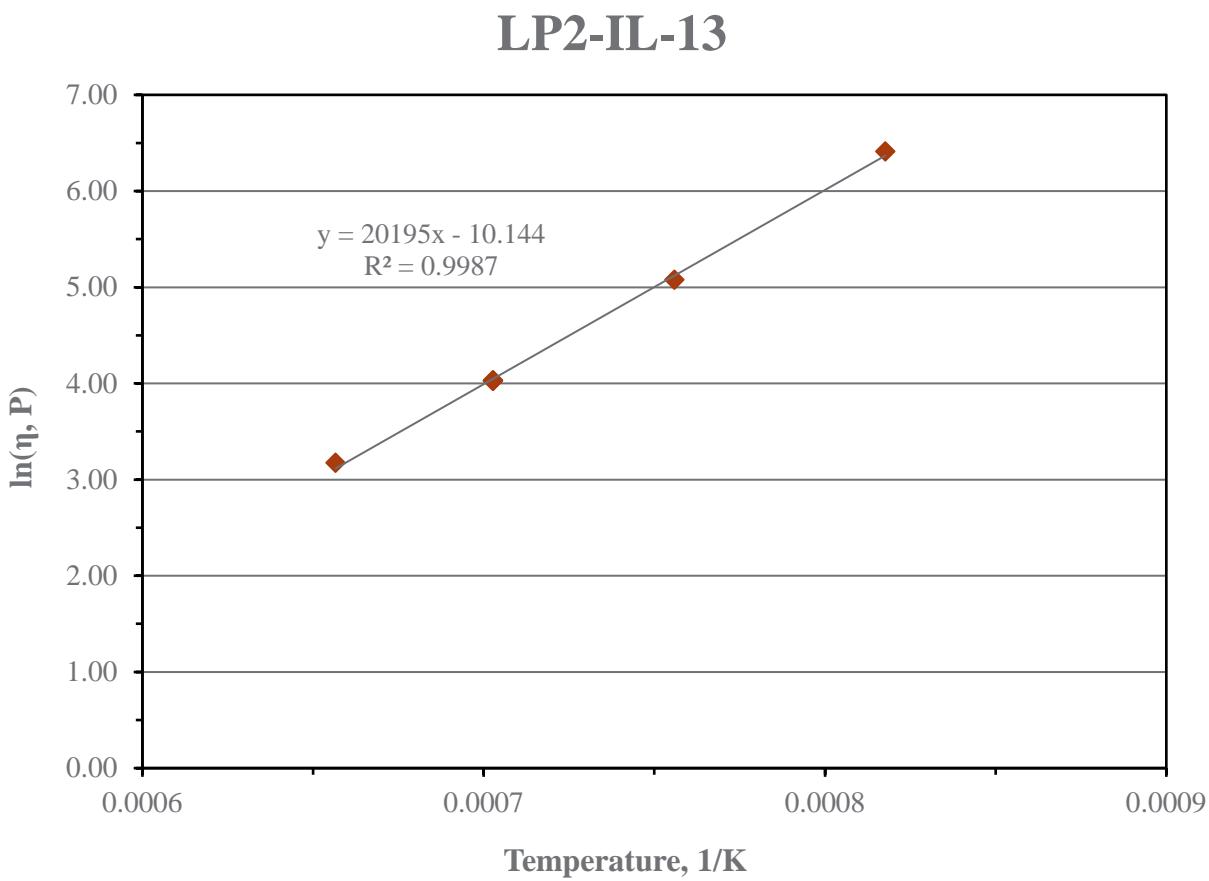


Figure C.13. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-13

## C.14 Glass LP2-IL-14 Viscosity Data

Table C.14. Viscosity Data for Glass LP2-IL-14

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	27.25	7.027	3.31
1050	72.64	7.559	4.29
950	249.22	8.177	5.52
1150	27.56	7.027	3.32
1250	12.56	6.566	2.53
1150	27.91	7.027	3.33

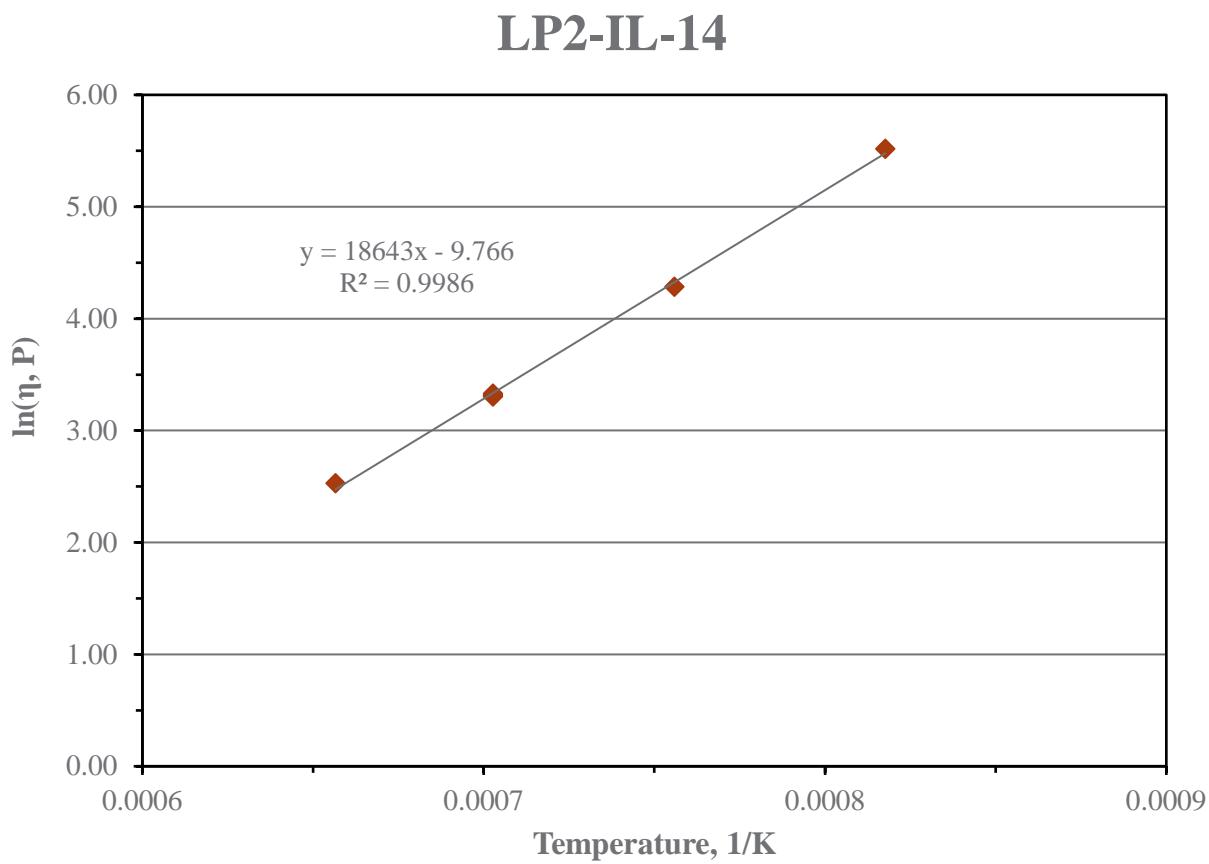


Figure C.14. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-14

## C.15 Glass LP2-IL-15 Viscosity Data

Table C.15. Viscosity Data for Glass LP2-IL-15

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	55.41	7.027	4.01
1050	160.09	7.559	5.08
950	613.20	8.177	6.42
1150	55.38	7.027	4.01
1250	23.70	6.566	3.17
1150	55.78	7.027	4.02

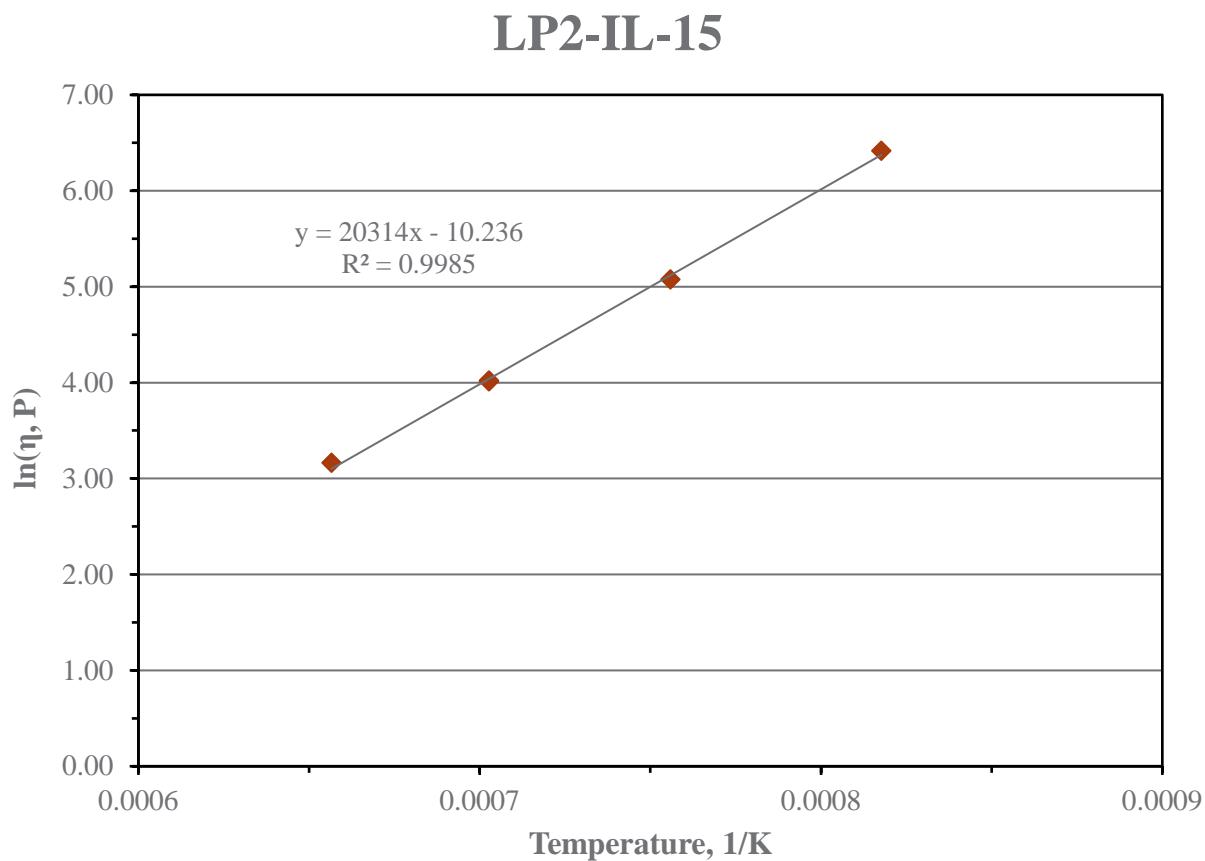


Figure C.15. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-15

## C.16 Glass LP2-IL-16 Viscosity Data

Table C.16. Viscosity Data for Glass LP2-IL-16

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	43.30	7.027	3.77
1050	123.13	7.559	4.81
950	461.02	8.177	6.13
1150	43.81	7.027	3.78
1250	18.62	6.566	2.92
1150	43.67	7.027	3.78

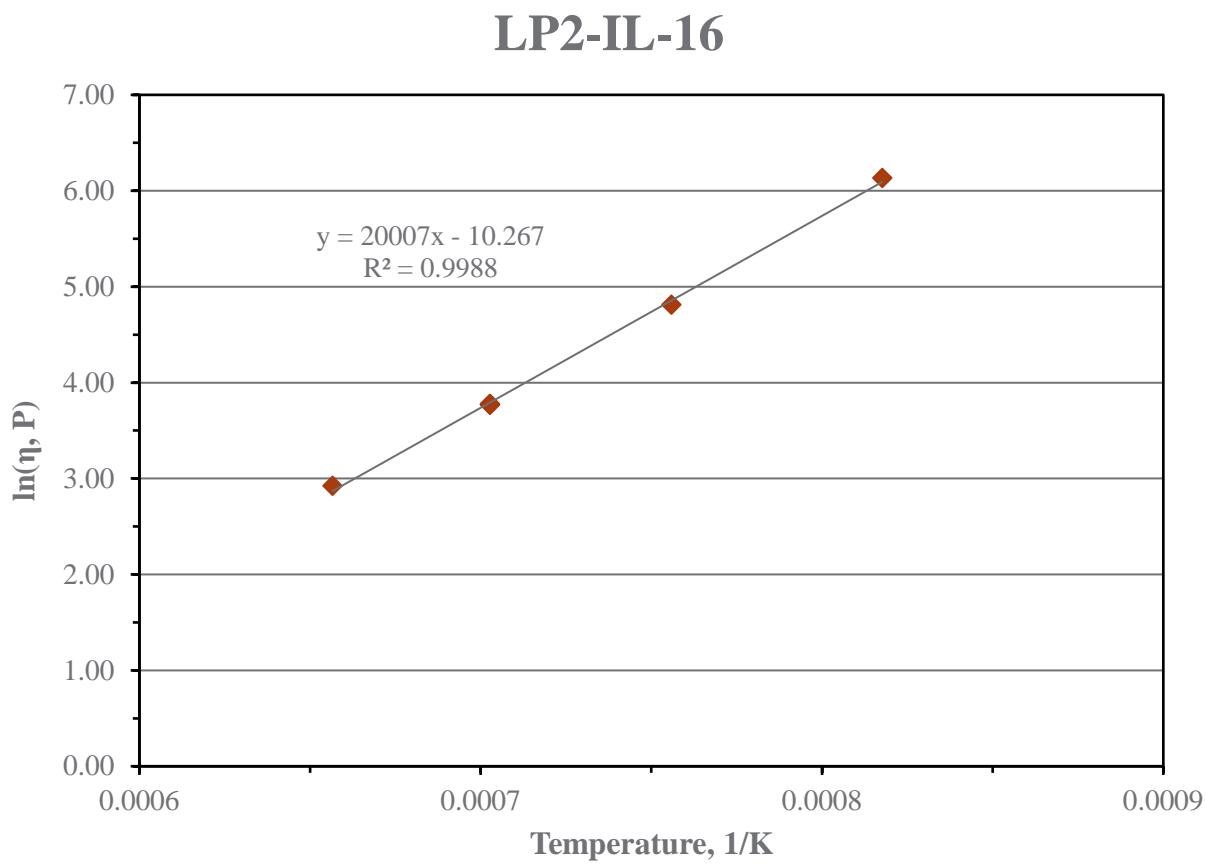


Figure C.16. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-16

## C.17 Glass LP2-IL-17 Viscosity Data

Table C.17. Viscosity Data for Glass LP2-IL-17

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	51.17	7.027	3.94
1050	139.00	7.559	4.93
950	500.00	8.177	6.21
1150	50.44	7.027	3.92
1250	22.34	6.566	3.11
1150	51.31	7.027	3.94

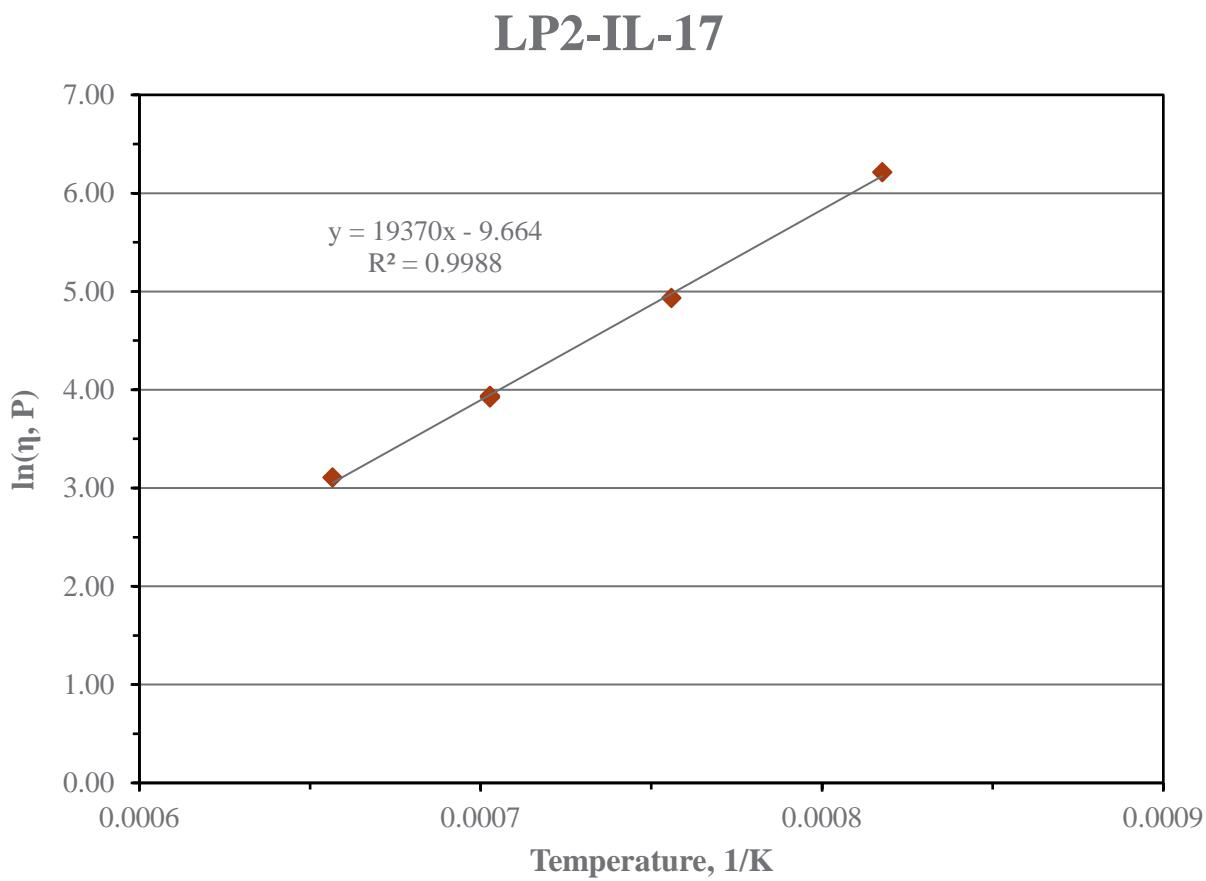


Figure C.17. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-17

## C.18 Glass LP2-OL-01-3 Viscosity Data

Table C.18. Viscosity Data for Glass LP2-OL-01-3

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	85.34	7.027	4.45
1050	287.00	7.559	5.66
950	1390.00	8.177	7.24
1150	85.91	7.027	4.45
1250	32.40	6.566	3.48
1150	86.13	7.027	4.46

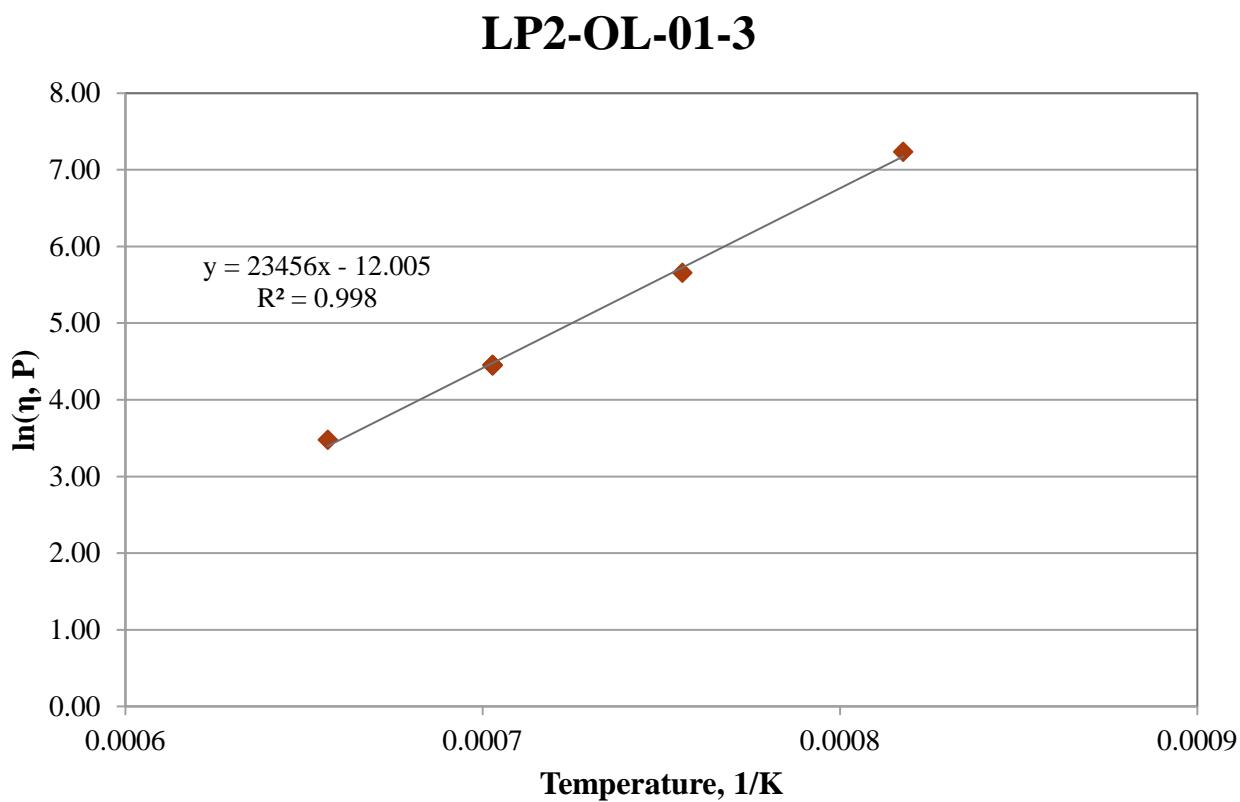


Figure C.18. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-01-3

## C.19 Glass LP2-OL-02-1 Viscosity Data

Table C.19. Viscosity Data for Glass LP2-OL-02-1

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	54.03	7.027	3.99
1050	137.75	7.559	4.93
950	440.75	8.177	6.09
1150	52.80	7.027	3.97
1250	22.93	6.566	3.13
1150	53.84	7.027	3.99

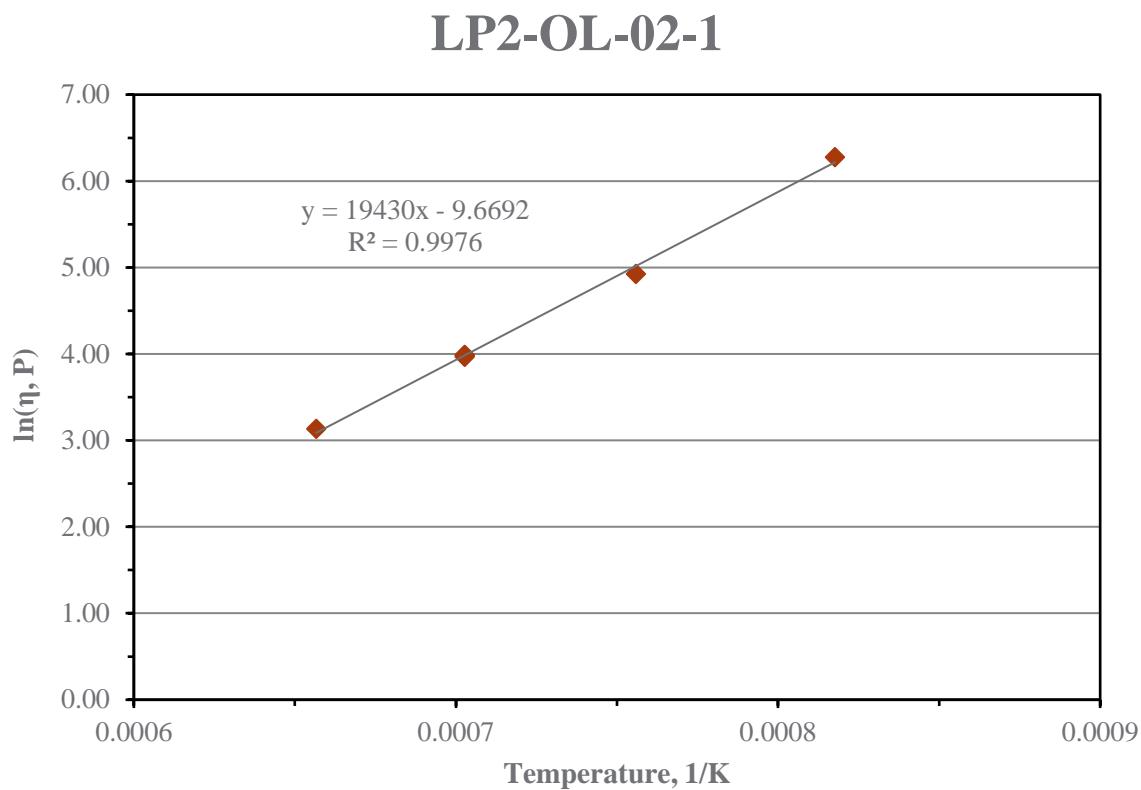


Figure C.19. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-02-1

## C.20 Glass LP2-OL-03 MOD2 Viscosity Data

Table C.20. Viscosity Data for Glass LP2-OL-03 MOD2

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	25.62	7.027	3.24
1050	73.11	7.559	4.29
950	275.07	8.177	5.62
1150	25.87	7.027	3.25
1250	11.10	6.566	2.41
1150	26.04	7.027	3.26

## LP2-OL-03-MOD2

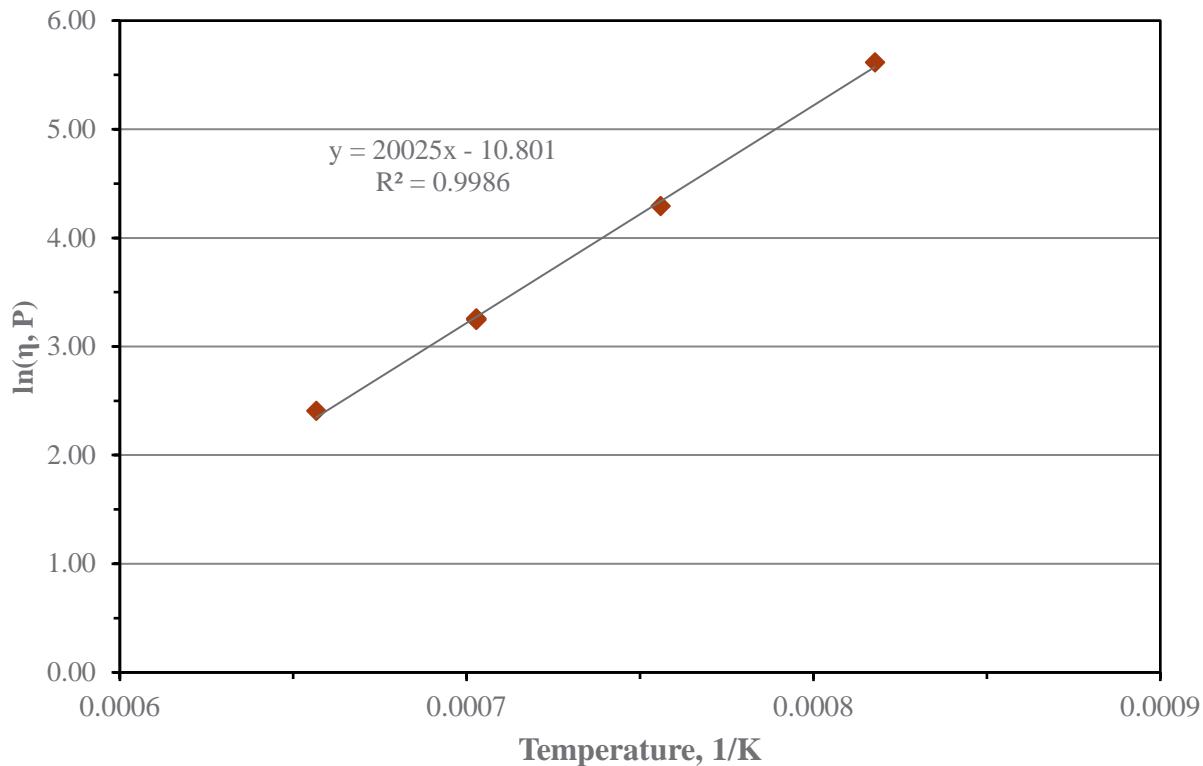


Figure C.20. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-03 MOD2

## C.21 Glass LP2-OL-04-1 Viscosity Data

Table C.21. Viscosity Data for Glass LP2-OL-04-1

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	38.69	7.027	3.66
1050	119.00	7.559	4.78
950	405.53	8.177	6.01
1150	38.80	7.027	3.66
1250	15.79	6.566	2.76
1150	39.79	7.027	3.68

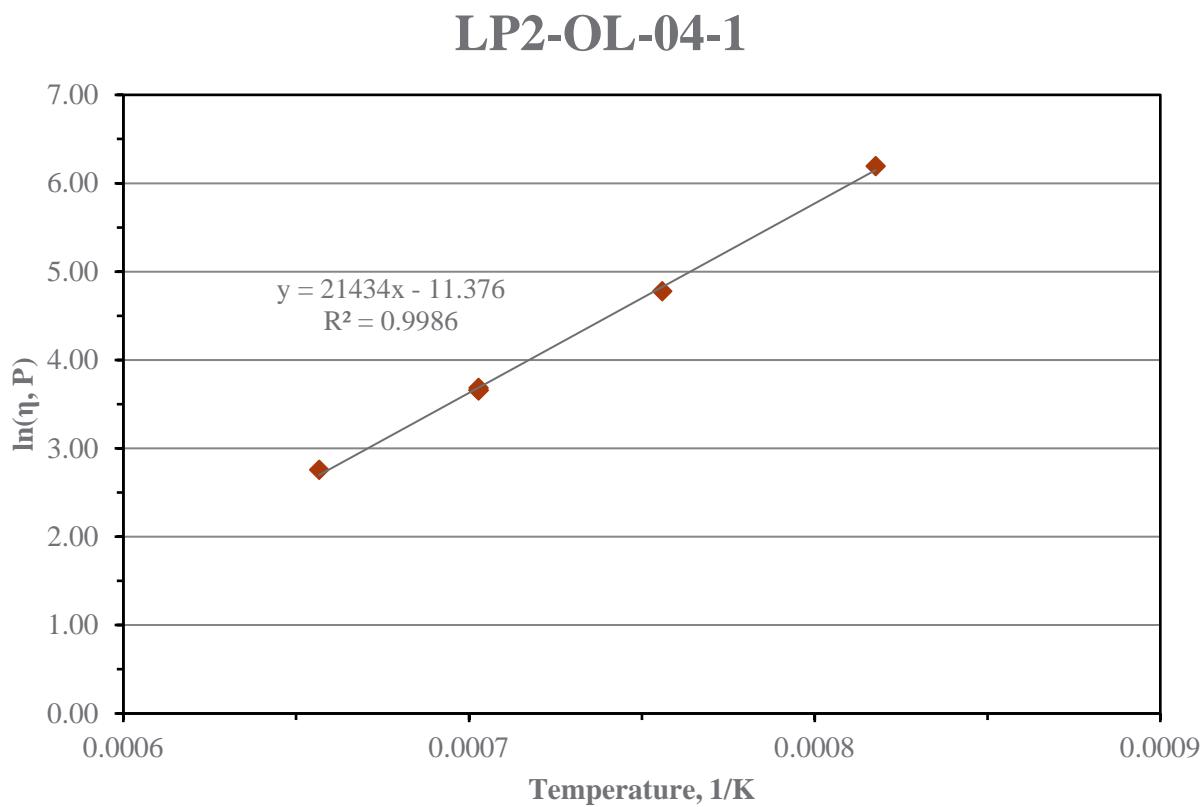


Figure C.21. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-04-1

## C.22 Glass LP2-OL-05 Viscosity Data

Table C.22. Viscosity Data for Glass LP2-OL-05

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	67.67	7.027	4.21
1050	212.00	7.559	5.36
950	1658.69	8.177	7.41
1150	68.44	7.027	4.23
1250	27.72	6.566	3.32
1150	69.97	7.027	4.25

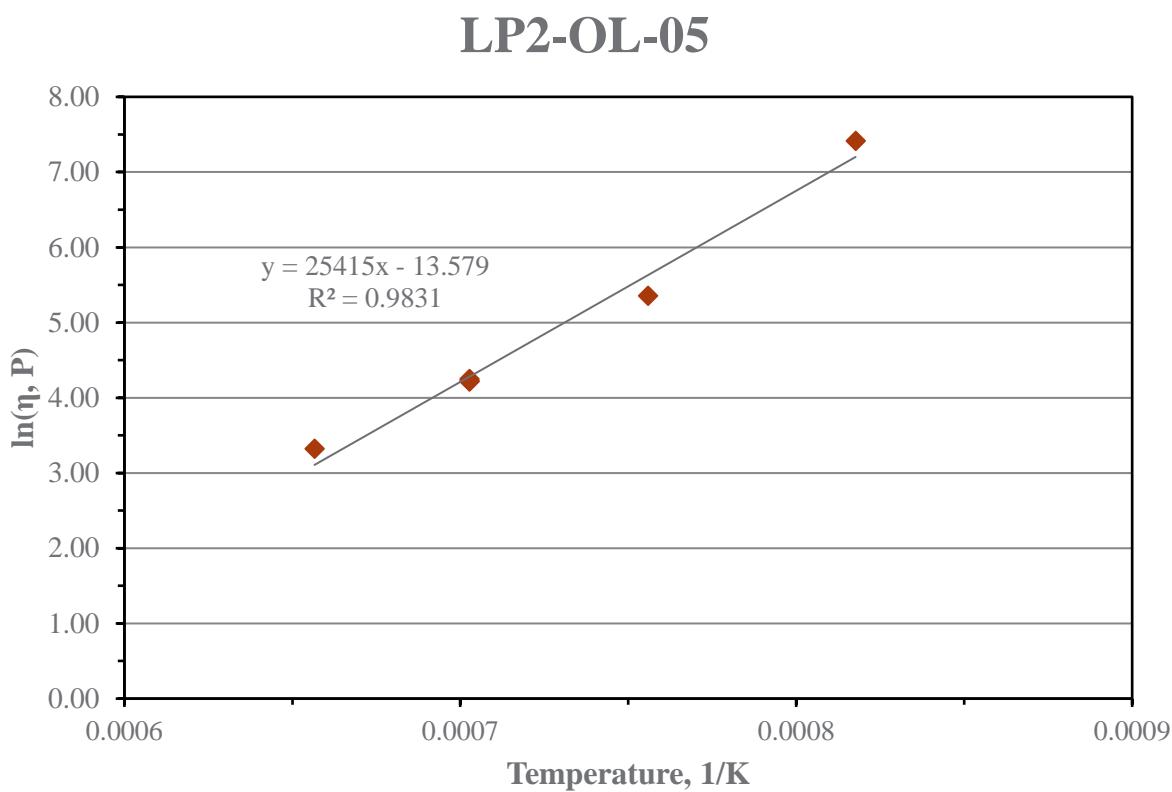


Figure C.22. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-05

## C.23 Glass LP2-OL-07-1 Viscosity Data

Table C.23. Viscosity Data for LP2-OL-07-1

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	29.98	7.027	3.40
1050	77.39	7.559	4.35
950	268.35	8.177	5.59
1150	29.65	7.027	3.39
1250	13.76	6.566	2.62
1150	30.93	7.027	3.43

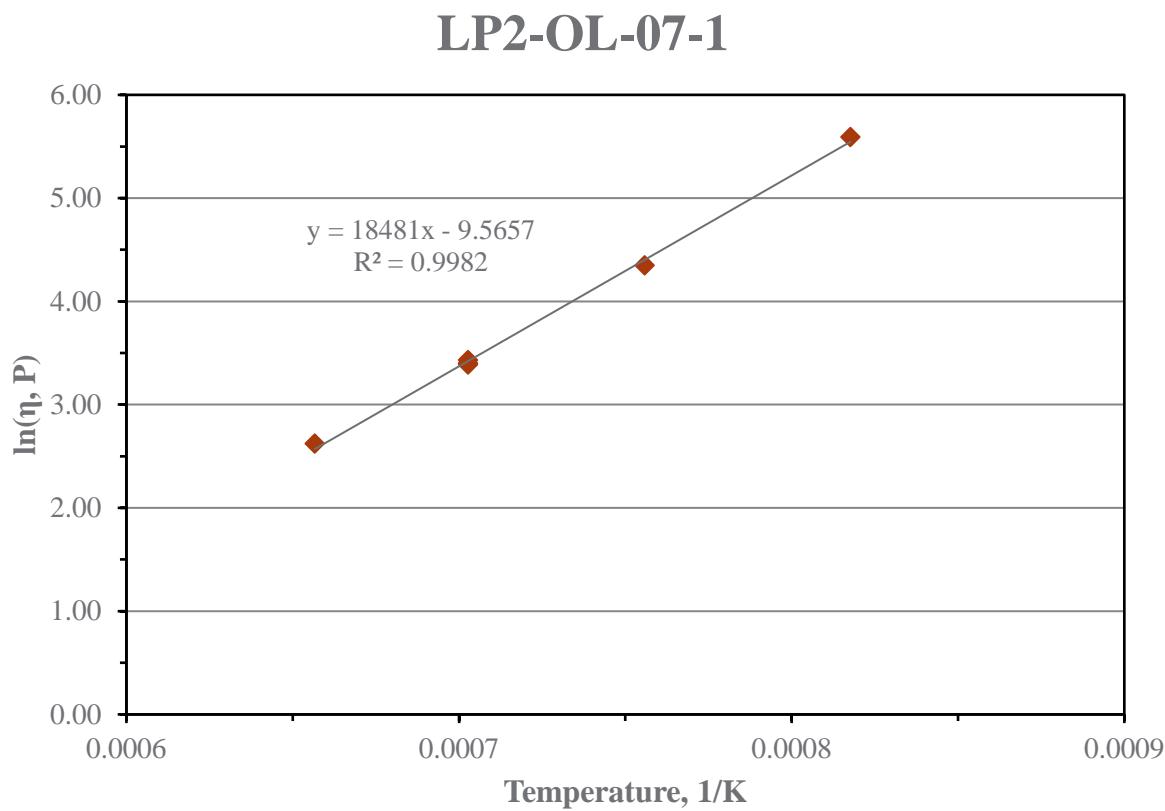


Figure C.23. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-07-1

## C.24 Glass LP2-OL-08 MOD Viscosity Data

Table C.24. Viscosity Data for Glass LP2-OL-08 MOD

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	12.80	7.027	2.55
1050	33.55	7.559	3.51
950	125.19	8.177	4.83
1150	12.90	7.027	2.56
1250	5.90	6.566	1.78
1150	12.81	7.027	2.55

## LP2-OL-08 MOD

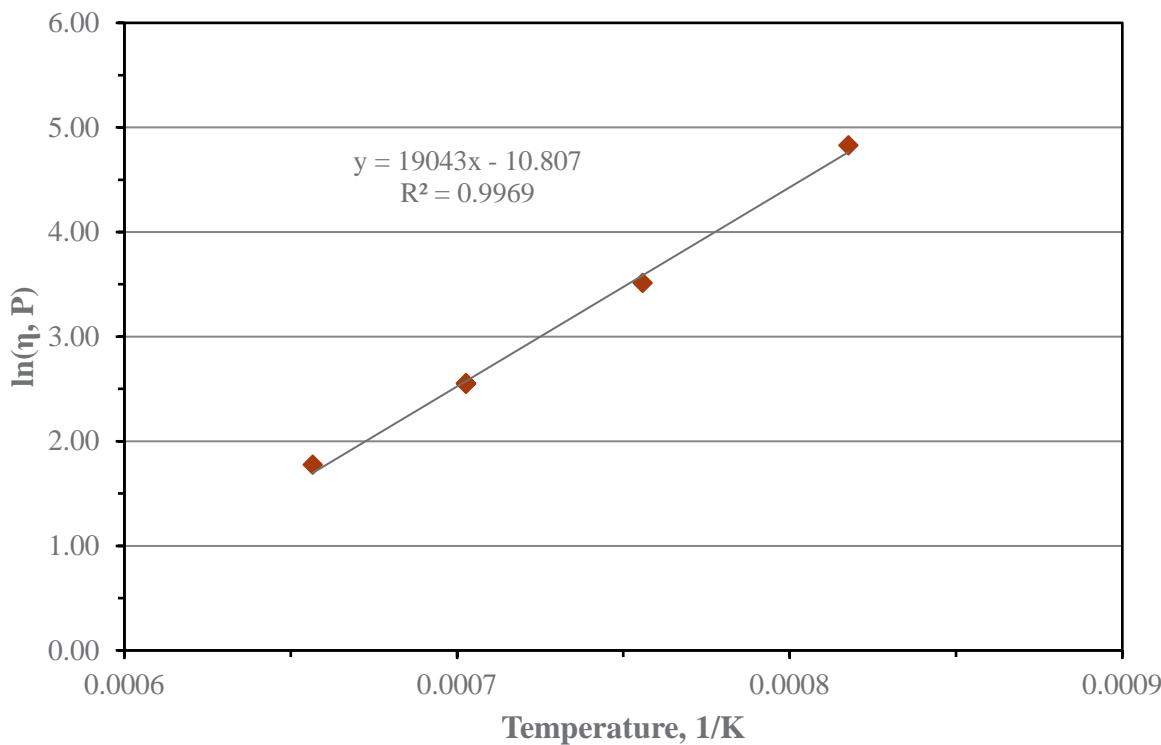


Figure C.24. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-08 MOD

## C.25 Glass LP2-OL-09-1 Viscosity Data

Table C.25. Viscosity Data for Glass LP2-OL-09-1

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	63.77	7.027	4.16
1050	170.30	7.559	5.14
950	630.37	8.177	6.45
1150	63.78	7.027	4.16
1250	28.55	6.566	3.35
1150	64.59	7.027	4.17

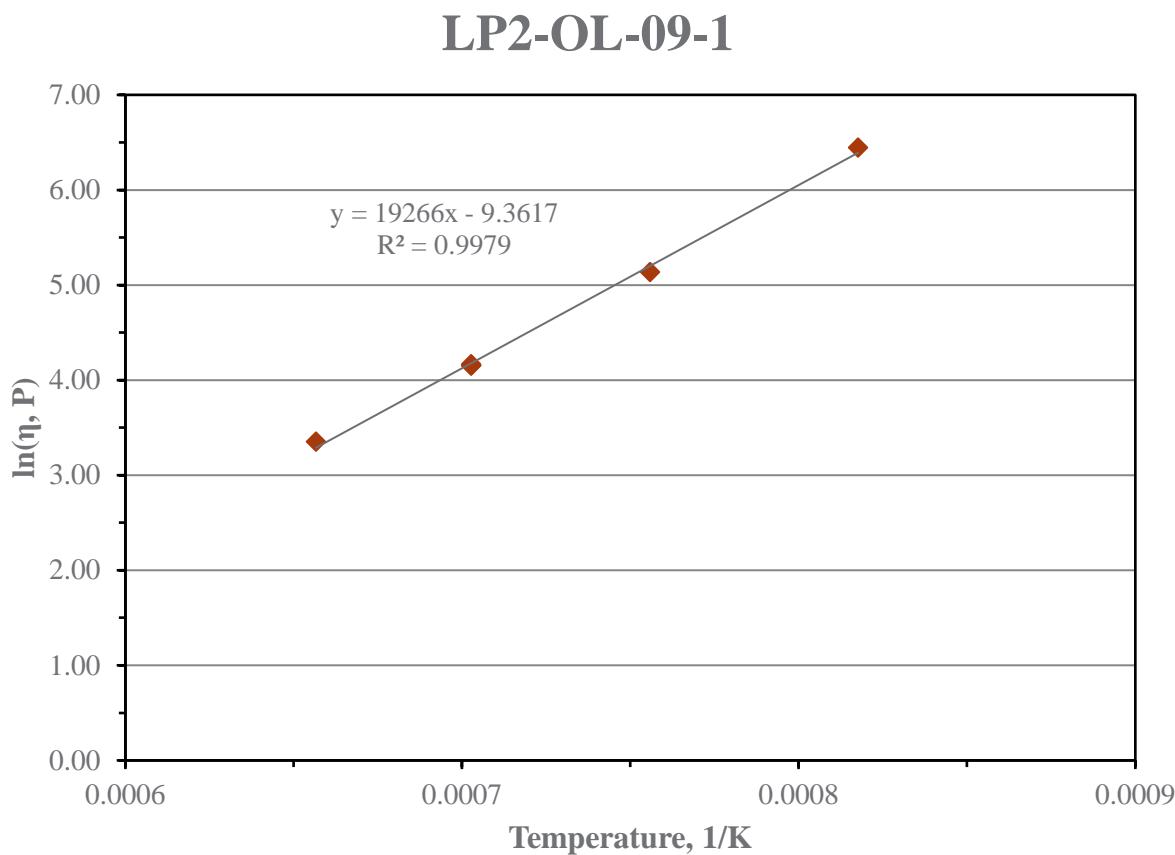


Figure C.25. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-09-1

## C.26 Glass LP2-OL-10 MOD Viscosity Data

Table C.26. Viscosity Data for Glass LP2-OL-10 MOD

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	63.72	7.027	4.15
1050	197.00	7.559	5.28
950	1450.00	8.177	7.28
1150	65.04	7.027	4.17
1250	26.57	6.566	3.28
1150	67.69	7.027	4.21

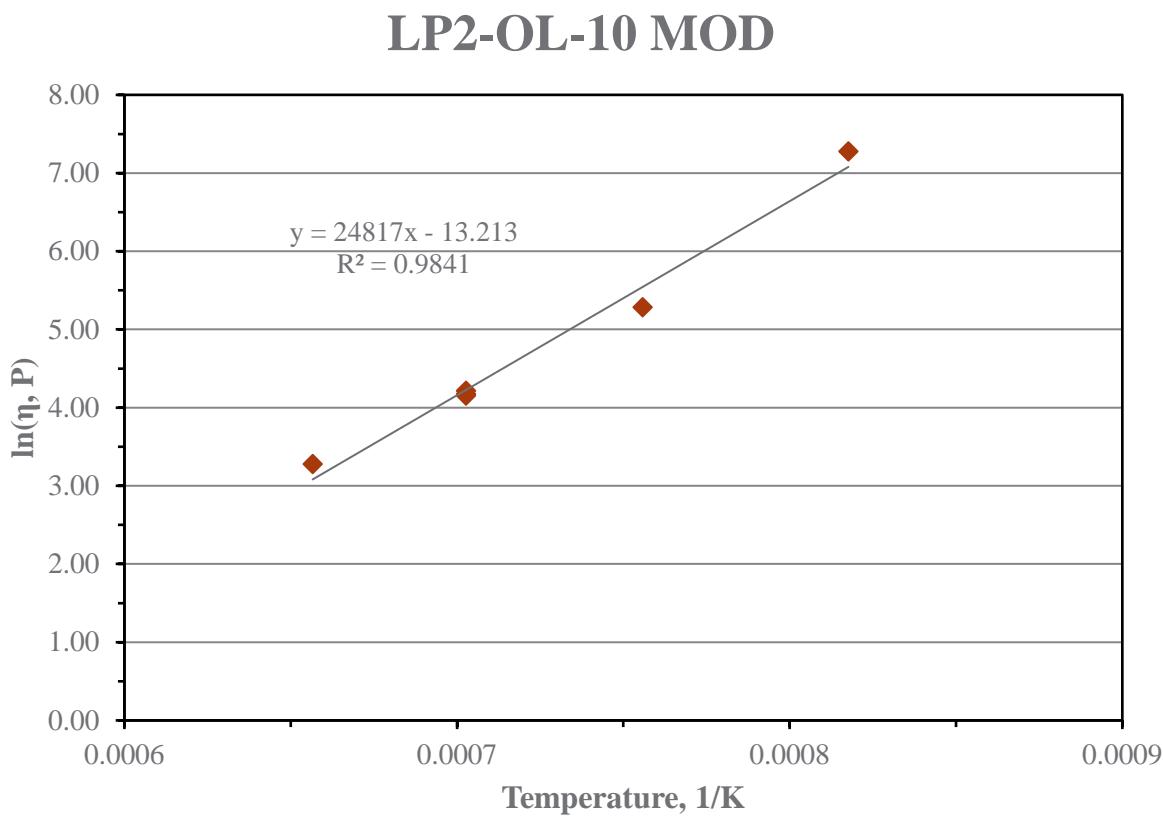


Figure C.26. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-10 MOD

## C.27 Glass LP2-OL-11 Viscosity Data

Table C.27. Viscosity Data for Glass LP2-OL-11

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	11.30	7.027	2.42
1050	27.30	7.559	3.31
950	83.93	8.177	4.43
1150	11.40	7.027	2.43
1250	5.59	6.566	1.72
1150	11.61	7.027	2.45

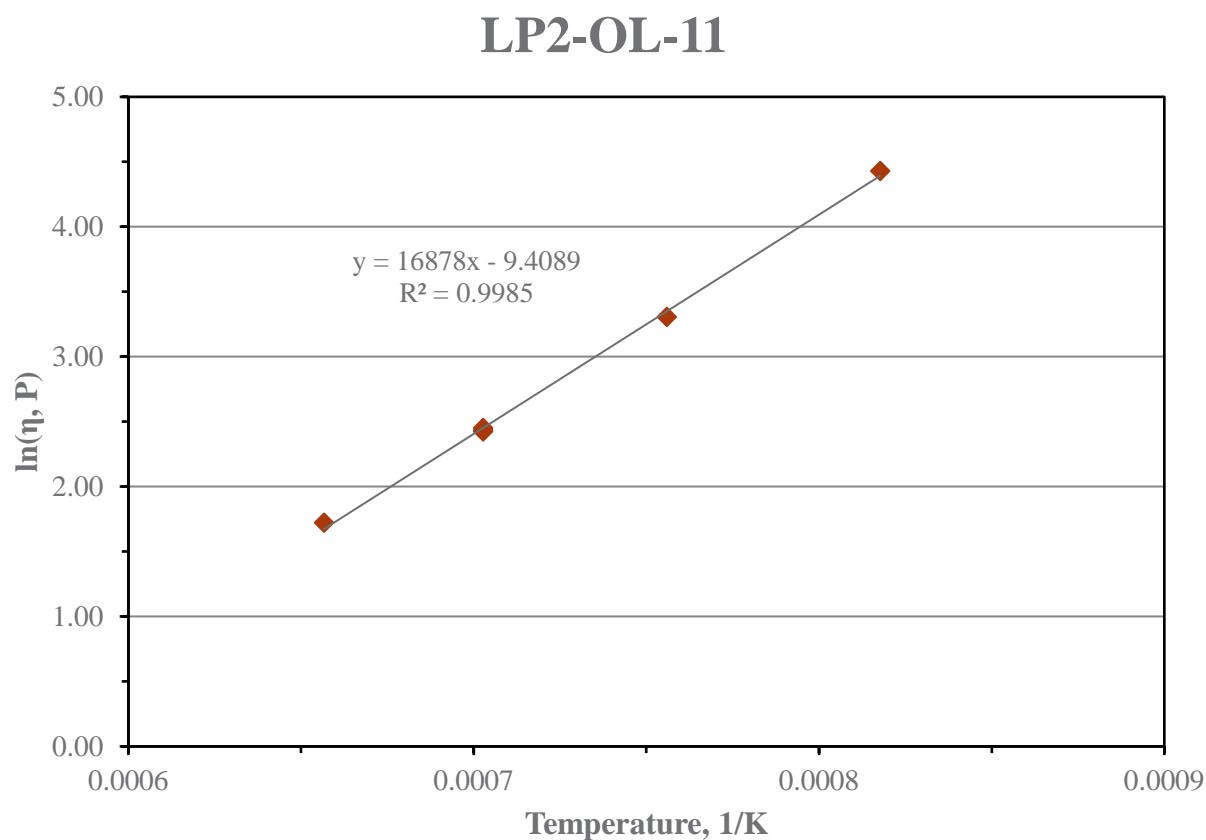


Figure C.27. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-11

## C.28 Glass LP2-OL-12 Viscosity Data

Table C.28. Viscosity Data for Glass LP2-OL-12

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	7.97	7.027	2.08
1050	17.58	7.559	2.87
950	48.70	8.177	3.89
1150	8.03	7.027	2.08
1250	4.24	6.566	1.44
1150	8.12	7.027	2.09

## LP2-OL-12

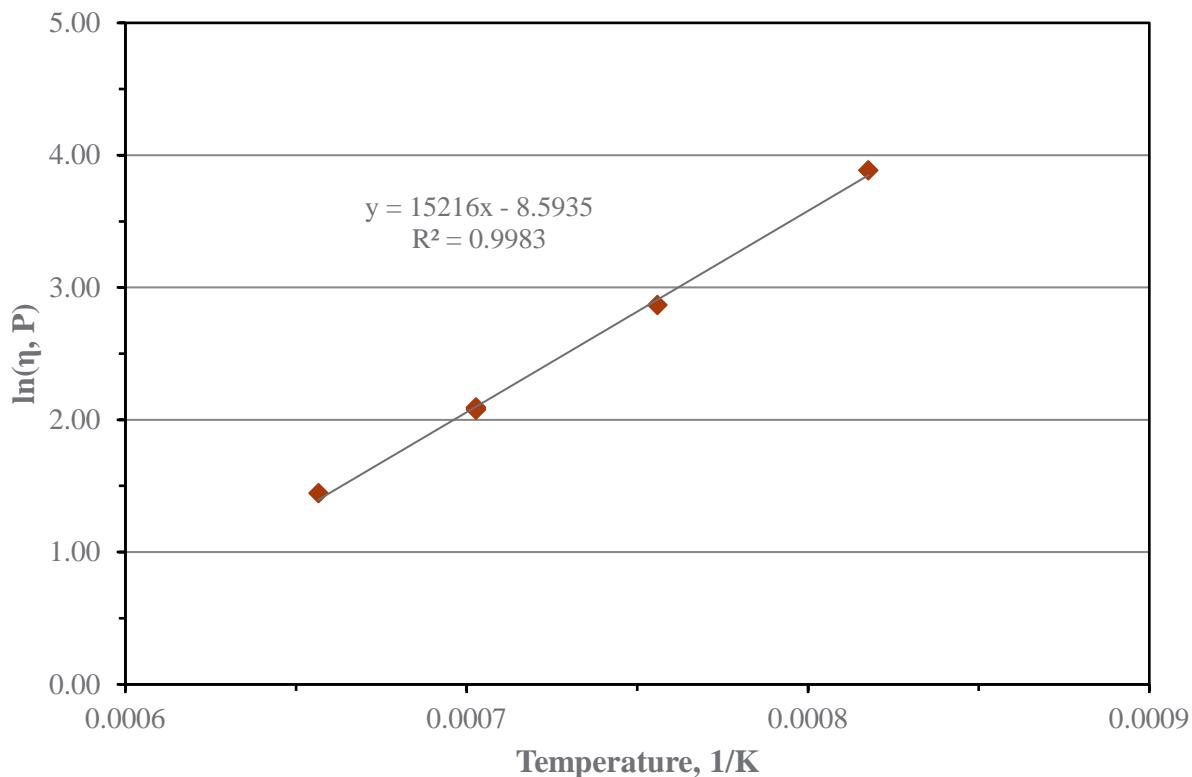


Figure C.28. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-12

## C.29 Glass LP2-OL-13 Viscosity Data

Table C.29. Viscosity Data for Glass LP2-OL-13

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	13.17	7.027	2.58
1050	31.86	7.559	3.46
950	90.97	8.177	4.51
1150	13.27	7.027	2.59
1250	6.42	6.566	1.86
1150	13.47	7.027	2.60

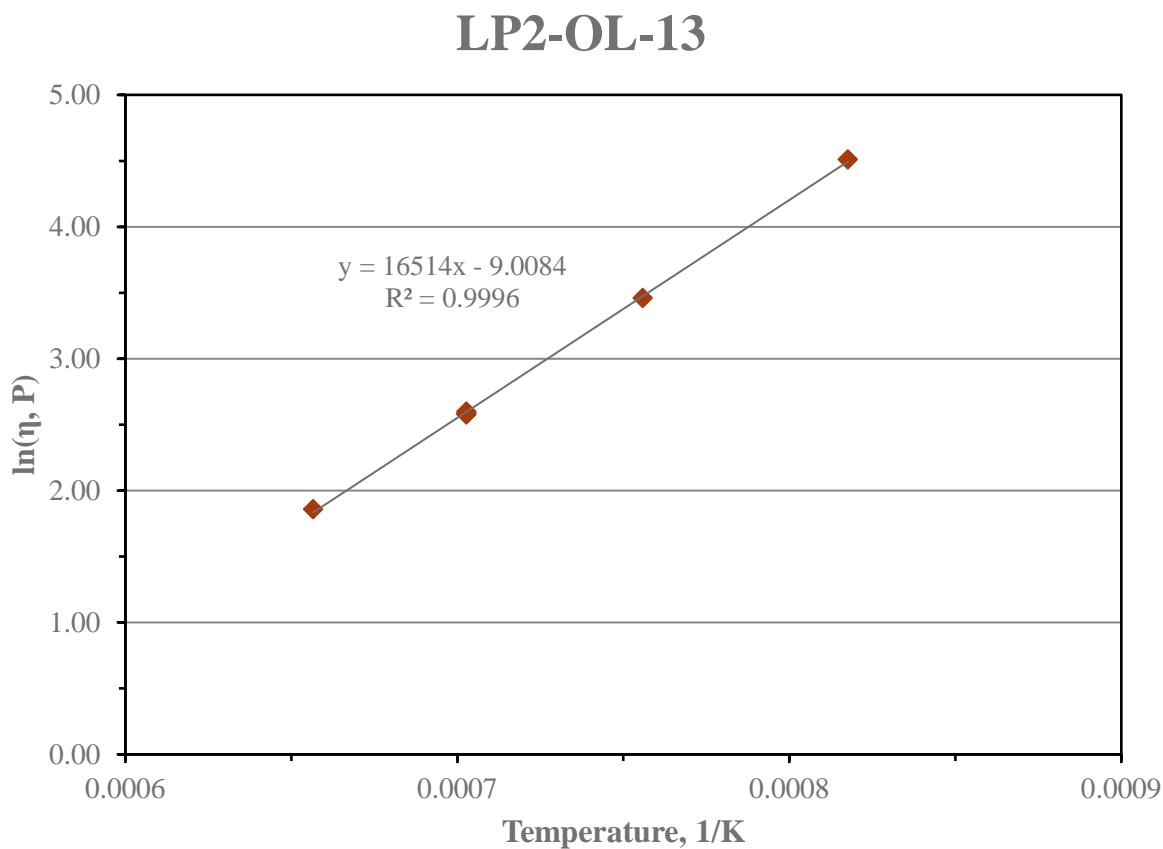


Figure C.29. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-13

### C.30 Glass LP2-OL-14 Viscosity Data

Table C.30. Viscosity Data for Glass LP2-OL-14

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	9.56	7.027	2.26
1050	21.33	7.559	3.06
950	59.80	8.177	4.09
1150	9.64	7.027	2.27
1250	5.04	6.566	1.62
1150	9.80	7.027	2.28

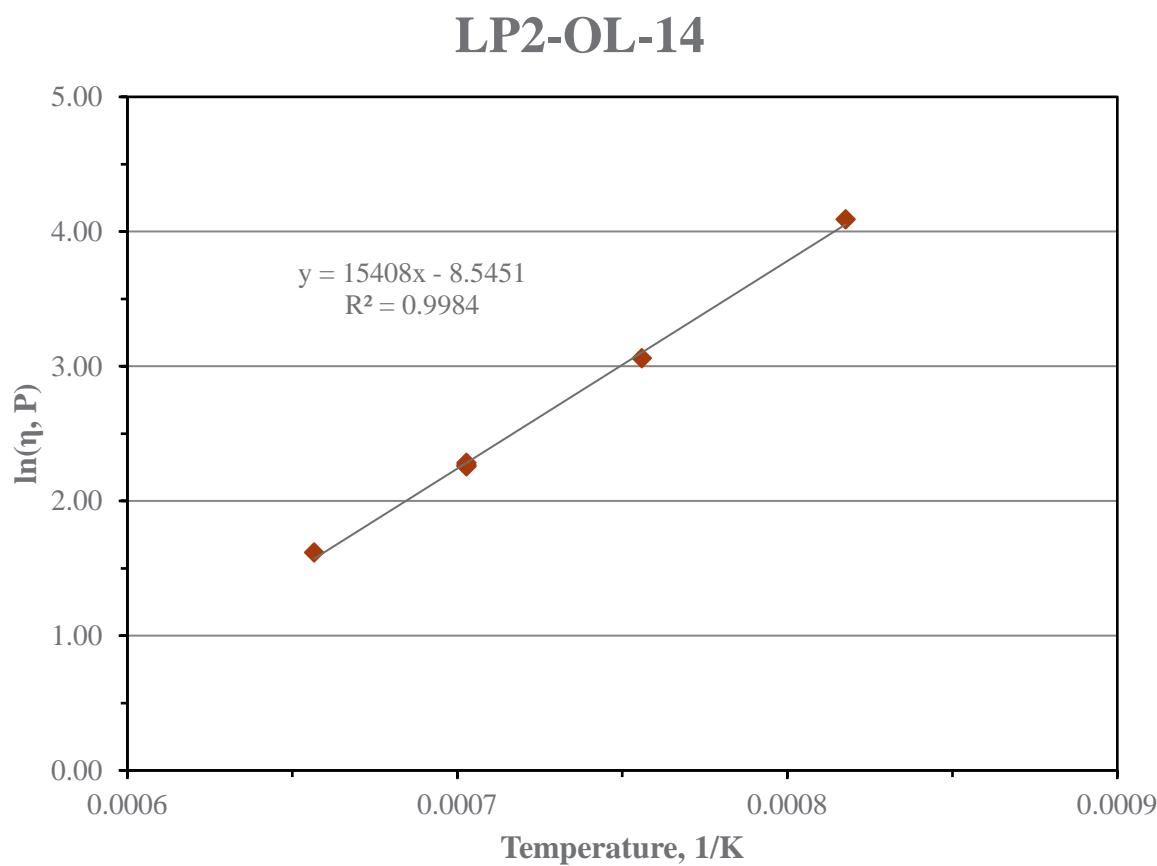


Figure C.30. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-14

### C.31 Glass LP2-OL-15 Viscosity Data

Table C.31. Viscosity Data for Glass LP2-OL-15

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	12.73	7.027	2.54
1050	33.84	7.559	3.52
950	122.00	8.177	4.80
1150	12.86	7.027	2.55
1250	6.00	6.566	1.79
1150	12.90	7.027	2.56

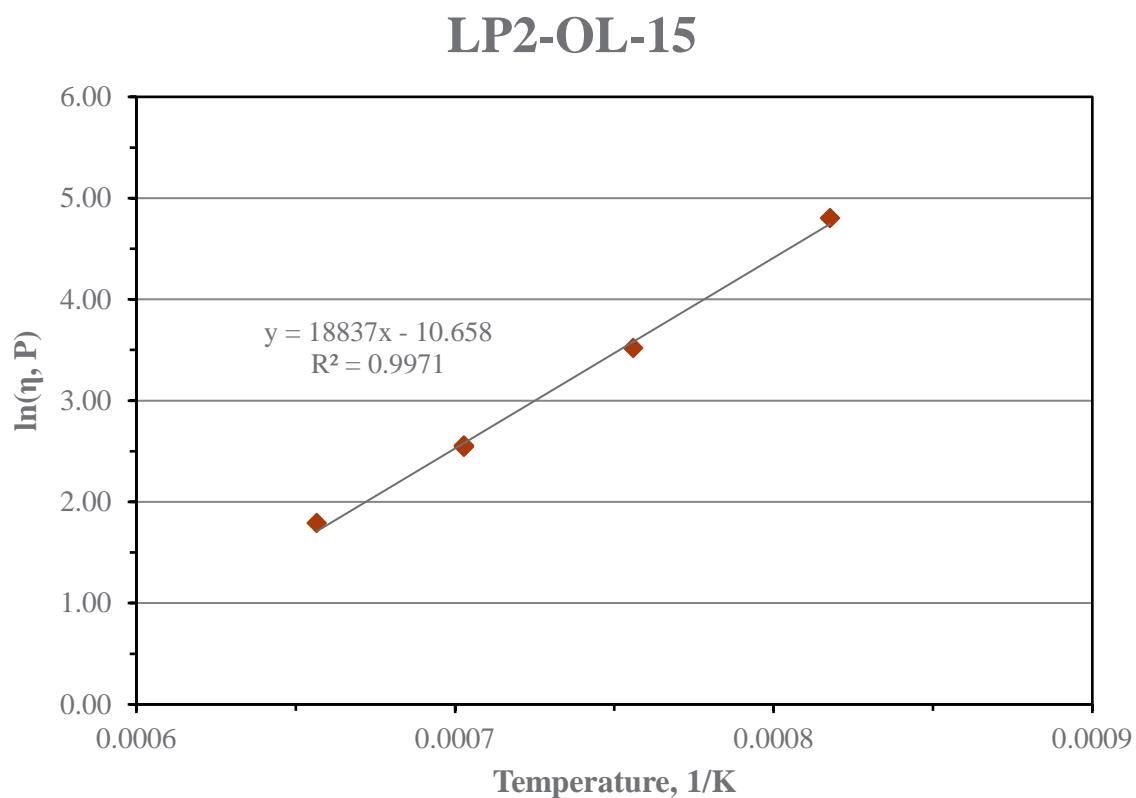


Figure C.31. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-15

### C.32 Glass LP2-OL-16 MOD Viscosity Data

Table C.32. Viscosity Data for Glass LP2-OL-16 MOD

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	72.67	7.027	4.29
1050	199.23	7.559	5.29
950	742.86	8.177	6.61
1150	73.71	7.027	4.30
1250	31.83	6.566	3.46
1150	73.87	7.027	4.30

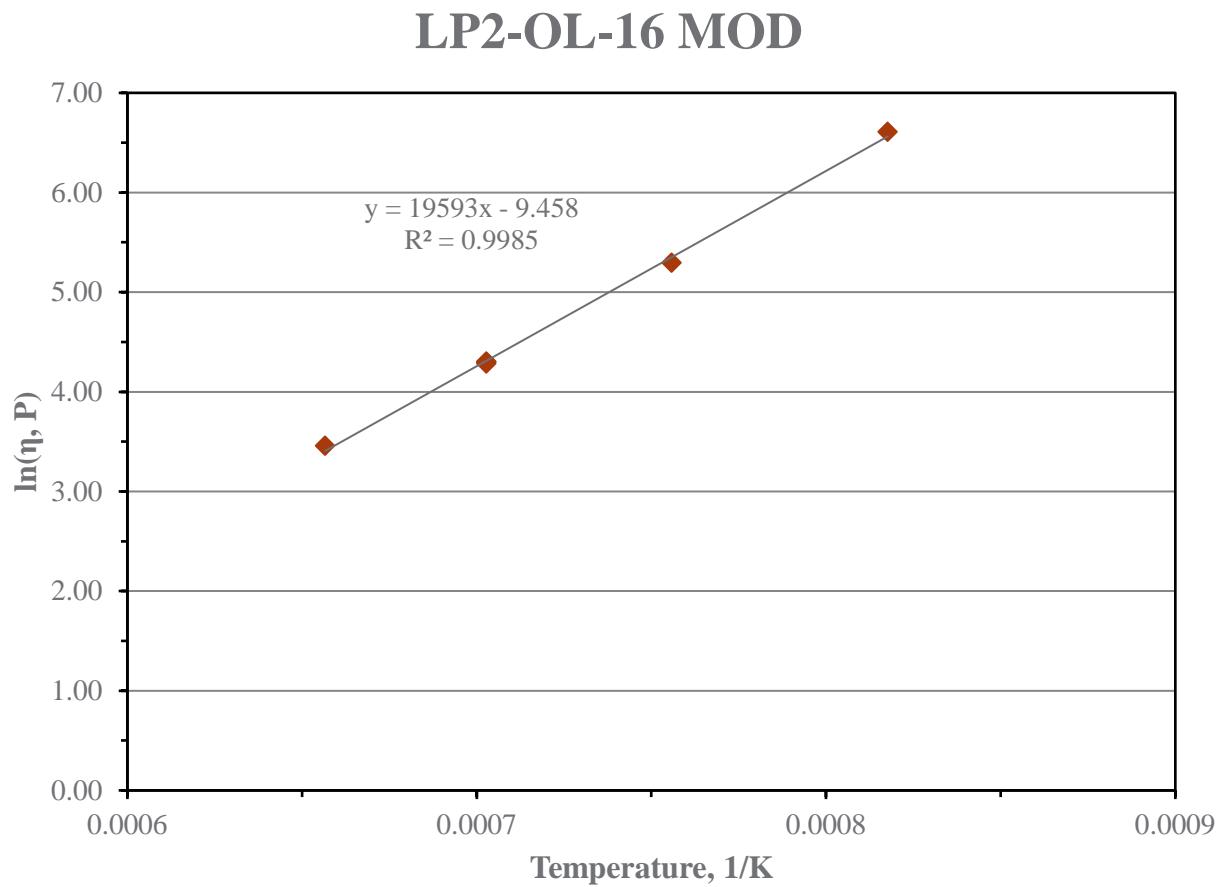


Figure C.32. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-16 MOD

### C.33 Glass LP2-OL-17 Viscosity Data

Table C.33. Viscosity Data for Glass LP2-OL-17

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	24.74	7.027	3.21
1050	66.82	7.559	4.20
950	229.21	8.177	5.43
1150	25.35	7.027	3.23
1250	11.28	6.566	2.42
1150	25.58	7.027	3.24

### LP2-OL-17

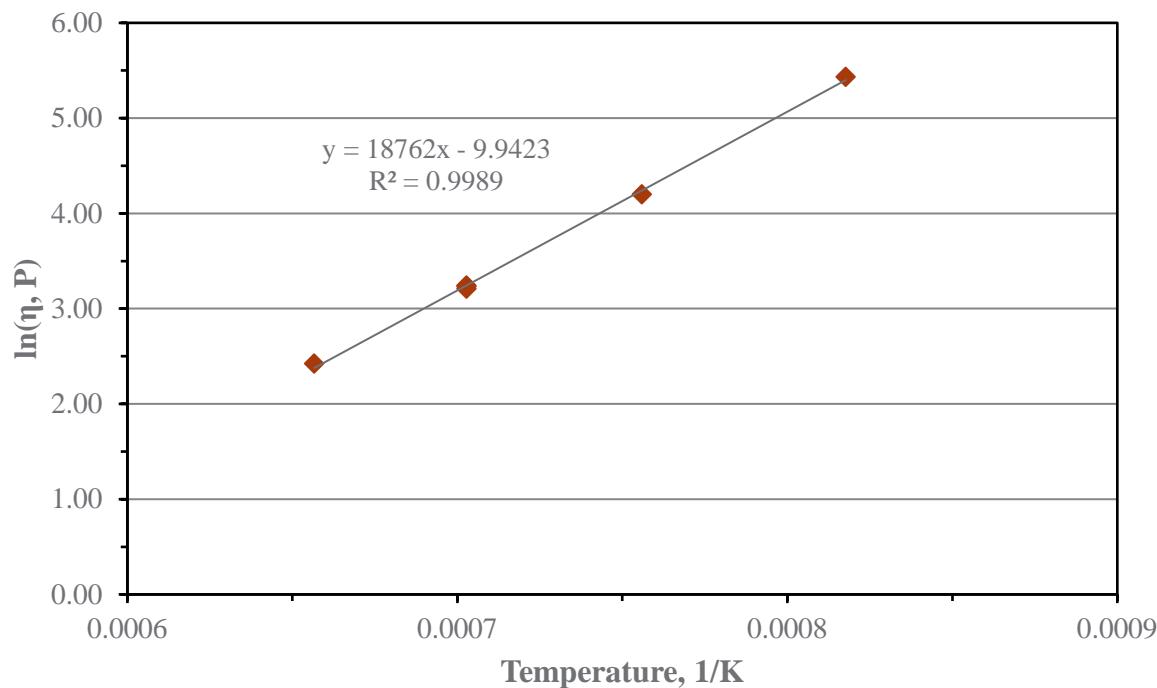


Figure C.33. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-17

### C.34 Glass LP2-OL-18 Viscosity Data

Table C.34. Viscosity Data for Glass LP2-OL-18

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	26.04	7.027	3.26
1050	94.03	7.559	4.54
950	408.64	8.177	6.01
1150	25.78	7.027	3.25
1250	10.60	6.566	2.36
1150	26.41	7.027	3.27

### LP2-OL-18

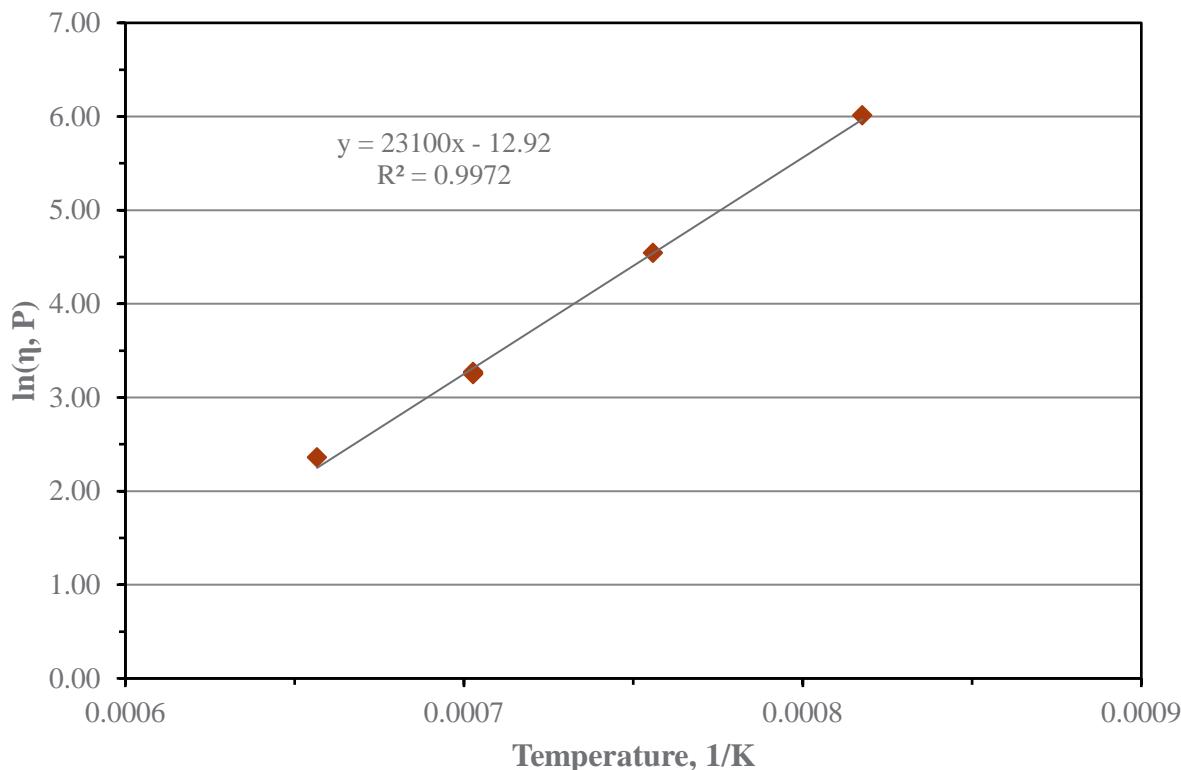


Figure C.34. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-18

### C.35 Glass LP2-OL-19 Viscosity Data

Table C.35. Viscosity Data for Glass LP2-OL-19

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	94.66	7.027	4.55
1050	286.22	7.559	5.66
950	1140.30	8.177	7.04
1150	96.15	7.027	4.57
1250	38.81	6.566	3.66
1150	97.63	7.027	4.58

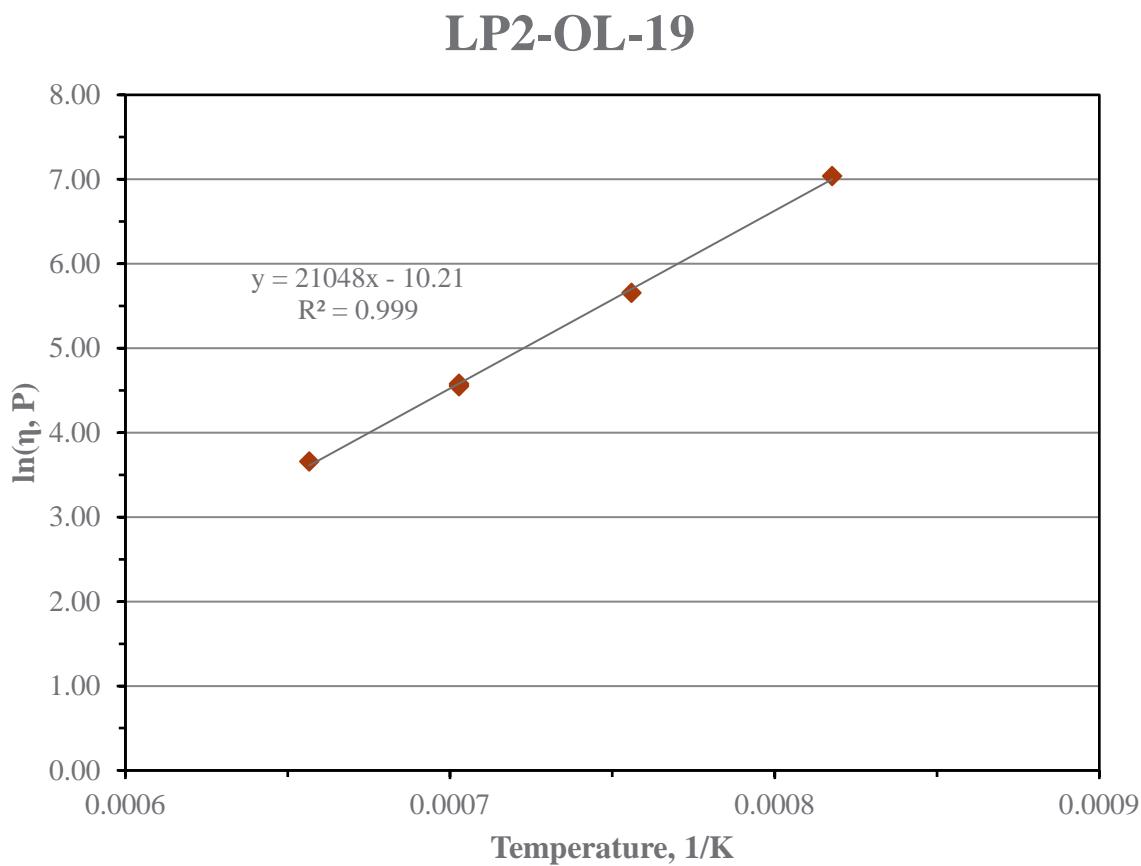


Figure C.35. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-19

### C.36 Glass LP2-OL-20 Viscosity Data

Table C.36. Viscosity Data for Glass LP2-OL-20

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	46.29	7.027	3.83
1050	122.00	7.559	4.80
950	419.93	8.177	6.04
1150	45.71	7.027	3.82
1250	20.37	6.566	3.01
1150	45.95	7.027	3.83

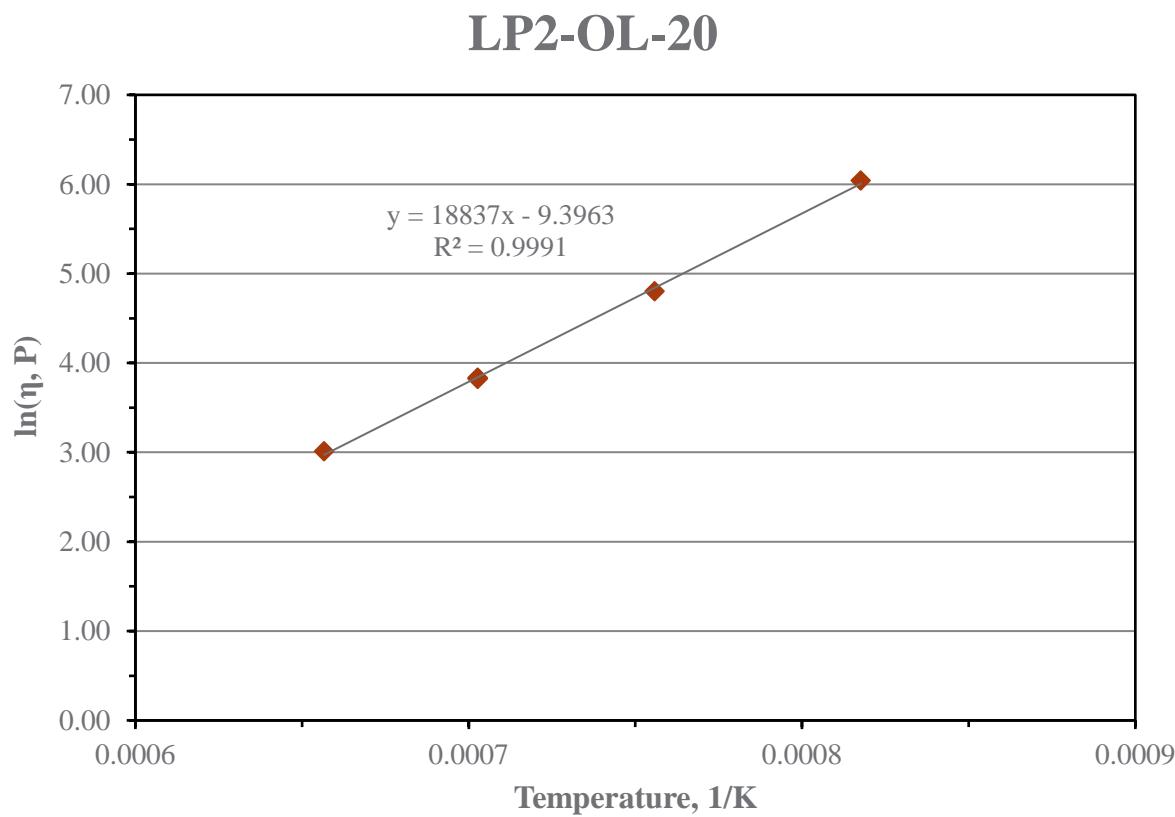


Figure C.36. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-20

### C.37 Glass LP2-OL-21 Viscosity Data

Table C.37. Viscosity Data for Glass LP2-OL-21

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	41.92	7.027	3.74
1050	116.00	7.559	4.75
950	423.52	8.177	6.05
1150	42.67	7.027	3.75
1250	18.50	6.566	2.92
1150	43.19	7.027	3.77

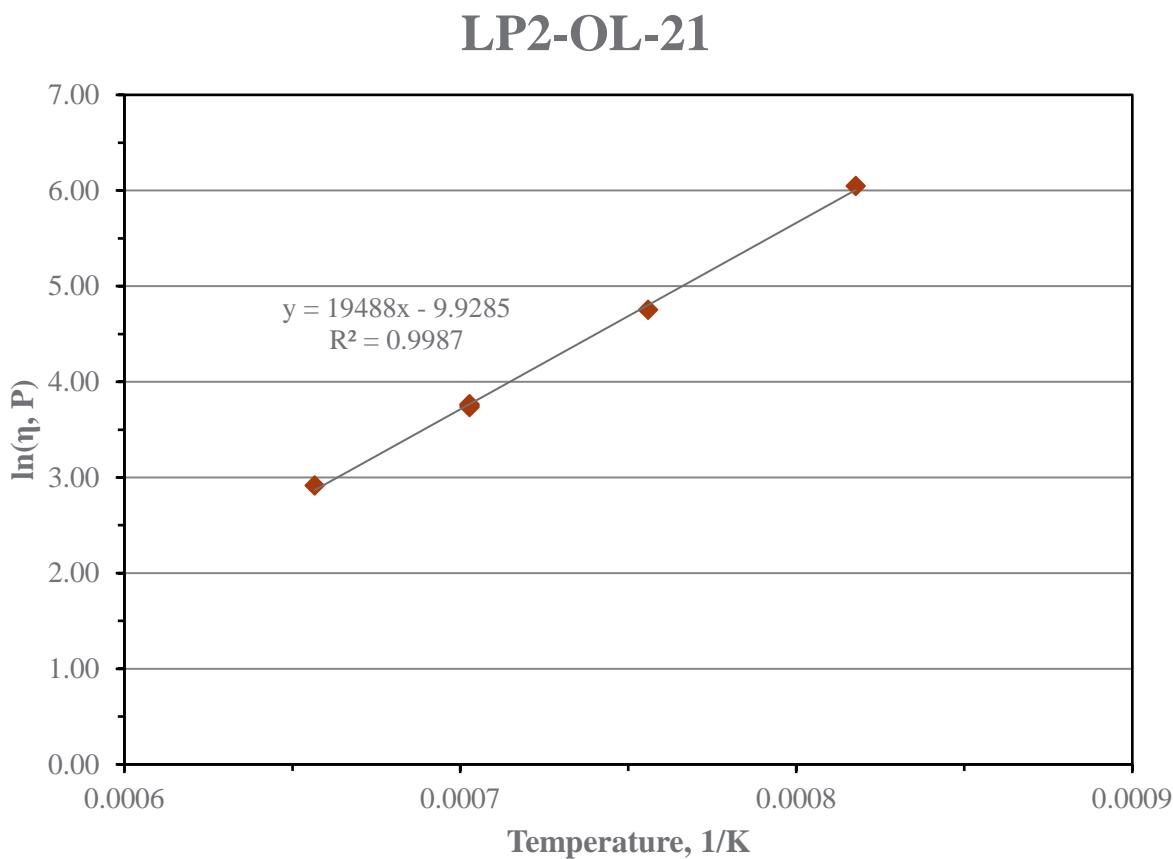


Figure C.37. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-21

### C.38 Glass LP2-OL-22 Viscosity Data

Table C.38. Viscosity Data for Glass LP2-OL-22

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	32.00	7.027	3.47
1050	106.00	7.559	4.66
950	515.78	8.177	6.25
1150	32.36	7.027	3.48
1250	12.70	6.566	2.54
1150	32.20	7.027	3.47

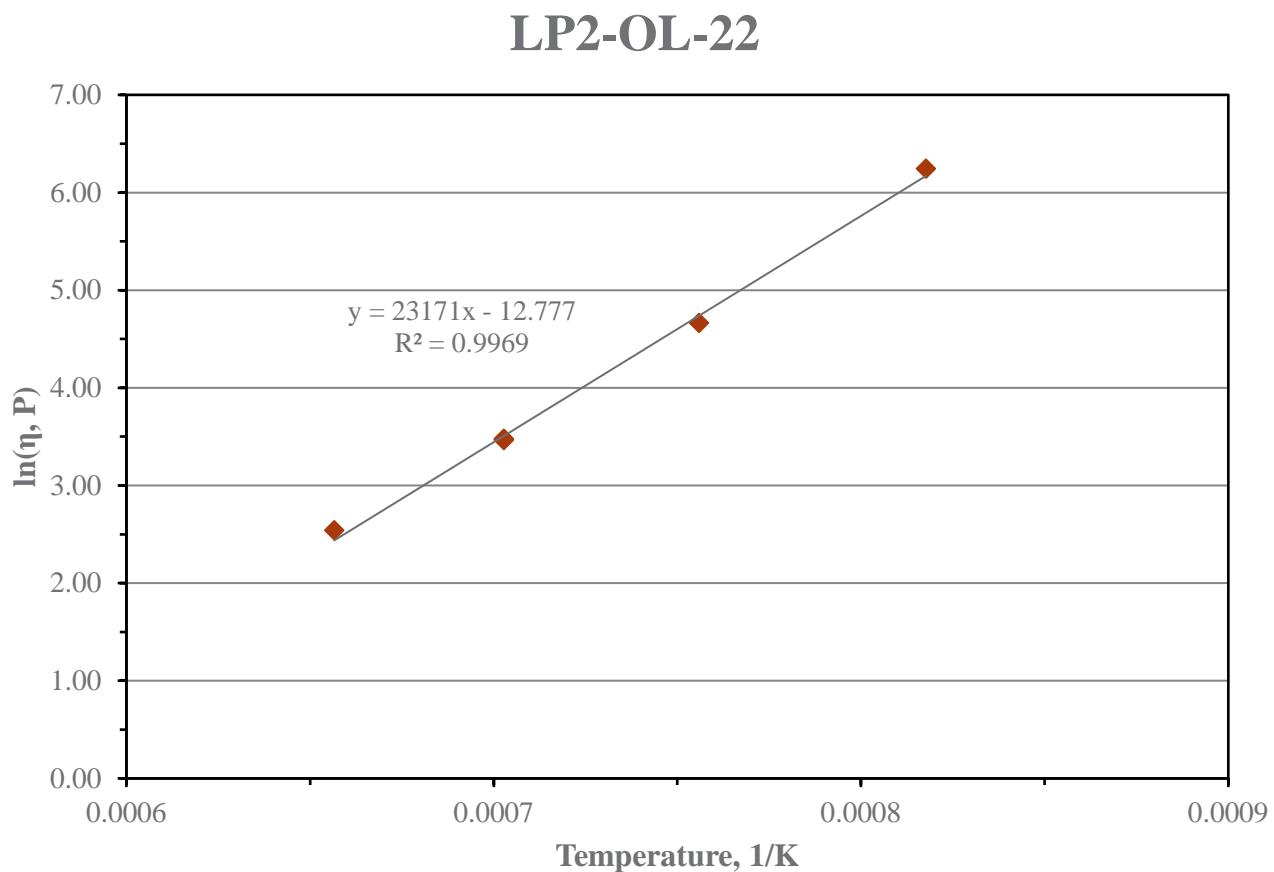


Figure C.38. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-22

### C.39 Glass LP2-OL-23 Viscosity Data

Table C.39. Viscosity Data for Glass LP2-OL-23

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	12.00	7.027	2.48
1050	31.80	7.559	3.46
950	116.00	8.177	4.75
1150	12.20	7.027	2.50
1250	5.63	6.566	1.73
1150	12.20	7.027	2.50

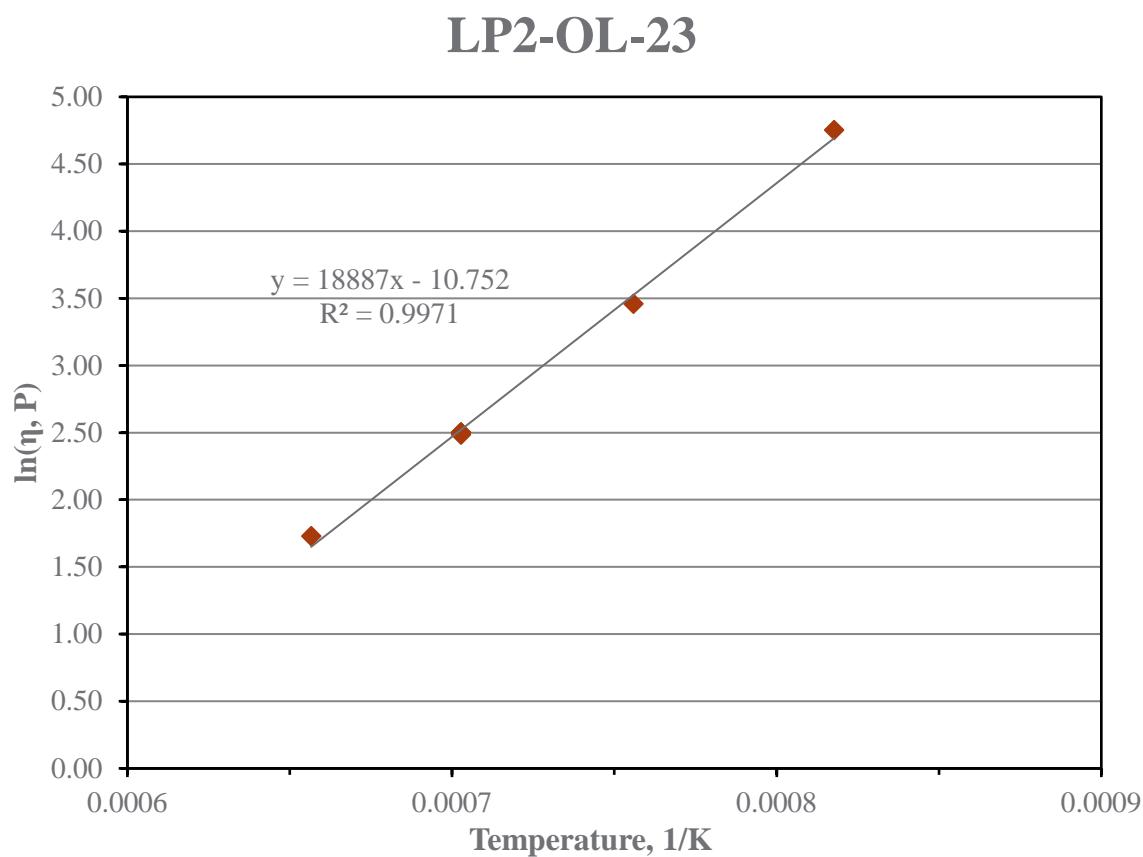


Figure C.39. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-23

## C.40 Glass LP2-OL-24 Viscosity Data

Table C.40. Viscosity Data for Glass LP2-OL-24

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	37.24	7.027	3.62
1050	103.72	7.559	4.64
950	372.04	8.177	5.92
1150	37.41	7.027	3.62
1250	16.00	6.566	2.77
1150	37.46	7.027	3.62

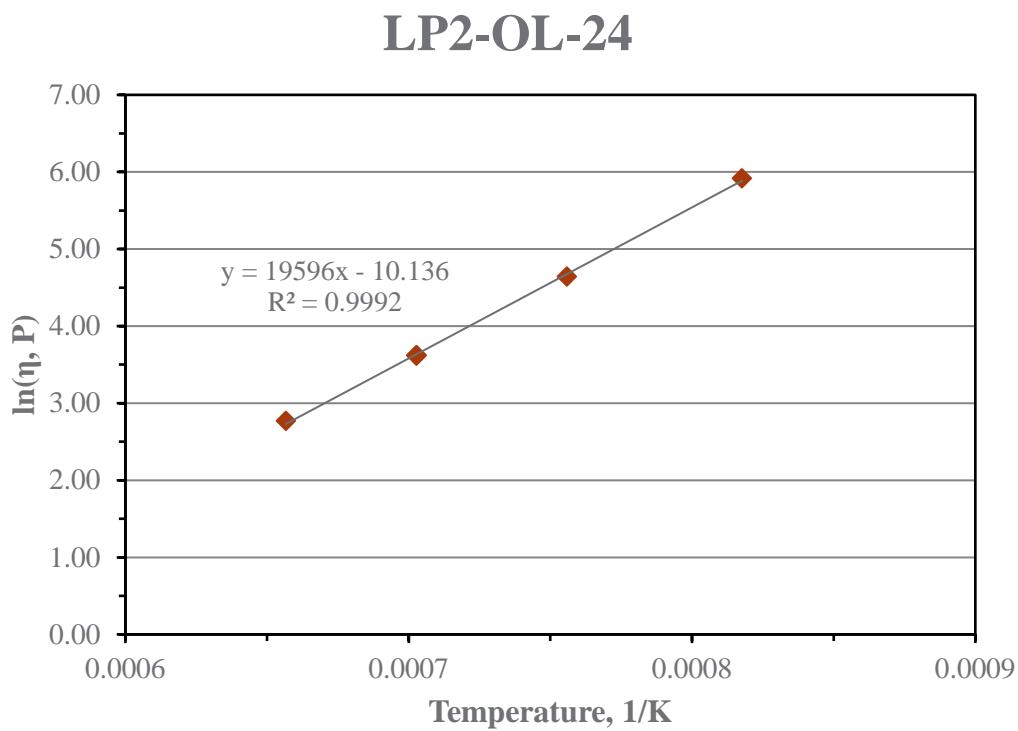


Figure C.40. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-24

## C.41 Glass LP2-OL-25 Viscosity Data

Table C.41. Viscosity Data for Glass LP2-OL-25

Measured Temp., °C	Viscosity, P	1/T x10000, K <sup>-1</sup>	ln η, P
1150	14.84	7.027	2.70
1050	39.06	7.559	3.67
950	138.00	8.177	4.93
1150	15.00	7.027	2.71
1250	6.88	6.566	1.93
1150	15.05	7.027	2.71

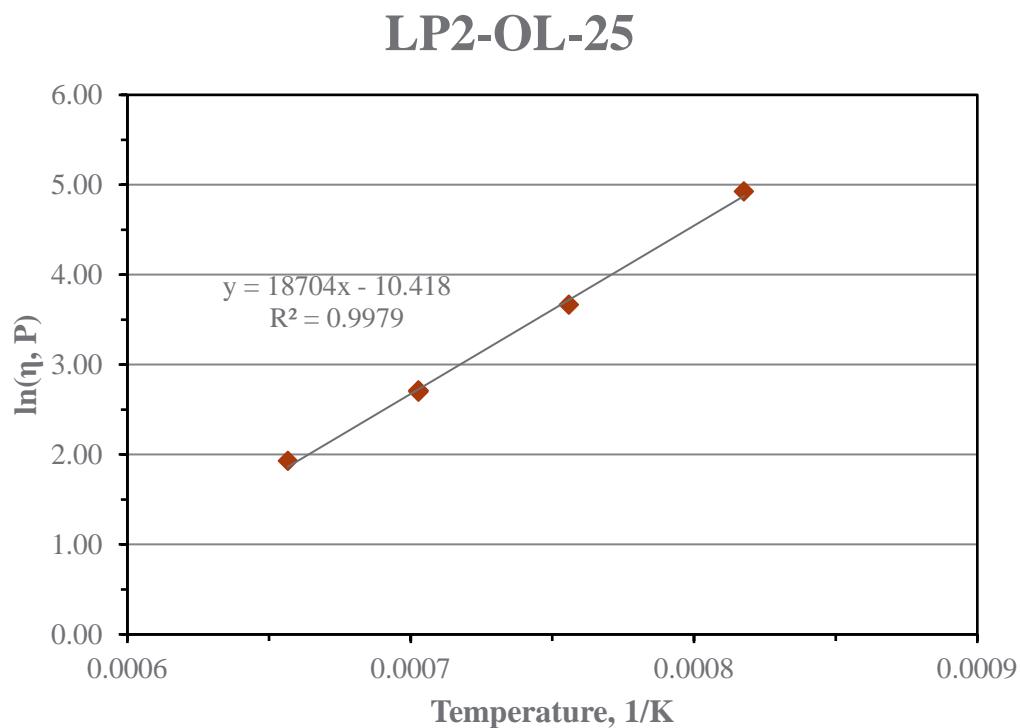


Figure C.41. Viscosity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-25

## Appendix D – Electrical Conductivity Data

This appendix contains the measured electrical conductivity data for each of the Phase 2 enhanced LAW glasses. The plots shown in this appendix were fitted to the Arrhenius equation

$$\ln(\varepsilon) = A + \frac{B}{T_K} \quad (\text{D.1})$$

where  $A$  and  $B$  are independent of temperature ( $T_K$ ) is in K ( $T(^{\circ}\text{C}) + 273.15$ ). If some of the plots showed curvature, the data would be better fit to the Vogel-Fulcher-Tamman (VFT) model

$$\ln(\varepsilon) = E + \frac{F}{T_K - T_0} \quad (\text{D.2})$$

where  $E$ ,  $F$ , and  $T_0$  are temperature independent coefficients and composition dependent coefficients and  $T_K$  is in  $^{\circ}\text{K}$  ( $T(^{\circ}\text{C}) + 273.15$ ). The intent of the figures and Arrhenius equation fits shown in this appendix is mainly to assess trends of the data and provide some observations about whether there may be sufficient curvature in the data to consider VFT fits in the subsequent work that will decide between fitting the electrical conductivity-temperature data to the Arrhenius or VFT equations. All of the Phase 2 enhanced LAW glasses appear to have very good fits to the Arrhenius equation and do not show a need for fitting to the VFT model.

## D.1 Glass LP2-IL-01 Electrical Conductivity Data

Table D.1. Electrical Conductivity Data for Glass LP2-IL-01

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln ε (S/m)
950	28.69	0.000818	3.356
950	28.91	0.000818	3.364
1250	71.99	0.000657	4.276
1250	71.88	0.000657	4.275
1150	56.95	0.000703	4.042
1150	57.02	0.000703	4.043
1050	42.19	0.000756	3.742
1050	42.38	0.000756	3.747

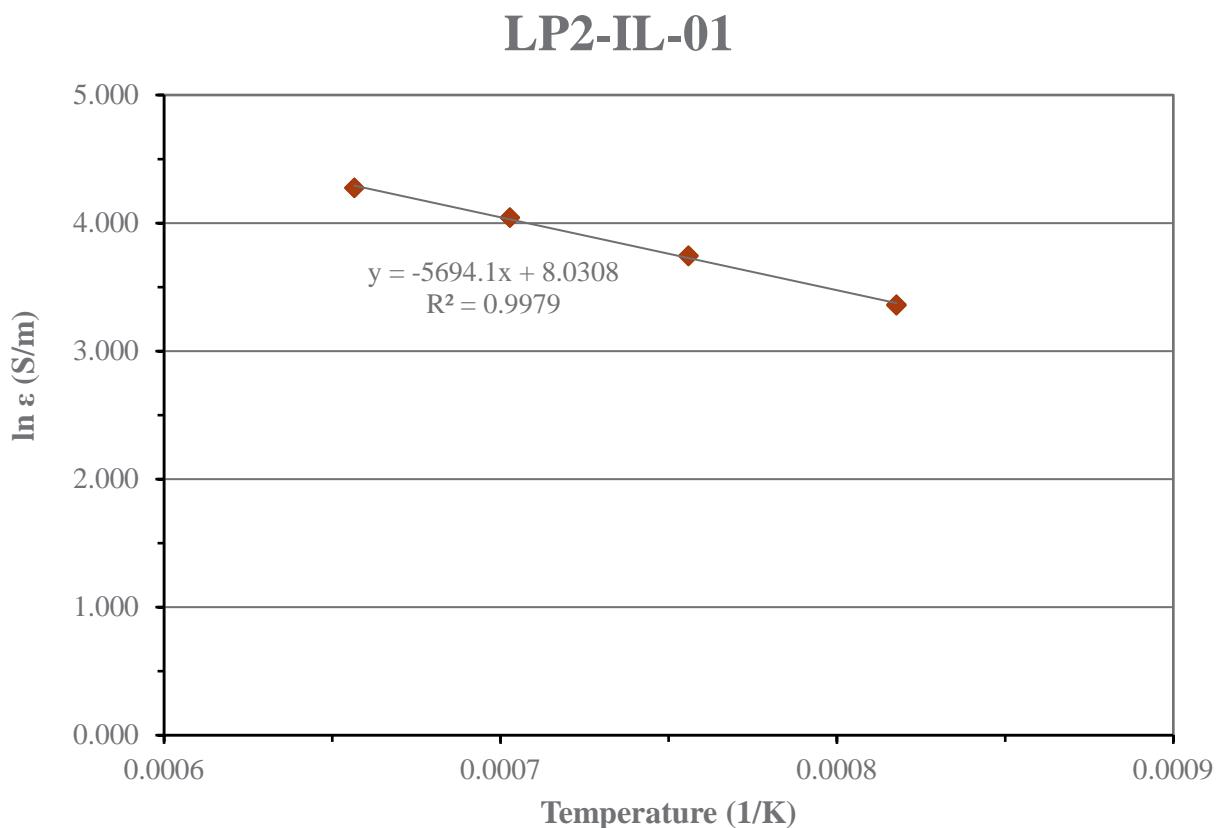


Figure D.1. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-01

## D.2 Glass LP2-IL-02 Electrical Conductivity Data

Table D.2. Electrical Conductivity Data for Glass LP2-IL-02

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	In (ε, S/m)
950	29.14	0.000818	3.372
950	29.39	0.000818	3.381
1250	73.11	0.000657	4.292
1250	72.98	0.000657	4.290
1150	57.99	0.000703	4.060
1150	58.08	0.000703	4.062
1050	42.77	0.000756	3.756
1050	42.97	0.000756	3.760

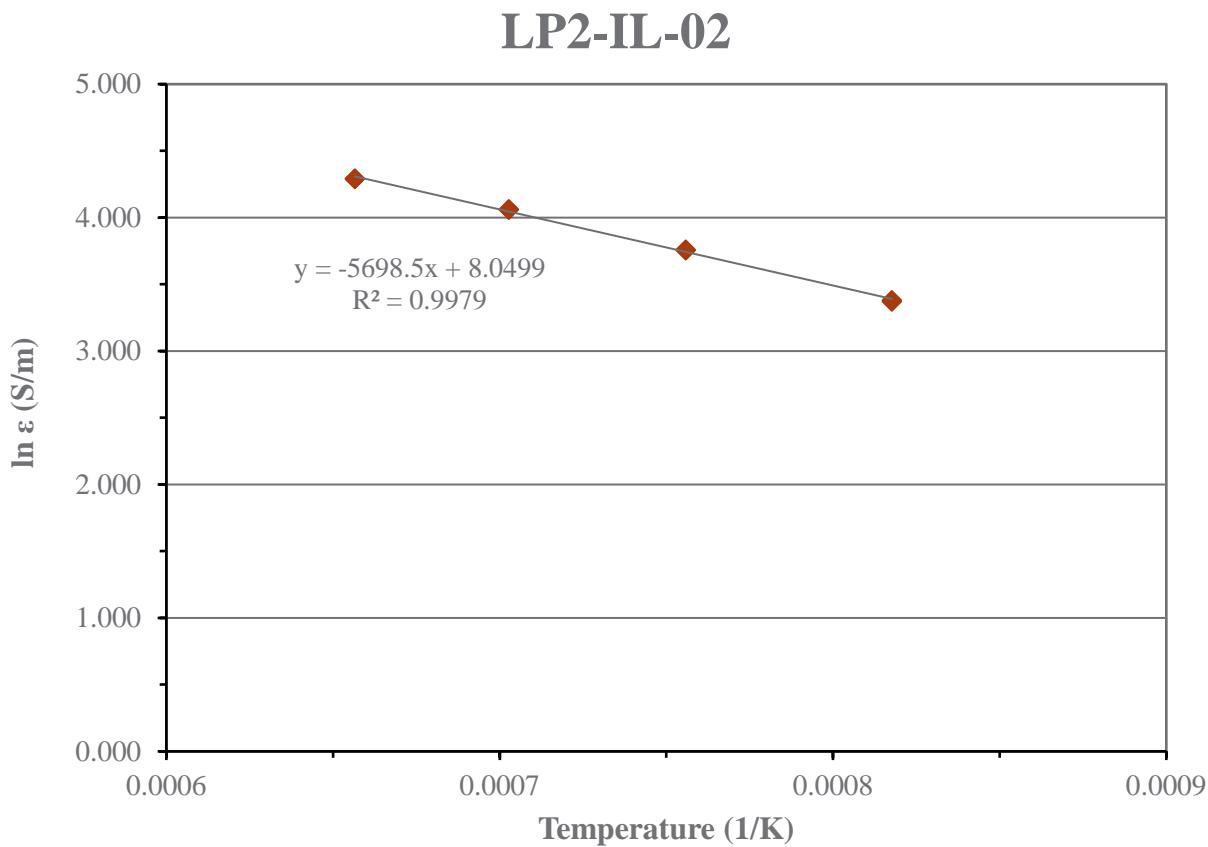


Figure D.2. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-02

### D.3 Glass LP2-IL-03 Electrical Conductivity Data

Table D.3. Electrical Conductivity Data for Glass LP2-IL-03

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	30.71	0.000818	3.425
950	30.92	0.000818	3.431
1250	73.79	0.000657	4.301
1150	59.05	0.000703	4.078
1150	59.28	0.000703	4.082
1050	44.21	0.000756	3.789
1050	44.50	0.000756	3.796

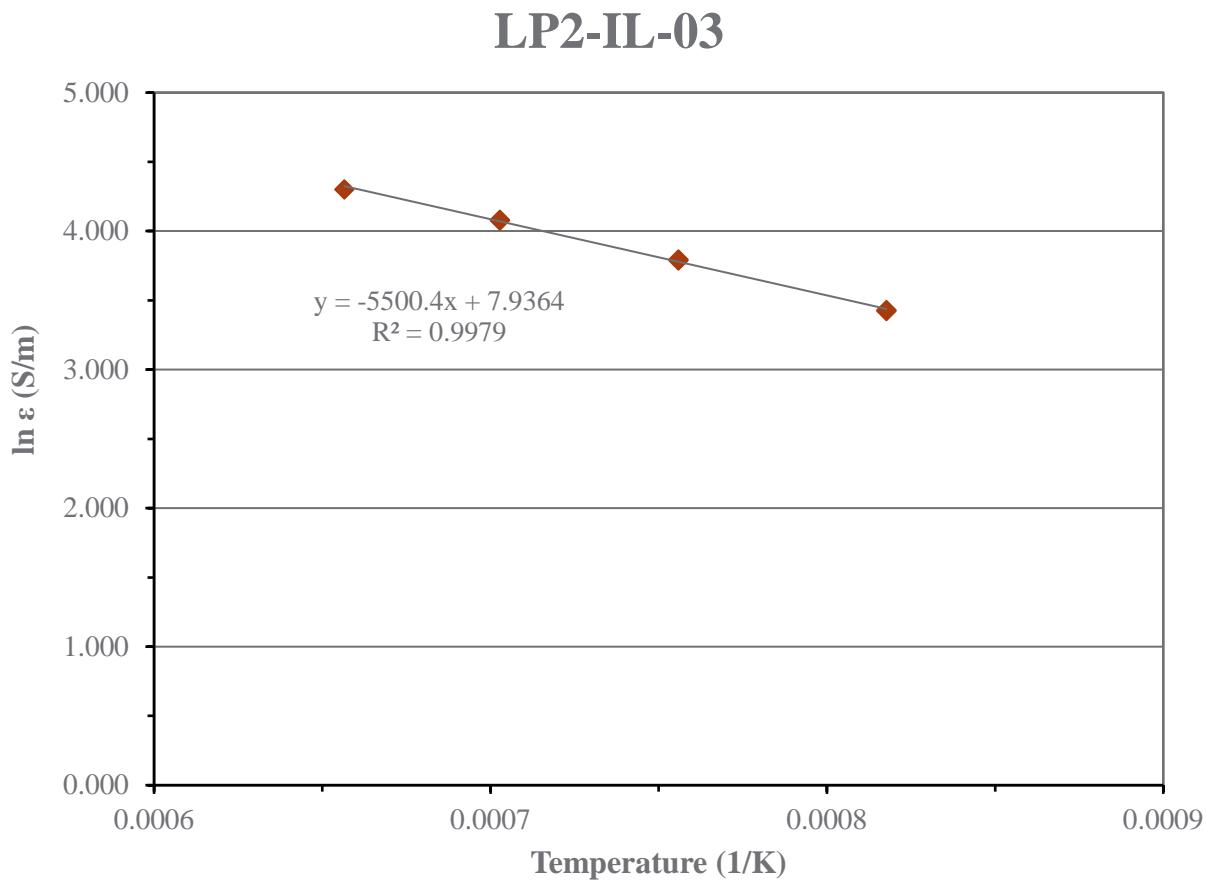


Figure D.3. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-03

## D.4 Glass LP2-IL-04 Electrical Conductivity Data

Table D.4. Electrical Conductivity Data for Glass LP2-IL-04

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	29.06	0.000818	3.369
950	29.26	0.000818	3.376
1250	73.74	0.000657	4.301
1250	73.45	0.000657	4.297
1150	58.39	0.000703	4.067
1150	58.52	0.000703	4.069
1050	42.93	0.000756	3.760
1050	43.12	0.000756	3.764

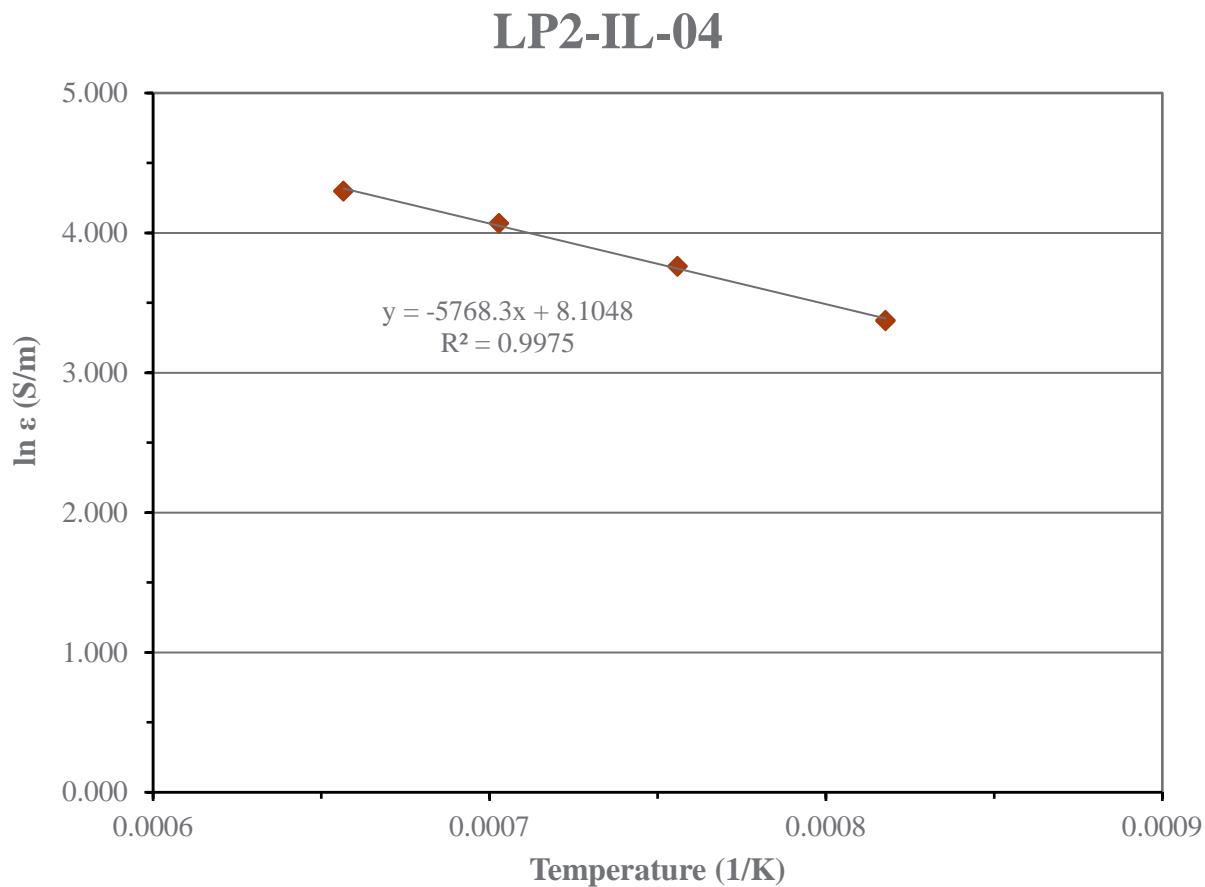


Figure D.4. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-04

## D.5 Glass LP2-IL-05 Electrical Conductivity Data

Table D.5. Electrical Conductivity Data for Glass LP2-IL-05

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	23.47	0.000818	3.156
950	23.65	0.000818	3.164
1250	65.02	0.000657	4.175
1250	64.77	0.000657	4.171
1150	50.30	0.000703	3.918
1150	50.55	0.000703	3.923
1050	35.93	0.000756	3.582
1050	36.09	0.000756	3.586

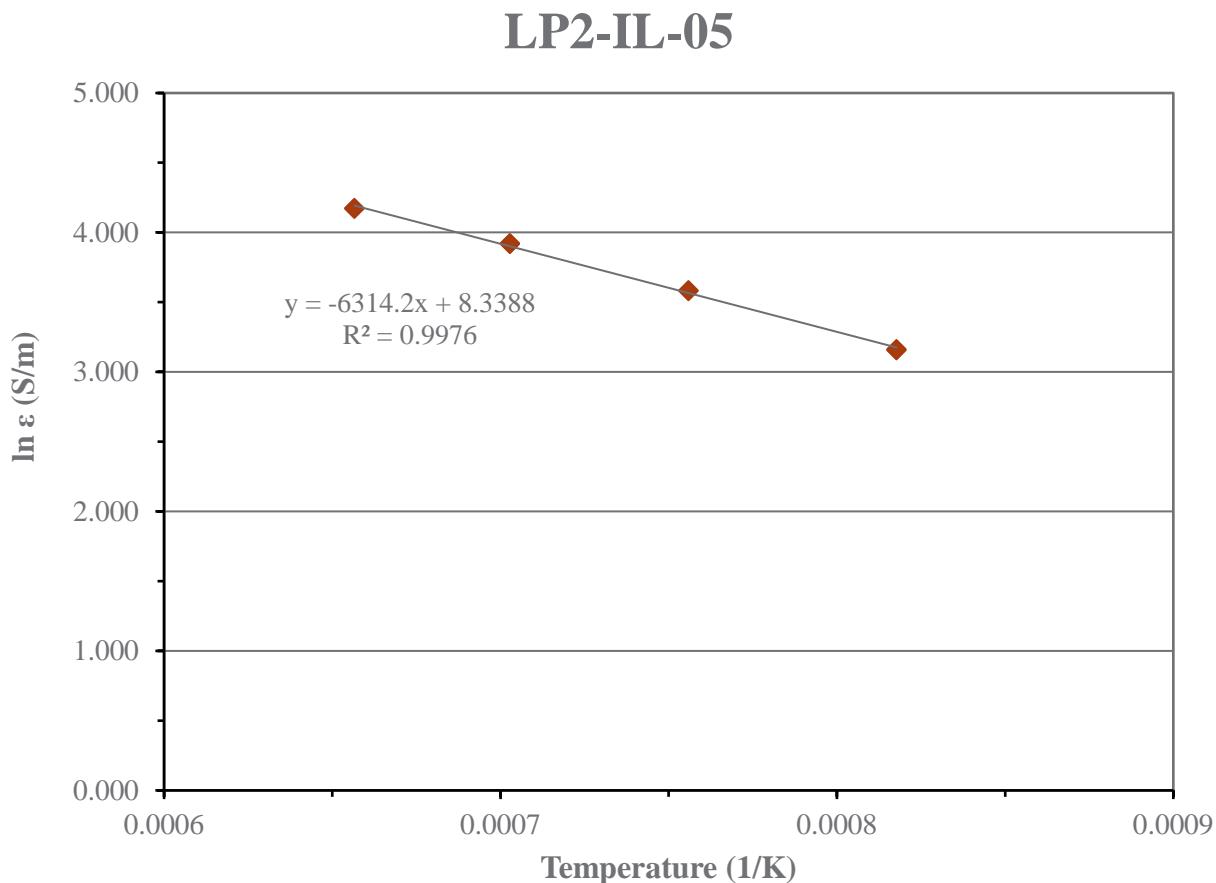


Figure D.5. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-05

## D.6 Glass LP2-IL-06 Electrical Conductivity Data

Table D.6. Electrical Conductivity Data for Glass LP2-IL-06

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	27.37	0.000818	3.310
950	27.54	0.000818	3.316
1250	67.52	0.000657	4.212
1250	67.16	0.000657	4.207
1150	53.87	0.000703	3.987
1150	53.94	0.000703	3.988
1050	40.06	0.000756	3.690
1050	40.20	0.000756	3.694

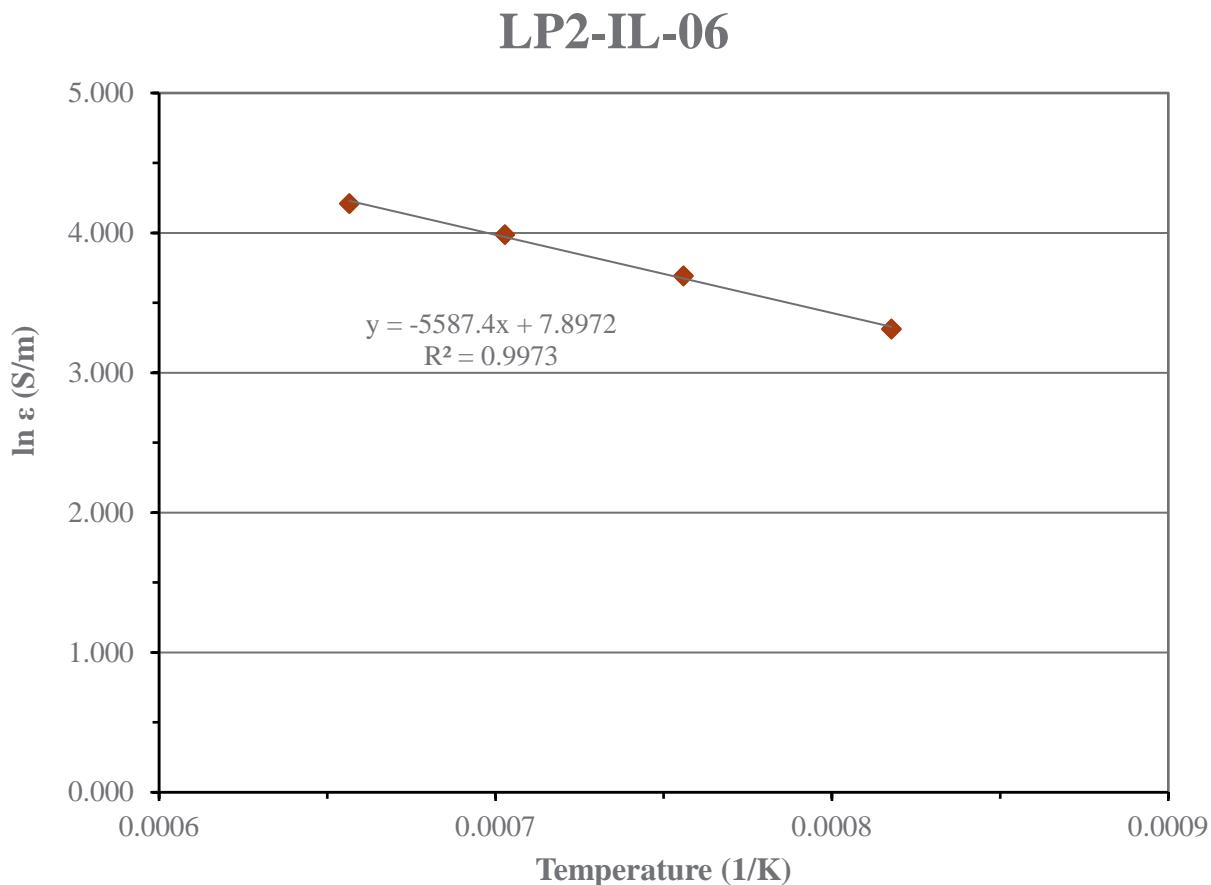


Figure D.6. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-06

## D.7 Glass LP2-IL-07 Electrical Conductivity Data

Table D.7. Electrical Conductivity Data for Glass LP2-IL-07

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	26.81	0.000818	3.289
950	27.00	0.000818	3.296
1250	67.53	0.000657	4.213
1150	53.48	0.000703	3.979
1150	53.59	0.000703	3.981
1050	39.52	0.000756	3.677
1050	39.69	0.000756	3.681

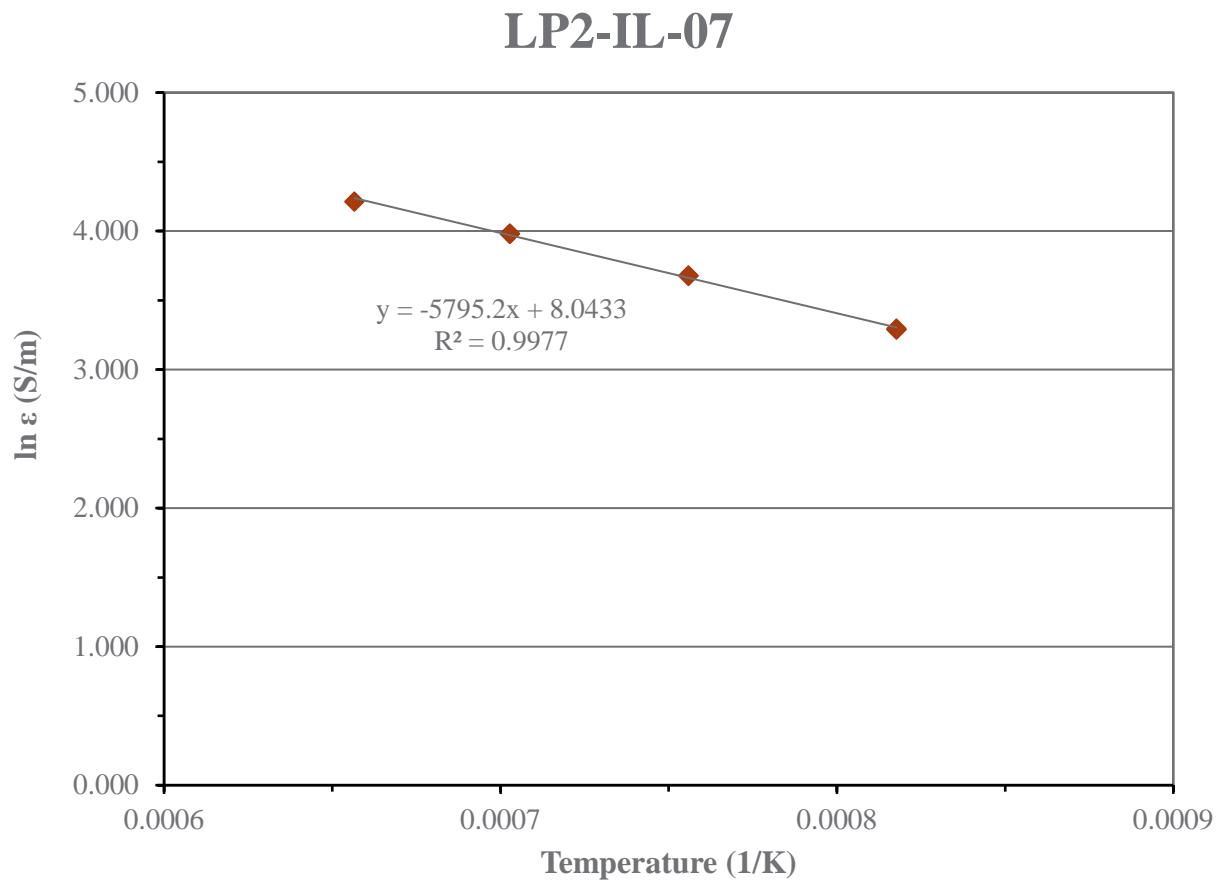


Figure D.7. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-07

## D.8 Glass LP2-IL-08 Electrical Conductivity Data

Table D.8. Electrical Conductivity Data for Glass LP2-IL-08

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	23.10	0.000818	3.140
950	23.27	0.000818	3.147
1250	63.59	0.000657	4.153
1250	63.35	0.000657	4.149
1150	49.16	0.000703	3.895
1150	49.26	0.000703	3.897
1050	35.25	0.000756	3.563
1050	35.40	0.000756	3.567

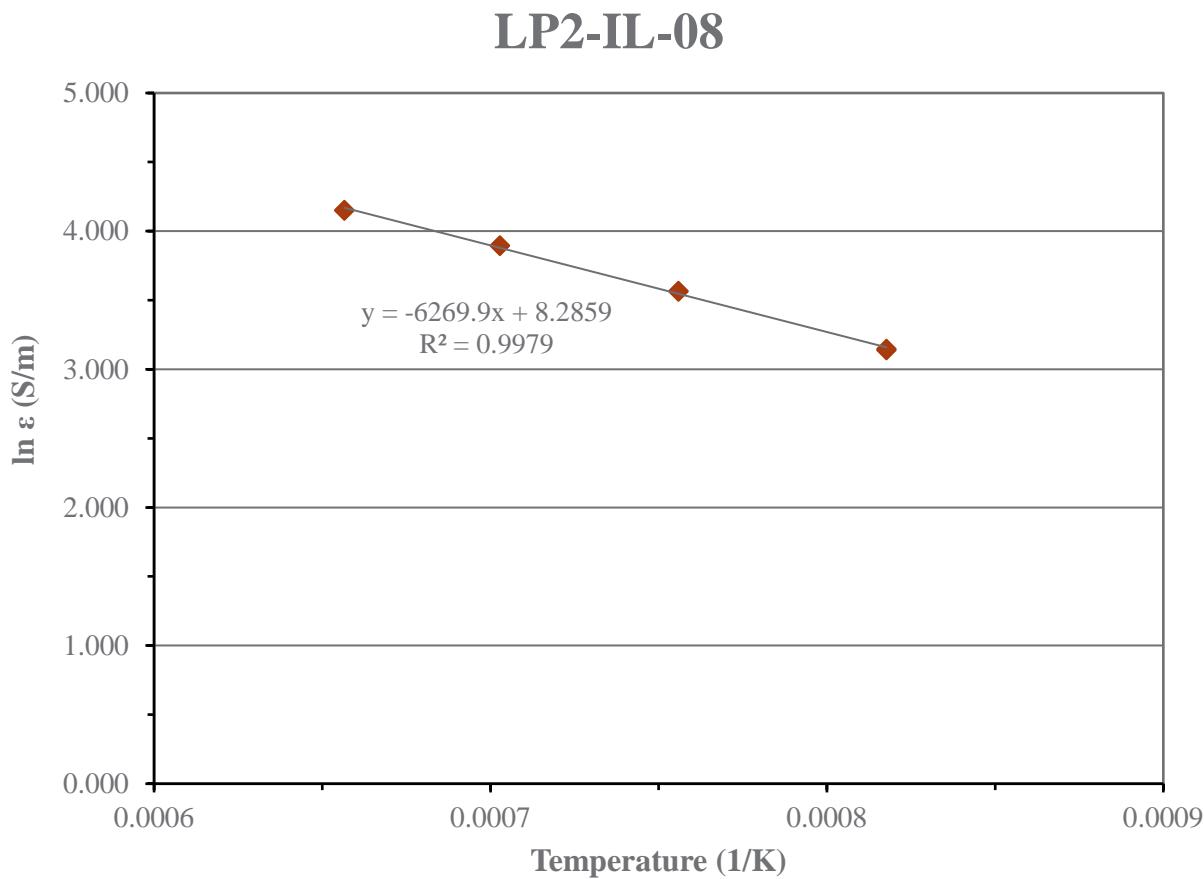


Figure D.8. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-08

## D.9 Glass LP2-IL-09 Electrical Conductivity Data

Table D.9. Electrical Conductivity Data for Glass LP2-IL-09

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	32.09	0.000818	3.468
950	32.33	0.000818	3.476
1250	78.02	0.000657	4.357
1250	78.09	0.000657	4.358
1150	62.90	0.000703	4.142
1150	63.09	0.000703	4.145
1050	46.69	0.000756	3.844
1050	47.03	0.000756	3.851

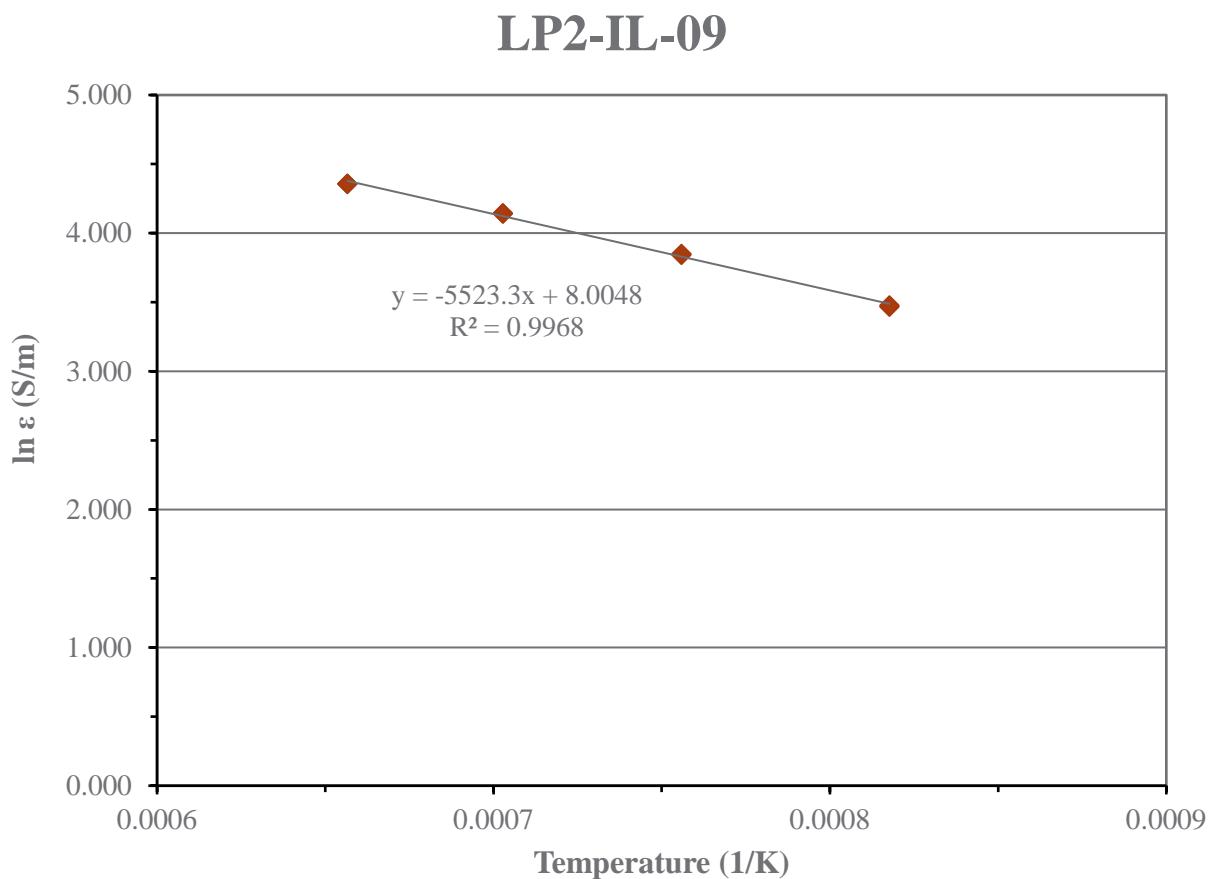


Figure D.9. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-09

## D.10 Glass LP2-IL-10 Electrical Conductivity Data

Table D.10. Electrical Conductivity Data for Glass LP2-IL-10

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	25.98	0.000818	3.257
950	26.15	0.000818	3.264
1250	66.30	0.000657	4.194
1150	52.45	0.000703	3.960
1150	52.49	0.000703	3.961
1050	38.43	0.000756	3.649
1050	38.58	0.000756	3.653

### LP2-IL-10

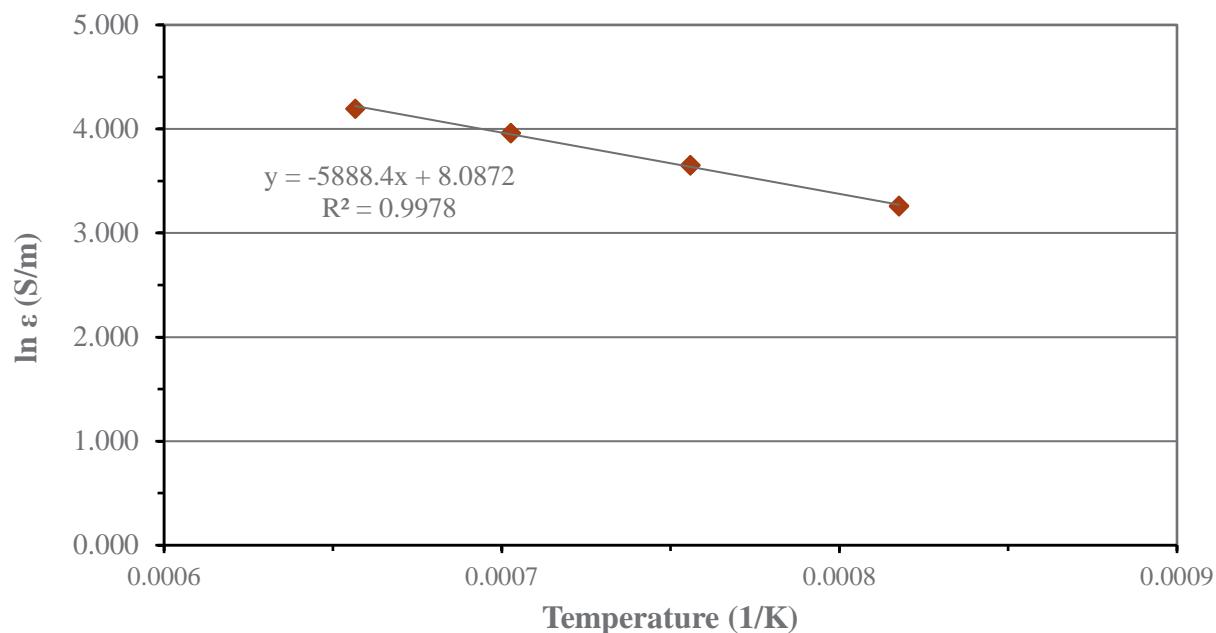


Figure D.10. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-10

## D.11 Glass LP2-IL-11 Electrical Conductivity Data

Table D.11. Electrical Conductivity Data for Glass LP2-IL-11

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	26.28	0.000818	3.269
950	26.46	0.000818	3.275
1250	67.31	0.000657	4.209
1250	67.15	0.000657	4.207
1150	53.36	0.000703	3.977
1150	53.51	0.000703	3.980
1050	39.20	0.000756	3.669
1050	39.35	0.000756	3.673

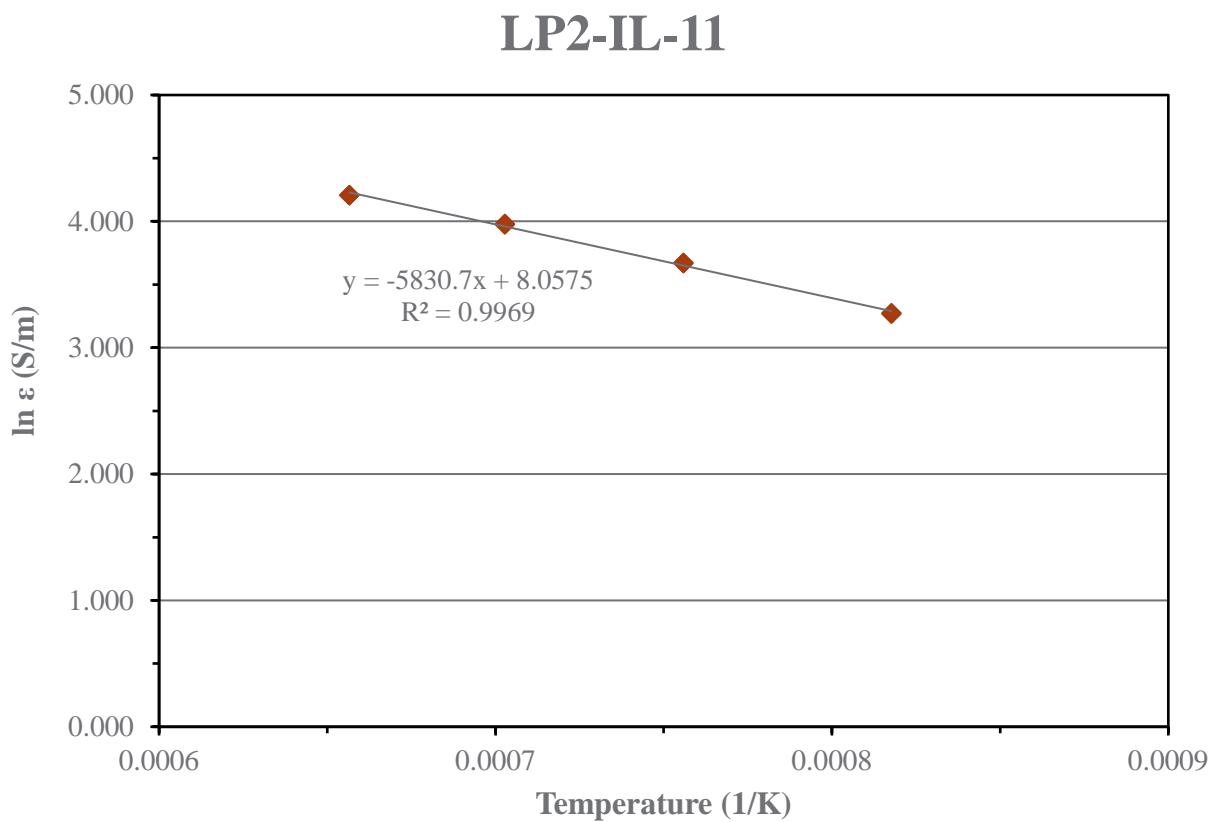


Figure D.11. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-11

## D.12 Glass LP2-IL-12 Electrical Conductivity Data

Table D.12. Electrical Conductivity Data for Glass LP2-IL-12

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	31.38	0.000818	3.446
950	31.56	0.000818	3.452
1250	72.80	0.000657	4.288
1250	72.57	0.000657	4.285
1150	58.67	0.000703	4.072
1150	58.76	0.000703	4.074
1050	44.61	0.000756	3.798
1050	44.76	0.000756	3.801

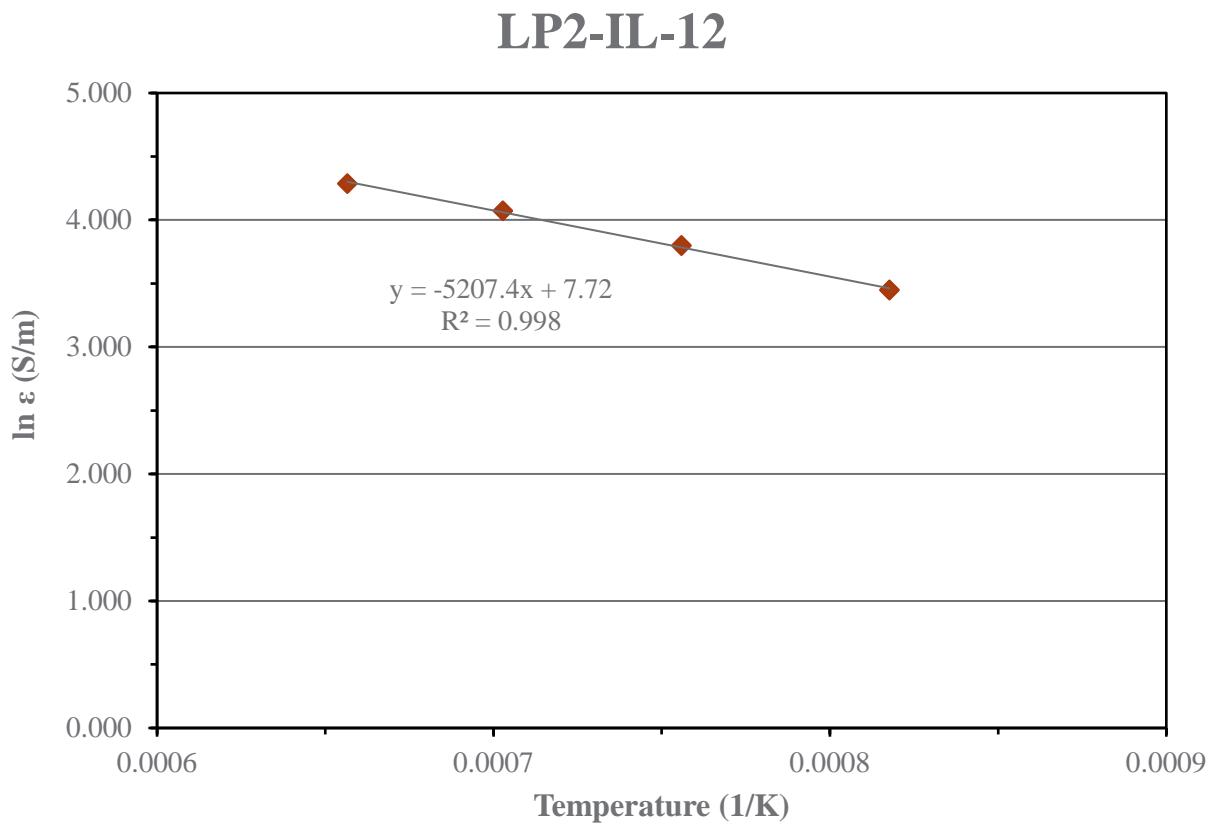


Figure D.12. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-12

## D.13 Glass LP2-IL-13 Electrical Conductivity Data

Table D.13. Electrical Conductivity Data for Glass LP2-IL-13

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	23.23	0.000818	3.146
950	23.43	0.000818	3.154
1250	59.73	0.000657	4.090
1250	59.59	0.000657	4.088
1150	46.95	0.000703	3.849
1150	47.02	0.000703	3.851
1050	34.51	0.000756	3.541
1050	34.64	0.000756	3.545

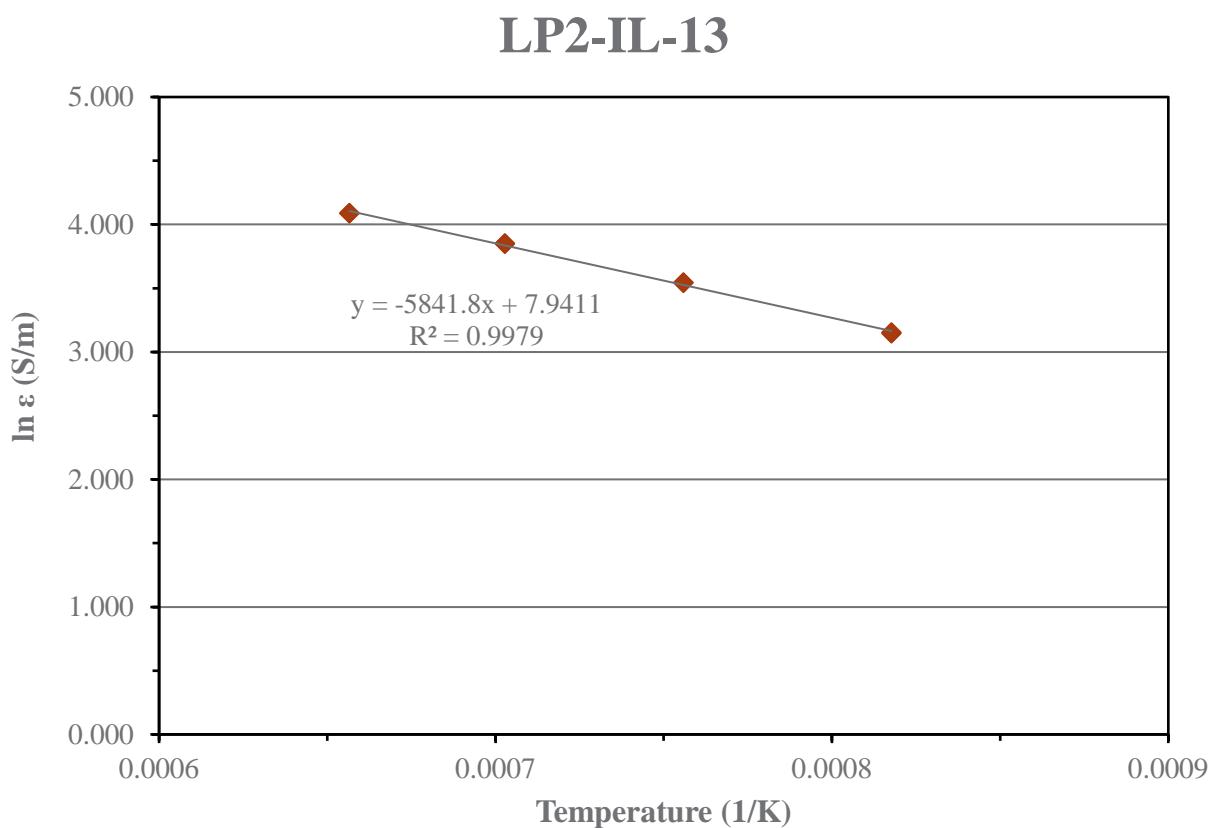


Figure D.13. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-13

## D.14 Glass LP2-IL-14 Electrical Conductivity Data

Table D.14. Electrical Conductivity Data for Glass LP2-IL-14

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	33.40	0.000818	3.509
950	33.60	0.000818	3.515
1250	77.16	0.000657	4.346
1250	77.08	0.000657	4.345
1150	62.61	0.000703	4.137
1150	62.67	0.000703	4.138
1050	47.55	0.000756	3.862
1050	47.71	0.000756	3.865

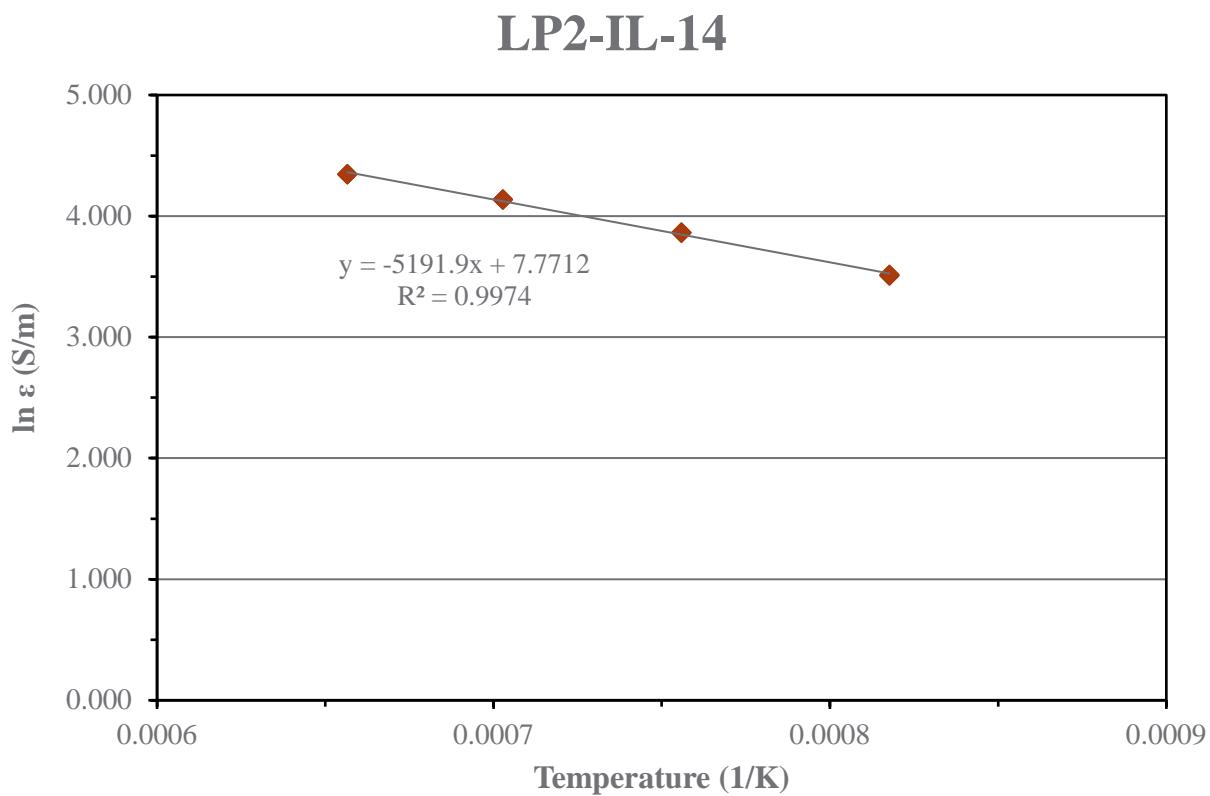


Figure D.14. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-14

## D.15 Glass LP2-IL-15 Electrical Conductivity Data

Table D.15. Electrical Conductivity Data for Glass LP2-IL-15

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	31.28	0.000818	3.443
950	31.54	0.000818	3.451
1250	76.13	0.000657	4.332
1250	75.99	0.000657	4.331
1150	61.16	0.000703	4.114
1150	61.25	0.000703	4.115
1050	45.69	0.000756	3.822
1050	45.83	0.000756	3.825

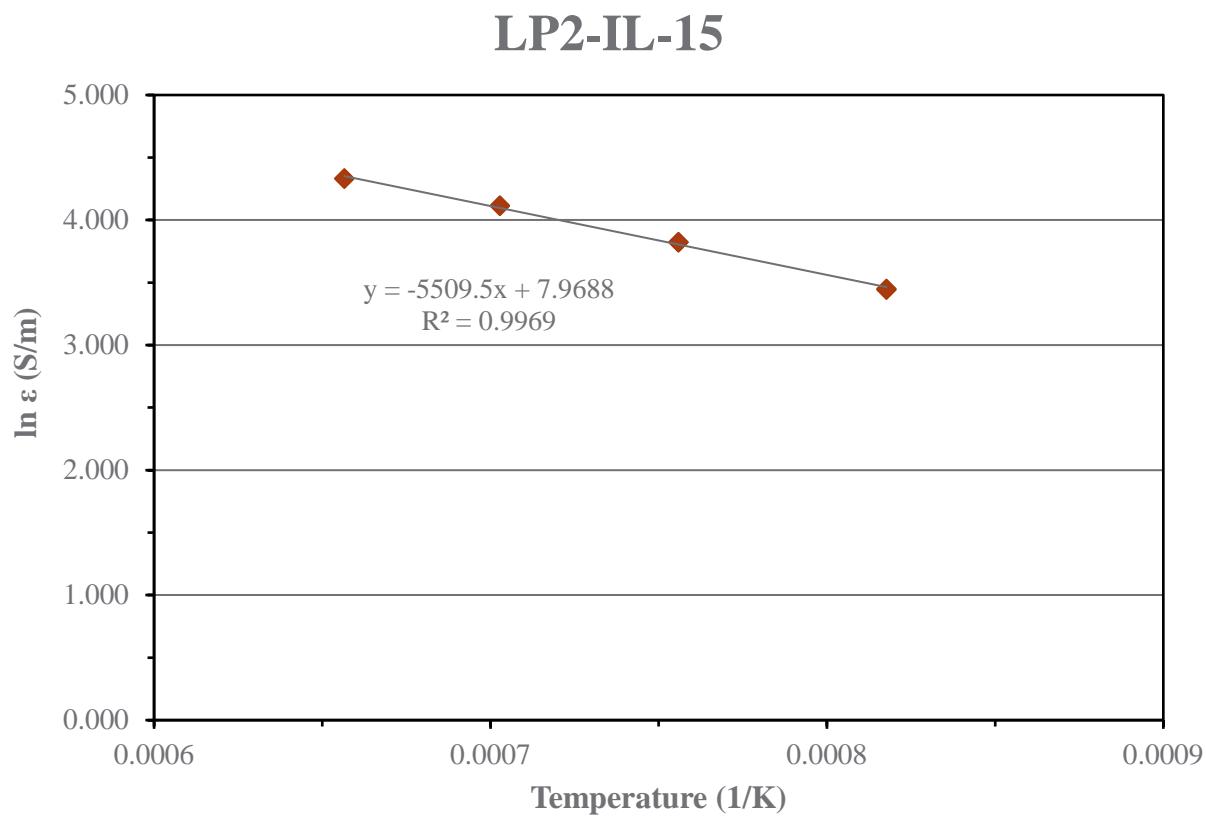


Figure D.15. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-15

## D.16 Glass LP2-IL-16 Electrical Conductivity Data

Table D.16. Electrical Conductivity Data for Glass LP2-IL-16

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	27.92	0.000818	3.329
950	28.12	0.000818	3.336
1250	71.28	0.000657	4.267
1150	56.26	0.000703	4.030
1150	56.44	0.000703	4.033
1050	41.34	0.000756	3.722
1050	41.53	0.000756	3.726

## LP2-IL-16

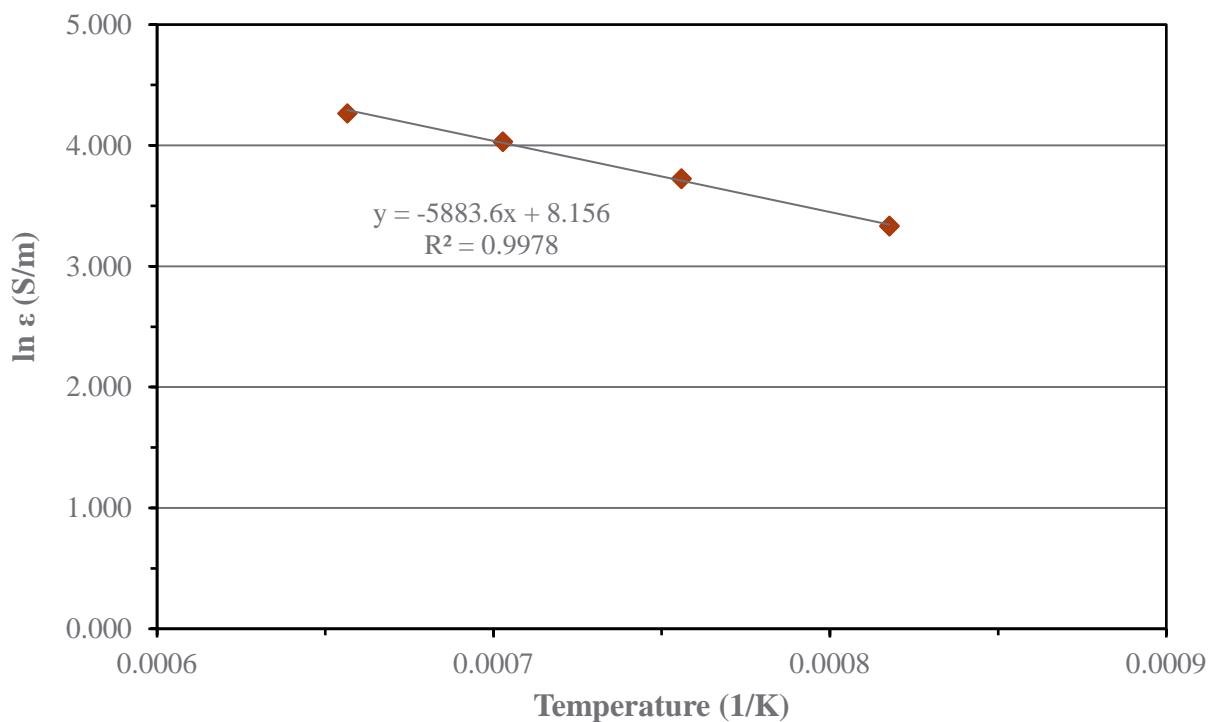


Figure D.16. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-16

## D.17 Glass LP2-IL-17 Electrical Conductivity Data

Table D.17. Electrical Conductivity Data for Glass LP2-IL-17

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	26.44	0.000818	3.275
950	26.74	0.000818	3.286
1250	63.45	0.000657	4.150
1250	63.35	0.000657	4.149
1150	51.45	0.000703	3.941
1150	51.58	0.000703	3.943
1050	38.74	0.000756	3.657
1050	38.95	0.000756	3.662

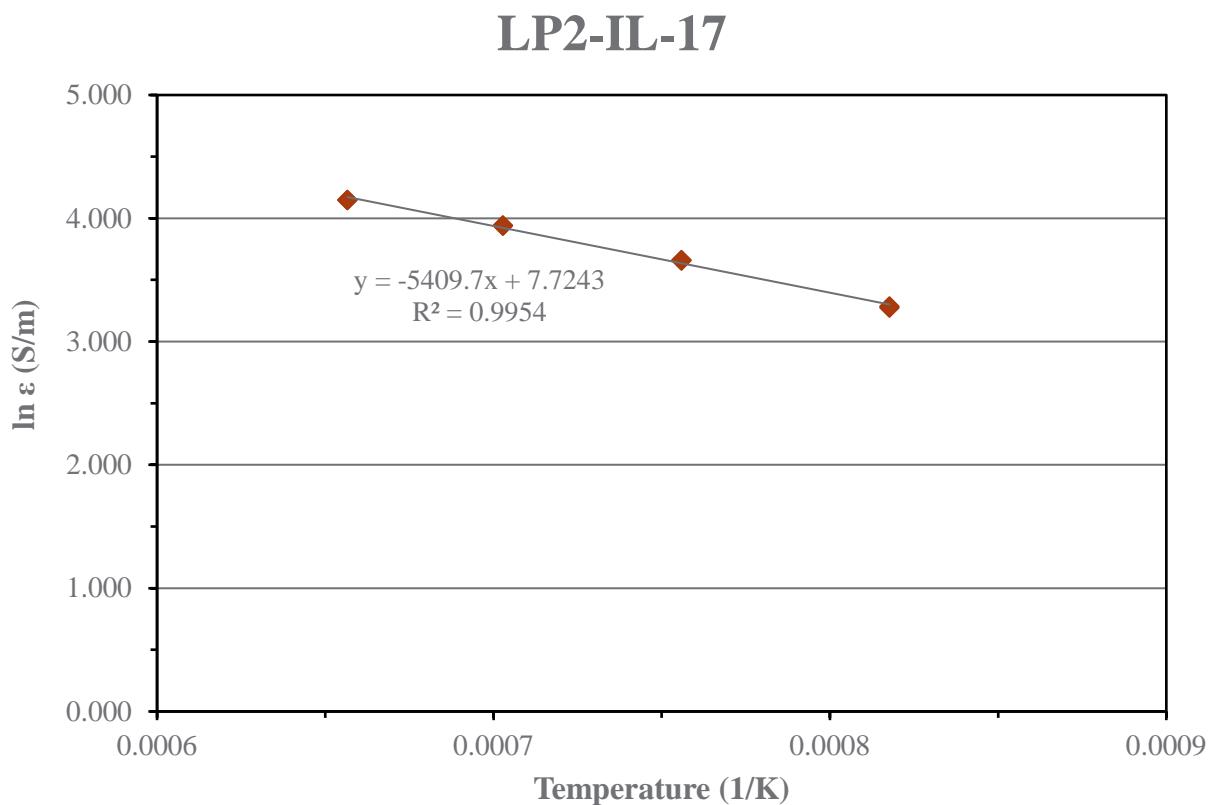


Figure D.17. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-IL-17

## D.18 Glass LP2-OL-01-3 Electrical Conductivity Data

Table D.18. Electrical Conductivity Data for Glass LP2-OL-01-3

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	14.83	0.000818	2.697
950	14.96	0.000818	2.705
1250	44.00	0.000657	3.784
1250	44.01	0.000657	3.785
1150	33.44	0.000703	3.510
1150	33.52	0.000703	3.512
1050	23.48	0.000756	3.156
1050	23.57	0.000756	3.160

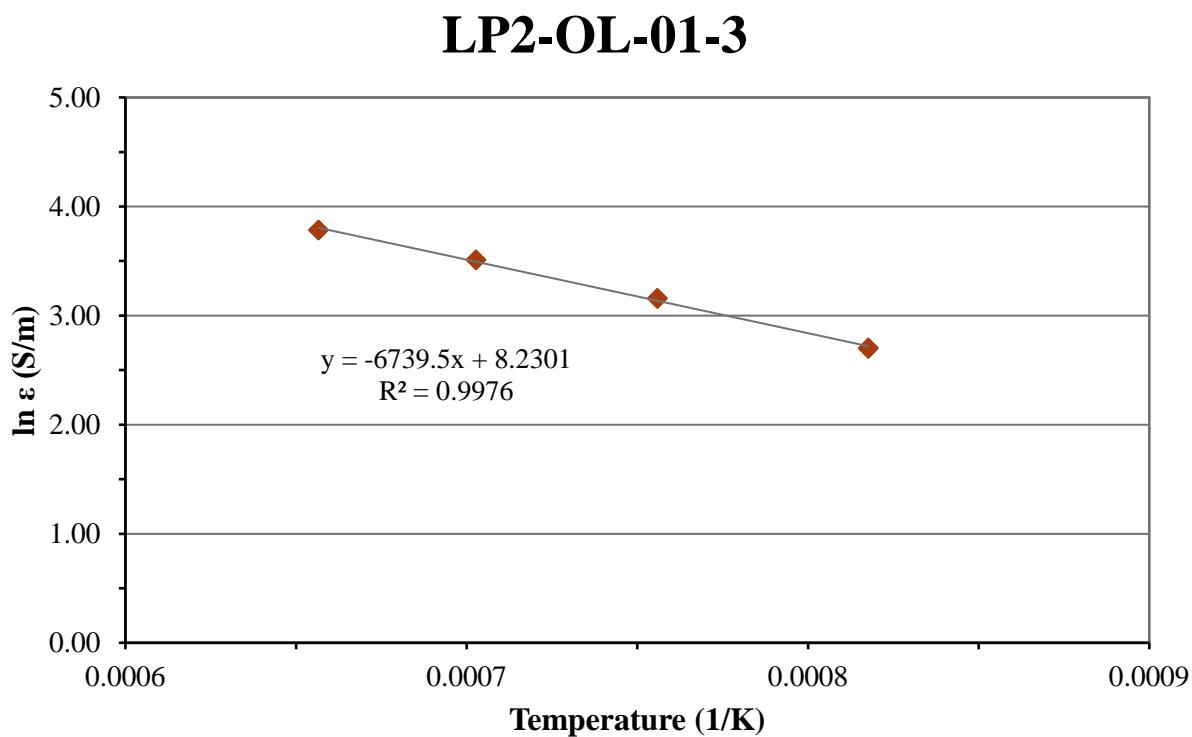


Figure D.18. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-01-3

## D.19 Glass LP2-OL-02-1 Electrical Conductivity Data

Table D.19. Electrical Conductivity Data for Glass LP2-OL-02-1

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	In (ε, S/m)
950	23.45	0.000818	3.155
950	23.59	0.000818	3.161
1250	57.98	0.000657	4.060
1250	57.83	0.000657	4.058
1150	46.24	0.000703	3.834
1150	46.41	0.000703	3.838
1050	34.37	0.000756	3.537
1050	34.50	0.000756	3.541

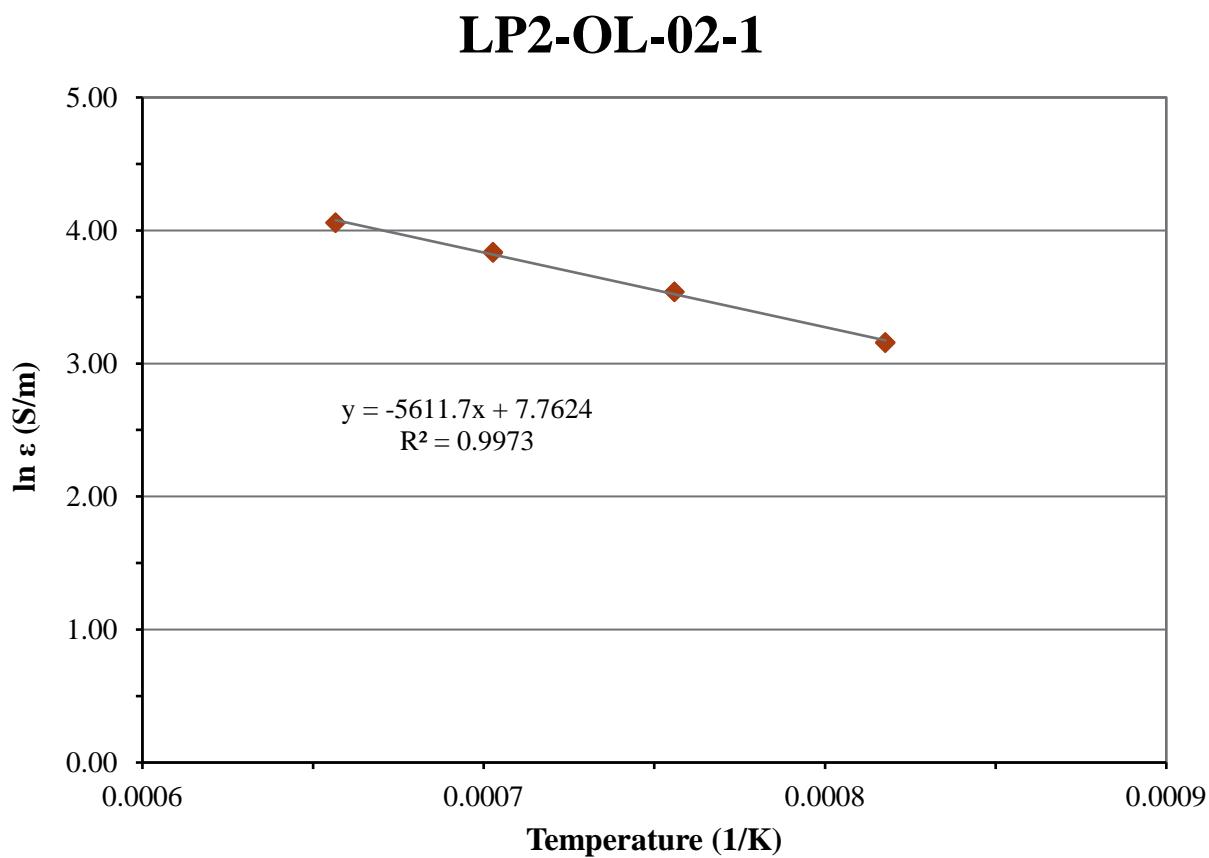


Figure D.19. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-02-1

## D.20 Glass LP2-OL-03 MOD2 Electrical Conductivity Data

Table D.20. Electrical Conductivity Data for Glass LP2-OL-03 MOD2

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	31.38	0.000818	3.446
950	31.62	0.000818	3.454
1250	75.08	0.000657	4.319
1150	60.88	0.000703	4.109
1150	61.02	0.000703	4.111
1050	45.59	0.000756	3.820
1050	45.77	0.000756	3.824

## LP2-OL-03 MOD2

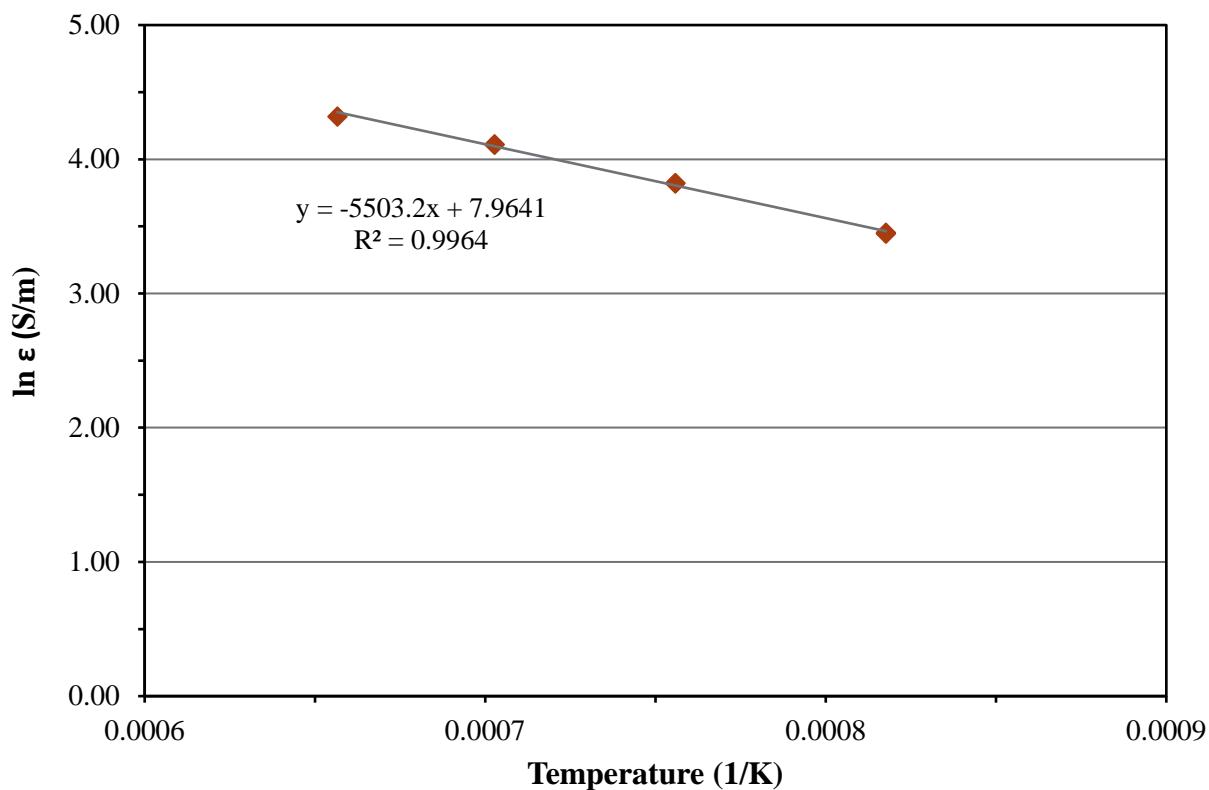


Figure D.20. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-03 MOD2

## D.21 Glass LP2-OL-04-1 Electrical Conductivity Data

Table D.21. Electrical Conductivity Data for Glass LP2-OL-04-1

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	19.23	0.000818	2.956
950	19.40	0.000818	2.965
1250	54.31	0.000657	3.995
1150	42.44	0.000703	3.748
1150	42.53	0.000703	3.750
1050	30.20	0.000756	3.408
1050	30.34	0.000756	3.413

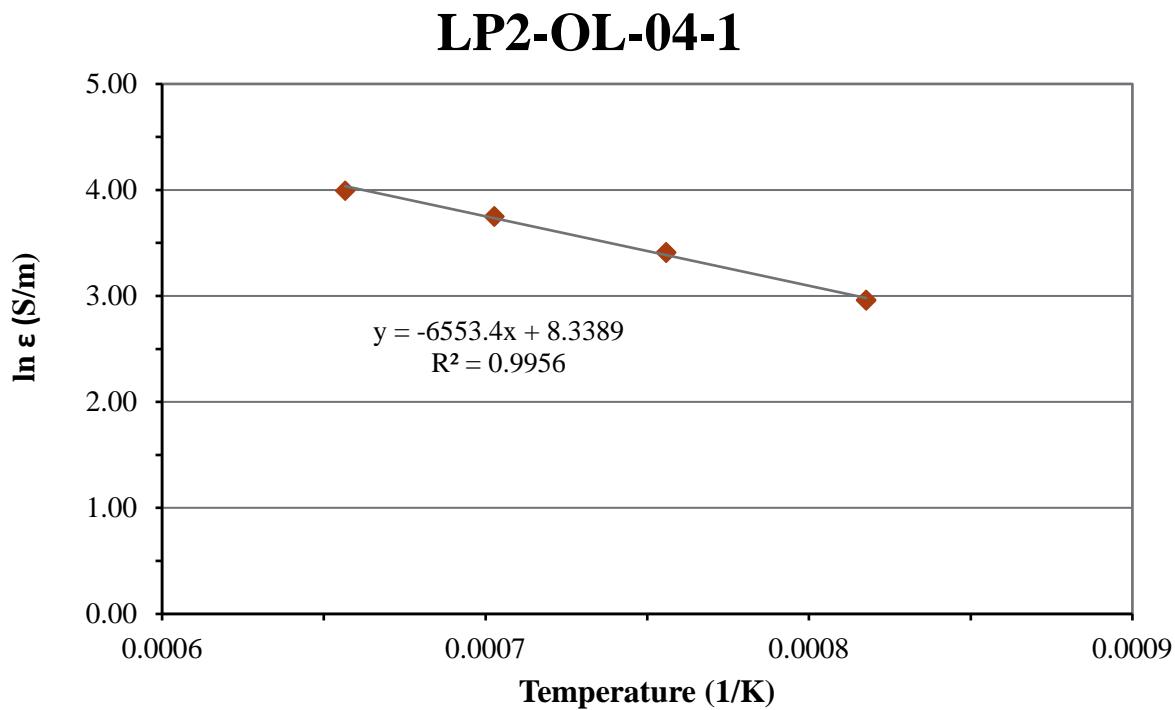


Figure D.21. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-04-1

## D.22 Glass LP2-OL-05 Electrical Conductivity Data

Table D.22. Electrical Conductivity Data for Glass LP2-OL-05

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	16.27	0.000818	2.789
950	16.40	0.000818	2.797
1250	46.29	0.000657	3.835
1250	46.13	0.000657	3.832
1150	35.81	0.000703	3.578
1150	35.90	0.000703	3.581
1050	25.42	0.000756	3.236
1050	25.55	0.000756	3.241

## LP2-OL-05

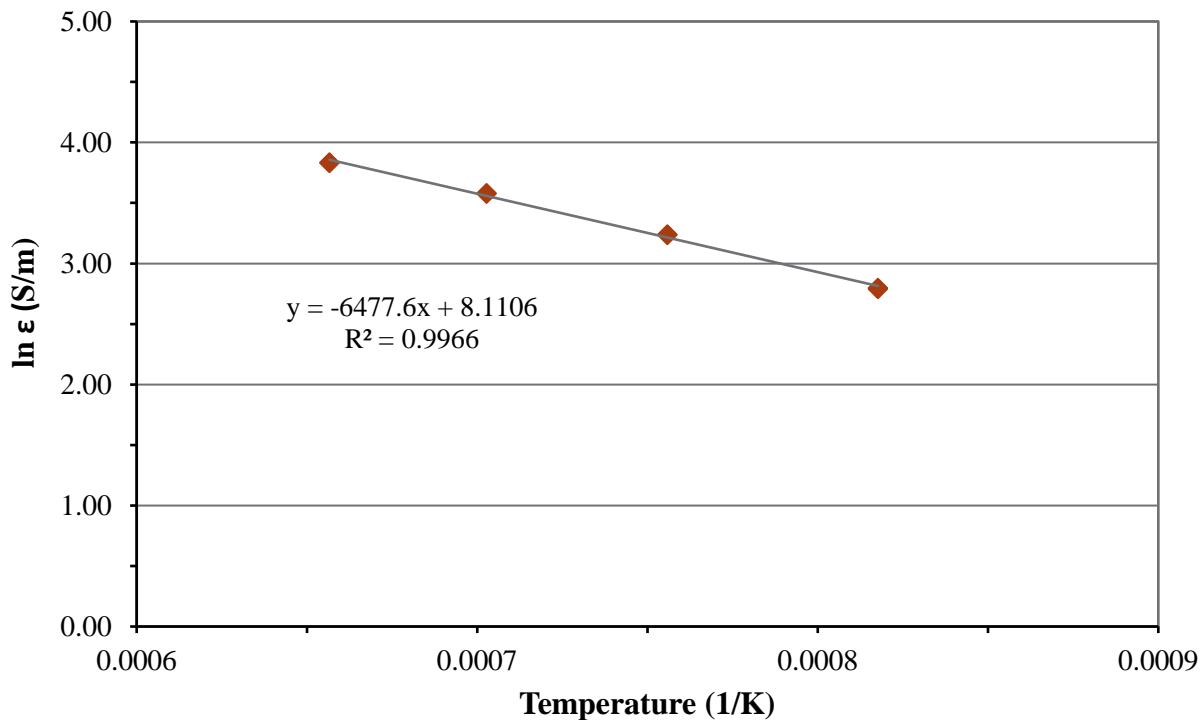


Figure D.22. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-05

## D.23 Glass LP2-OL-07-1 Electrical Conductivity Data

Table D.23. Electrical Conductivity Data for Glass LP2-OL-07-1

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	17.50	0.000818	2.862
950	17.64	0.000818	2.870
1250	48.69	0.000657	3.885
1150	37.82	0.000703	3.633
1150	37.84	0.000703	3.633
1050	27.05	0.000756	3.298
1050	27.17	0.000756	3.302

## LP2-OL-07-1

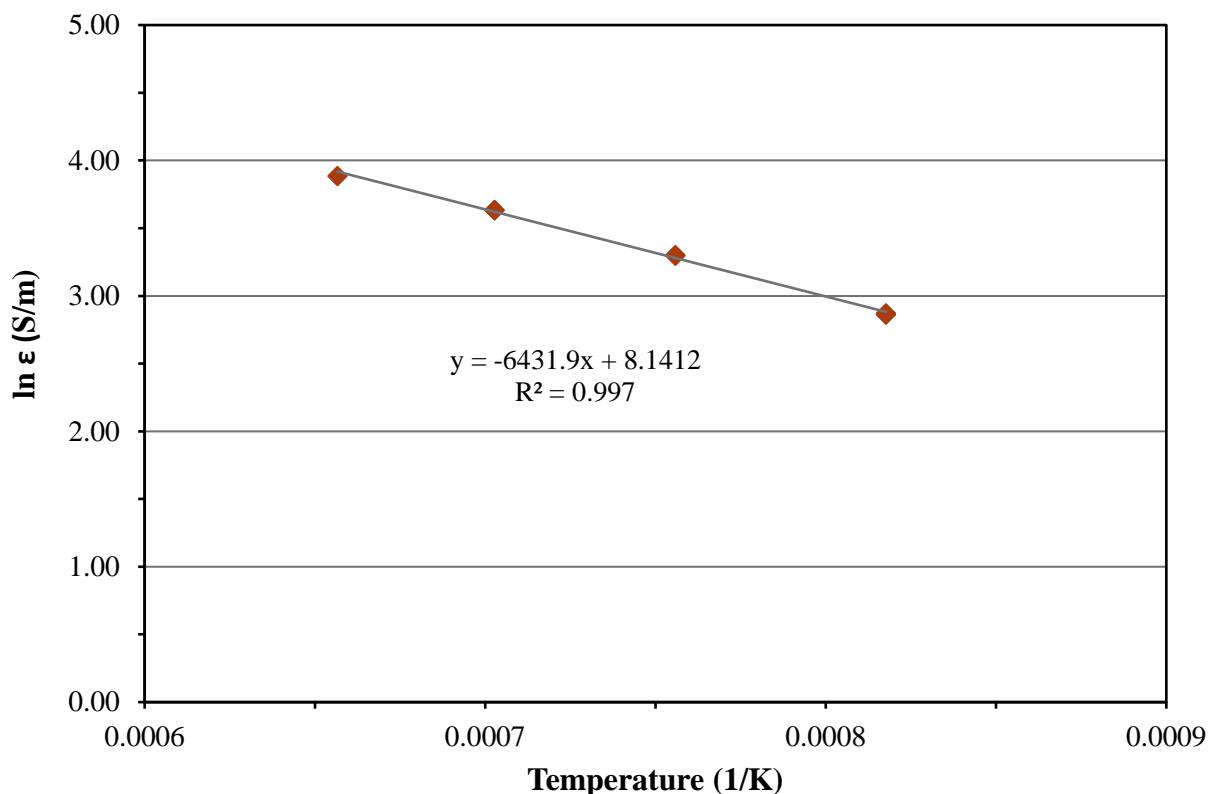


Figure D.23. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-07-1

## D.24 Glass LP2-OL-08 MOD Electrical Conductivity Data

Table D.24. Electrical Conductivity Data for Glass LP2-OL-08 MOD

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	36.85	0.000818	3.607
950	37.08	0.000818	3.613
1250	80.67	0.000657	4.390
1150	65.99	0.000703	4.189
1150	66.09	0.000703	4.191
1050	51.18	0.000756	3.935
1050	51.28	0.000756	3.937

## LP2-OL-08 MOD

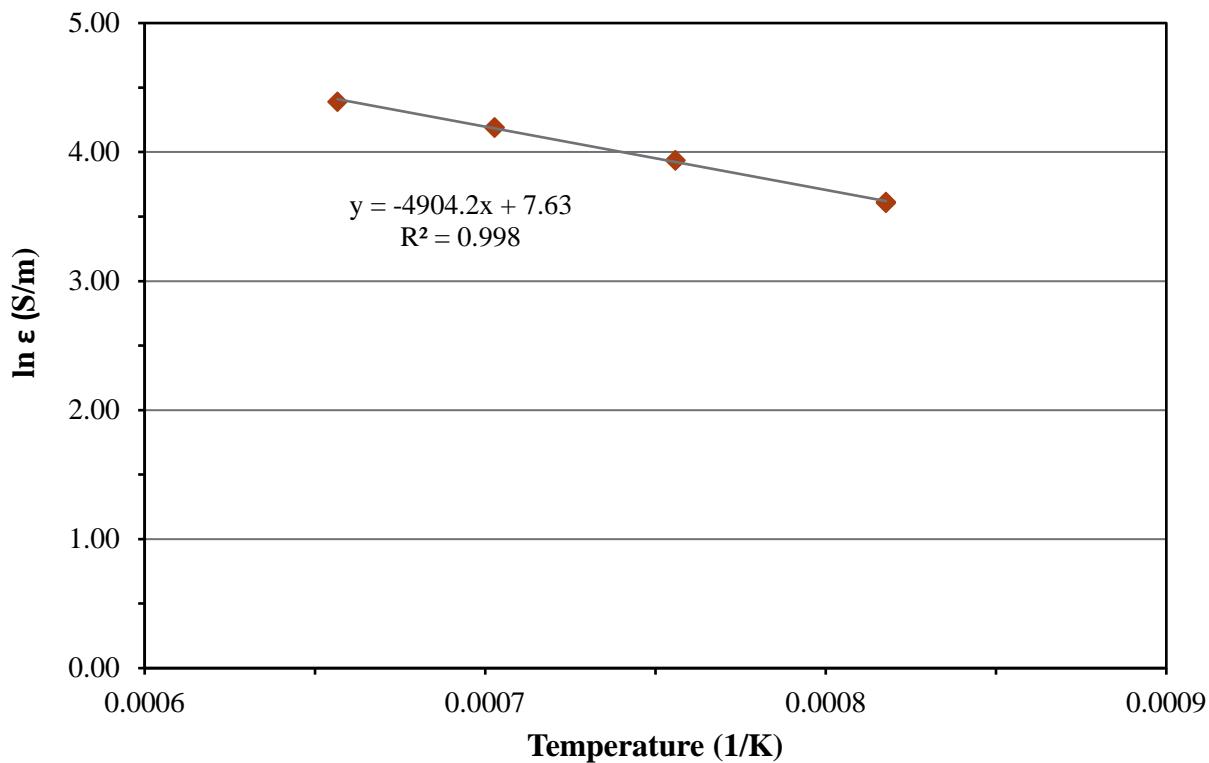


Figure D.24. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-08 MOD

## D.25 Glass LP2-OL-09-1 Electrical Conductivity Data

Table D.25. Electrical Conductivity Data for Glass LP2-OL-09-1

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	19.36	0.000818	2.963
950	19.49	0.000818	2.970
1250	49.63	0.000657	3.905
1250	49.52	0.000657	3.902
1150	39.48	0.000703	3.676
1150	39.56	0.000703	3.678
1050	28.89	0.000756	3.364
1050	29.01	0.000756	3.368

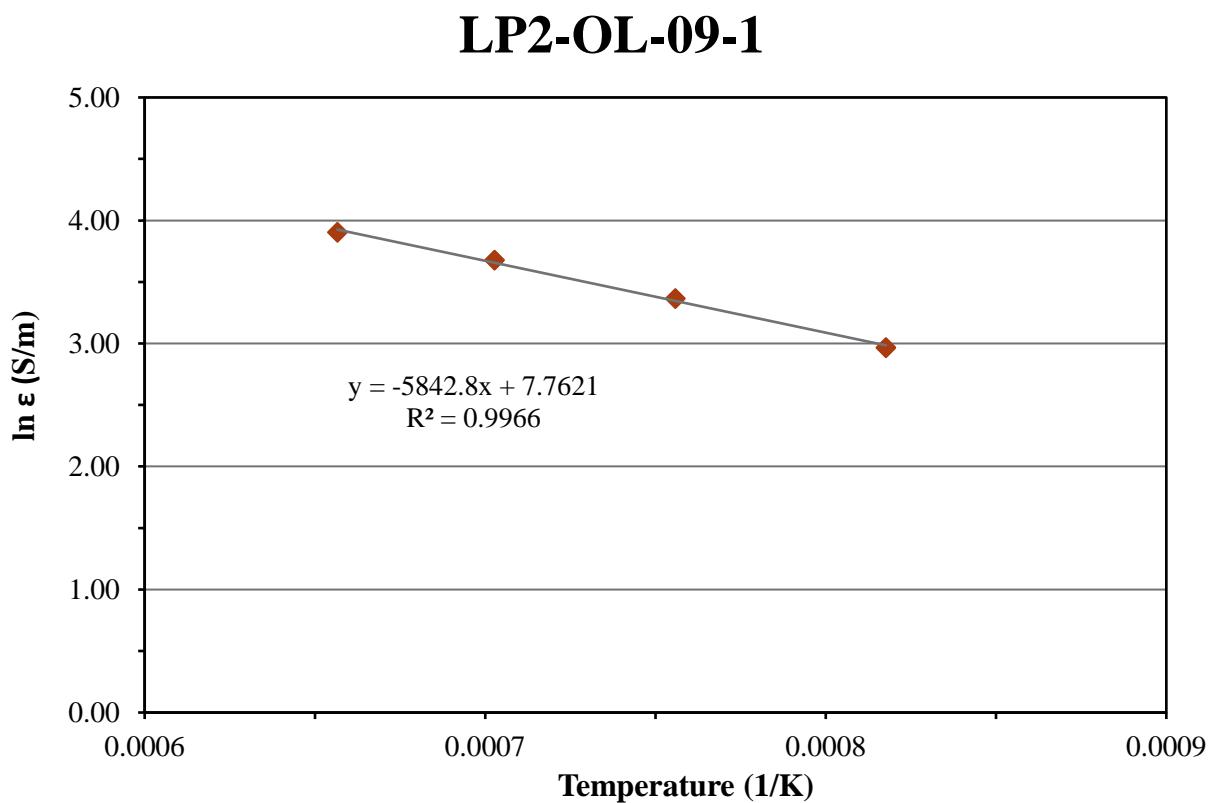


Figure D.25. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-09-1

## D.26 Glass LP2-OL-10 MOD Electrical Conductivity Data

Table D.26. Electrical Conductivity Data for Glass LP2-OL-10 MOD

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	17.28	0.000818	2.850
950	17.43	0.000818	2.858
1250	47.47	0.000657	3.860
1150	36.95	0.000703	3.610
1150	37.05	0.000703	3.612
1050	26.60	0.000756	3.281
1050	26.72	0.000756	3.285

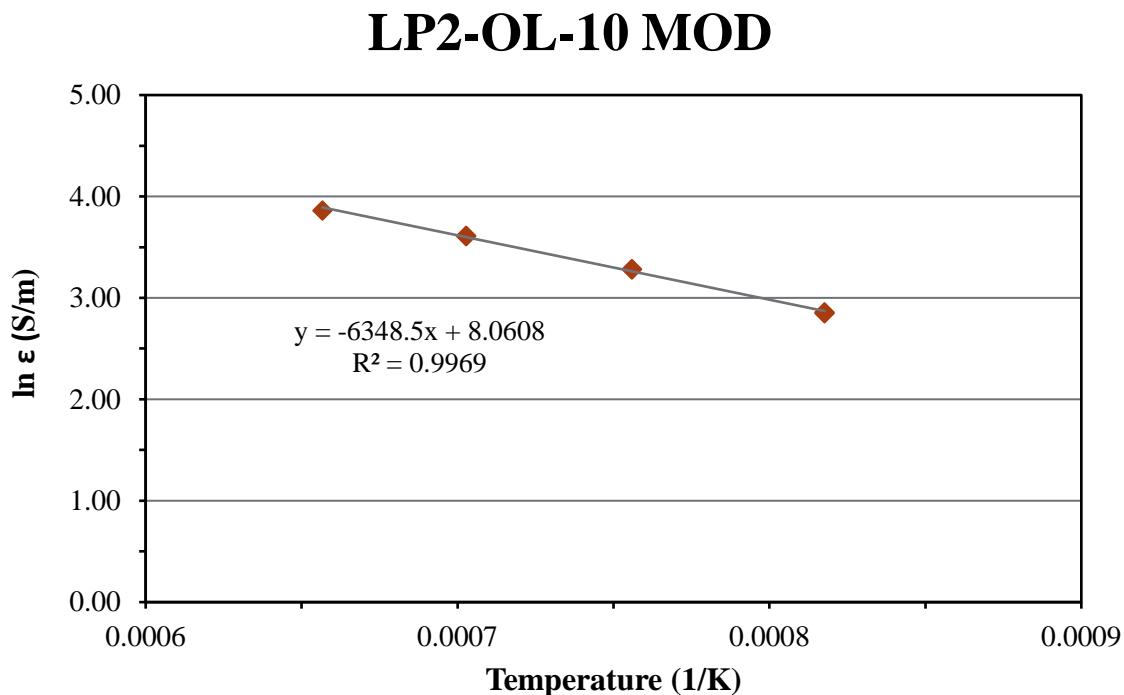


Figure D.26. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-10 MOD

## D.27 Glass LP2-OL-11 Electrical Conductivity Data

Table D.27. Electrical Conductivity Data for Glass LP2-OL-11

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	23.42	0.000818	3.154
950	23.58	0.000818	3.161
1250	61.58	0.000657	4.120
1150	48.62	0.000703	3.884
1150	48.77	0.000703	3.887
1050	35.57	0.000756	3.571
1050	35.70	0.000756	3.575

## LP2-OL-11

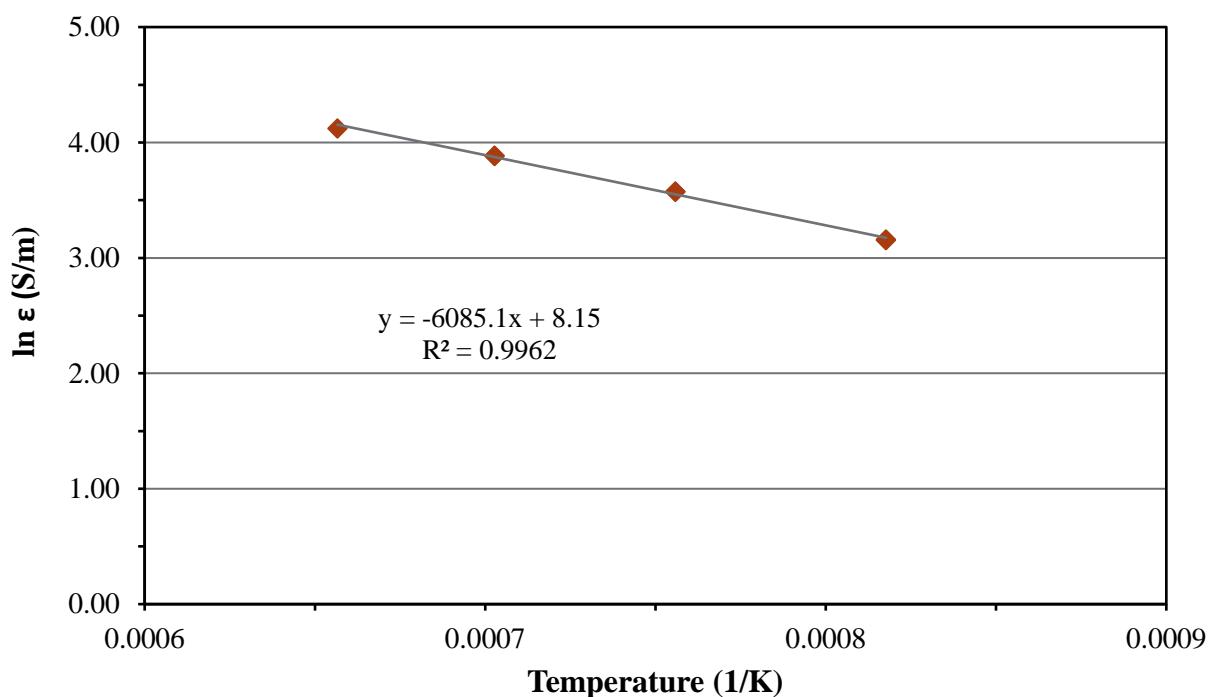


Figure D.27. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-11

## D.28 Glass LP2-OL-12 Electrical Conductivity Data

Table D.28. Electrical Conductivity Data for Glass LP2-OL-12

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	32.16	0.000818	3.471
950	32.33	0.000818	3.476
1250	74.87	0.000657	4.316
1150	60.44	0.000703	4.102
1150	60.68	0.000703	4.106
1050	45.87	0.000756	3.826
1050	46.09	0.000756	3.831

## LP2-OL-12

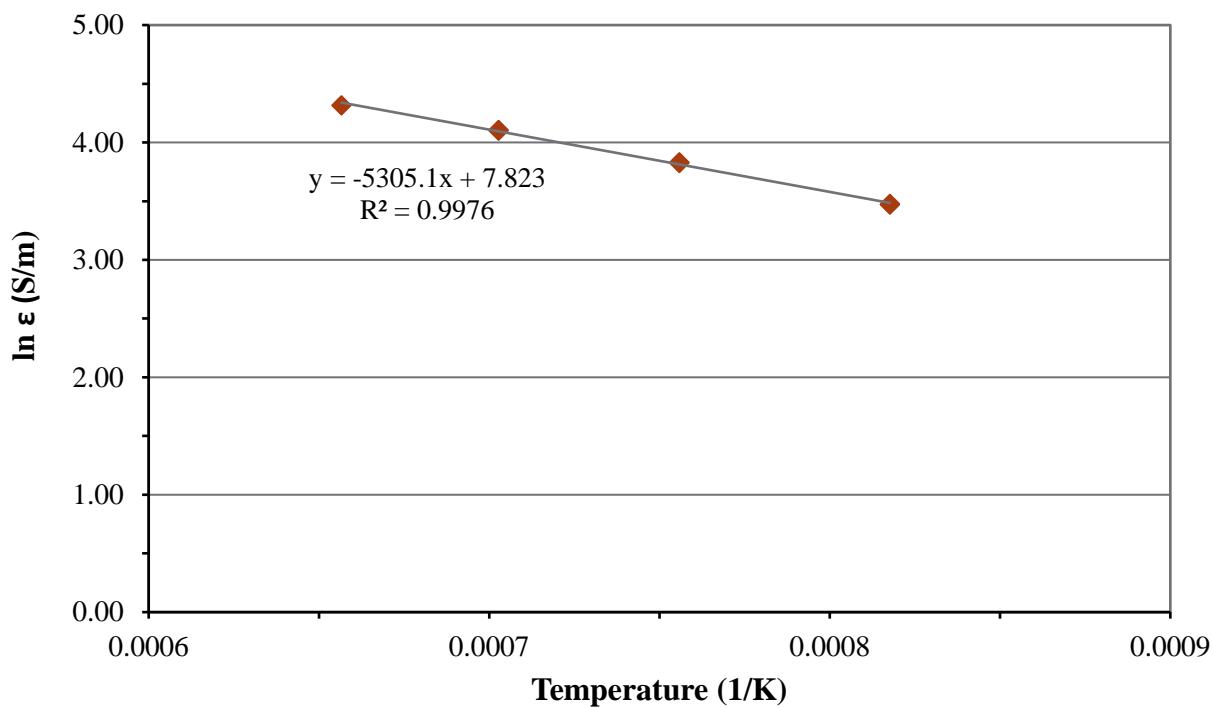


Figure D.28. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-12

## D.29 Glass LP2-OL-13 Electrical Conductivity Data

Table D.29. Electrical Conductivity Data for Glass LP2-OL-13

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	29.13	0.000818	3.372
950	29.43	0.000818	3.382
1250	69.77	0.000657	4.245
1250	69.52	0.000657	4.242
1150	56.89	0.000703	4.041
1150	57.02	0.000703	4.043
1050	42.86	0.000756	3.758
1050	43.01	0.000756	3.762

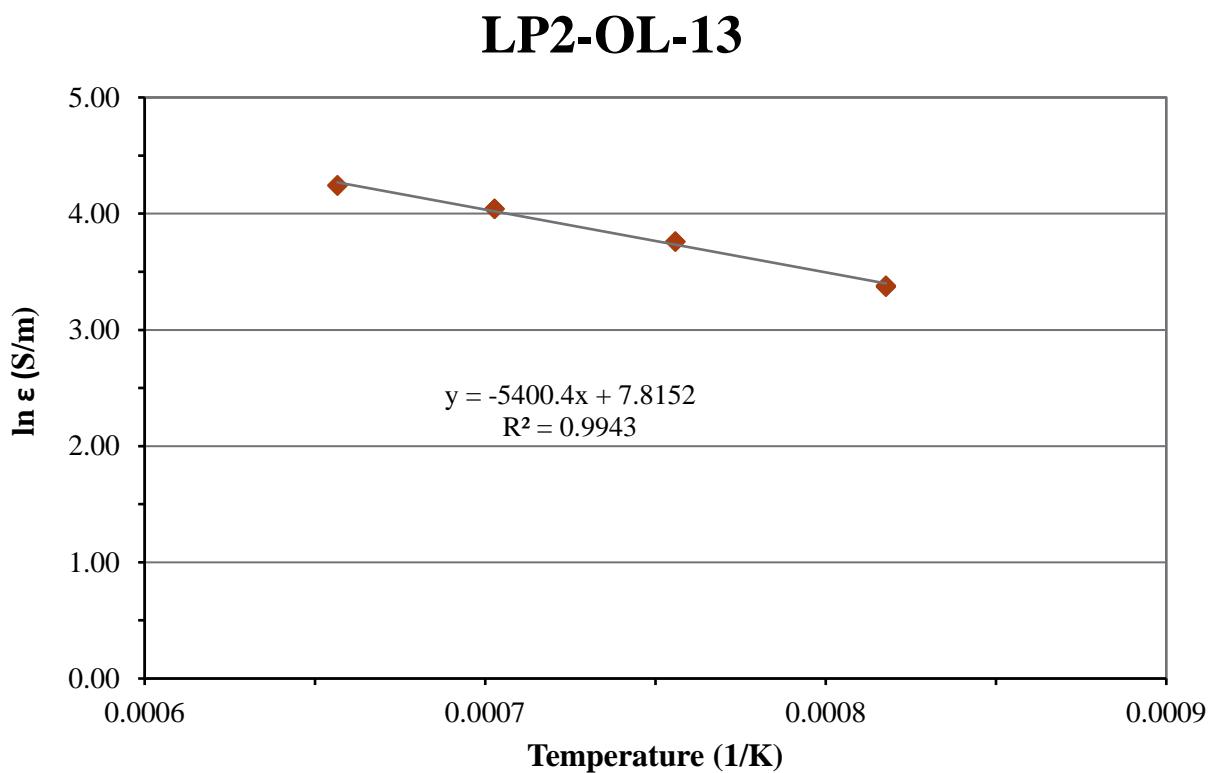


Figure D.29. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-13

### D.30 Glass LP2-OL-14 Electrical Conductivity Data

Table D.30. Electrical Conductivity Data for Glass LP2-OL-14

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	25.46	0.000818	3.237
950	25.64	0.000818	3.244
1250	64.31	0.000657	4.164
1250	64.06	0.000657	4.160
1150	51.32	0.000703	3.938
1050	37.98	0.000756	3.637
1050	38.18	0.000756	3.642

### LP2-OL-14

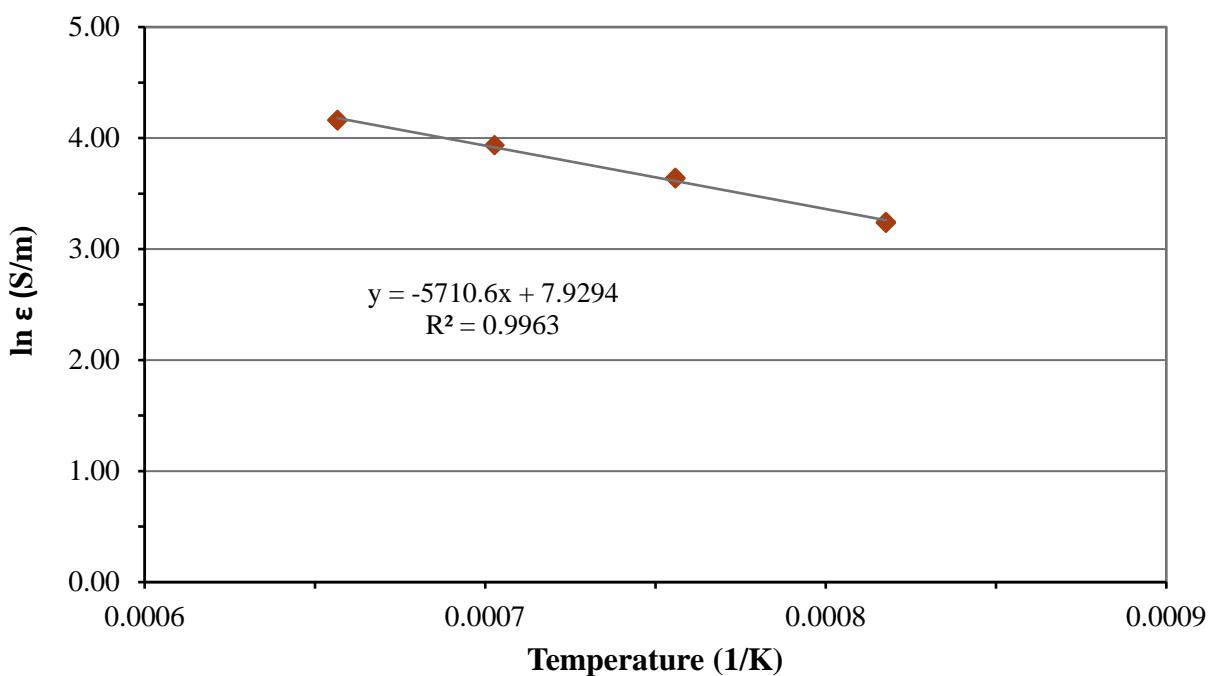


Figure D.30. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-14

### D.31 Glass LP2-OL-15 Electrical Conductivity Data

Table D.31. Electrical Conductivity Data for Glass LP2-OL-15

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	16.36	0.000818	2.795
950	16.52	0.000818	2.804
1250	53.12	0.000657	3.973
1250	52.90	0.000657	3.968
1150	39.76	0.000703	3.683
1150	39.88	0.000703	3.686
1050	27.04	0.000756	3.297
1050	27.20	0.000756	3.303

### LP2-OL-15

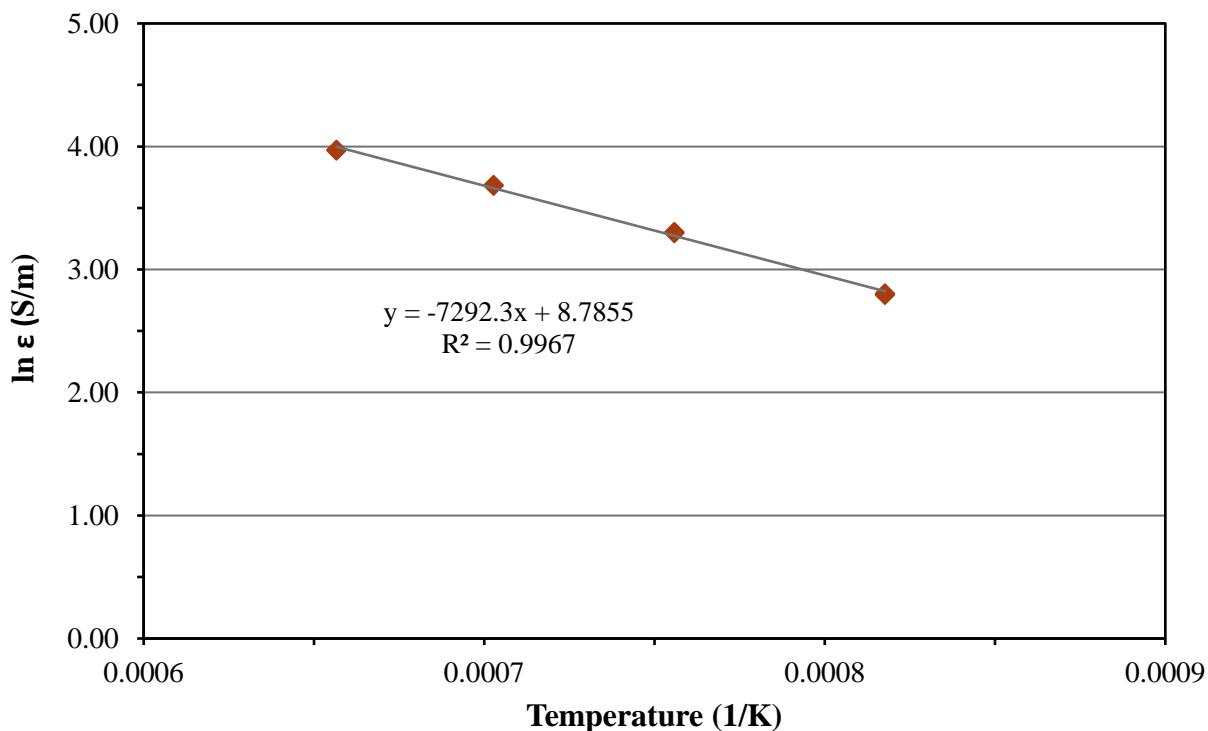


Figure D.31. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-15

### D.32 Glass LP2-OL-16 MOD Electrical Conductivity Data

Table D.32. Electrical Conductivity Data for Glass LP2-OL-16 MOD

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	21.94	0.000818	3.088
950	22.10	0.000818	3.096
1250	52.45	0.000657	3.960
1150	42.11	0.000703	3.740
1150	42.05	0.000703	3.739
1050	31.69	0.000756	3.456
1050	31.84	0.000756	3.461

### LP2-OL-16 MOD

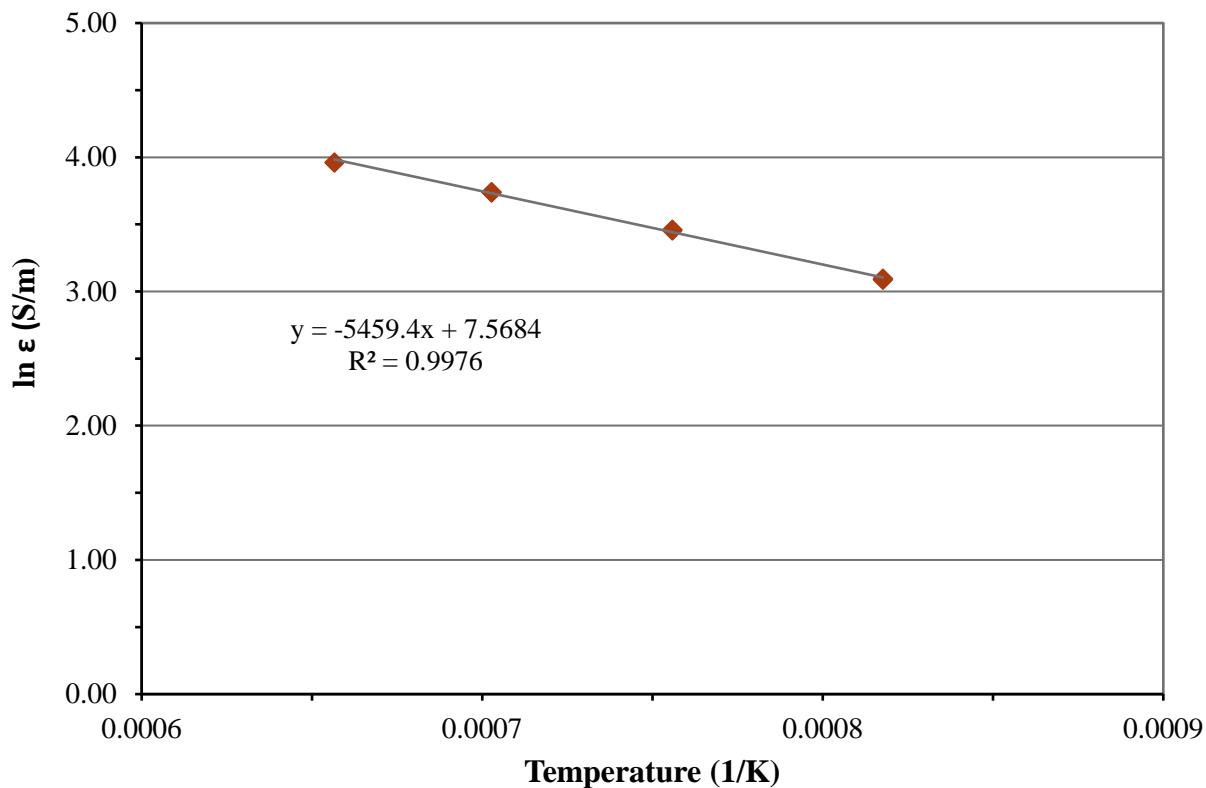


Figure D.32. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-16 MOD

### D.33 Glass LP2-OL-17 Electrical Conductivity Data

Table D.33. Electrical Conductivity Data for Glass LP2-OL-17

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	29.46	0.000818	3.383
950	29.65	0.000818	3.389
1250	70.24	0.000657	4.252
1150	56.52	0.000703	4.035
1050	42.63	0.000756	3.752
1050	42.74	0.000756	3.755

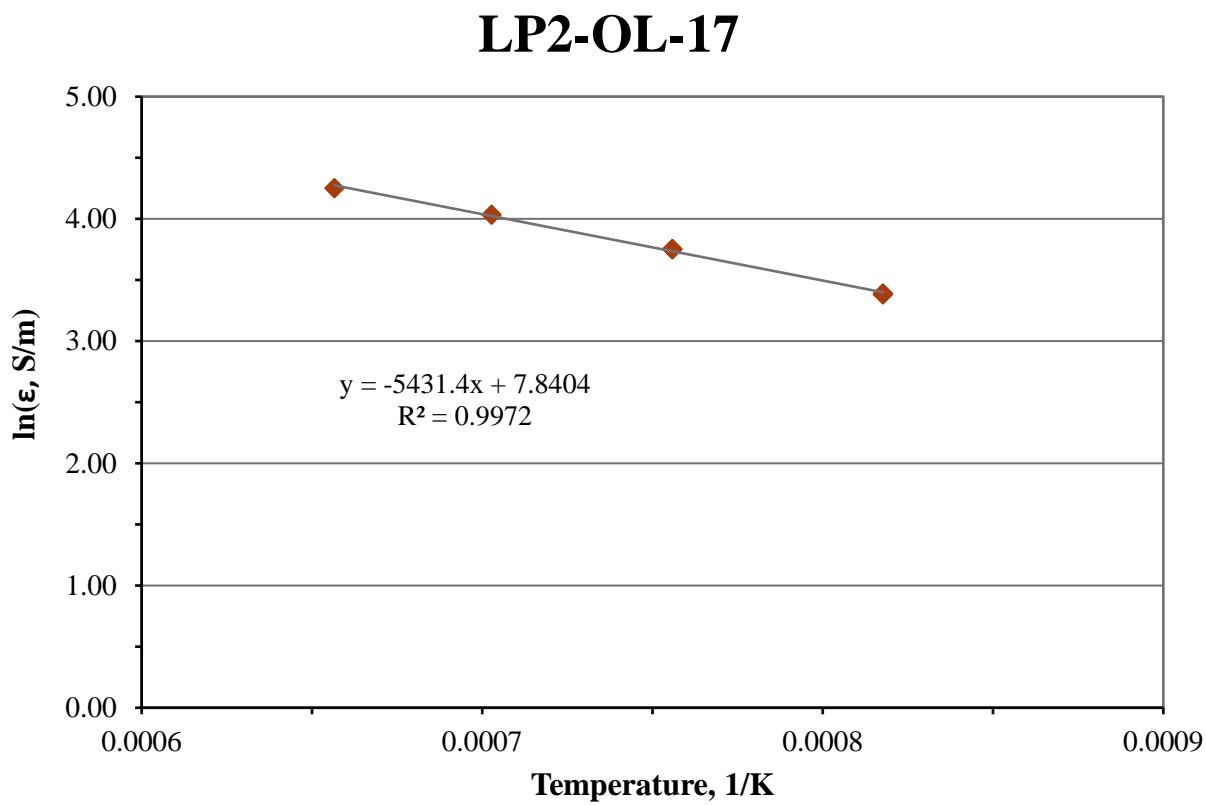


Figure D.33. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-17

### D.34 Glass LP2-OL-18 Electrical Conductivity Data

Table D.34. Electrical Conductivity Data for Glass LP2-OL-18

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	19.86	0.000818	2.989
950	19.99	0.000818	2.995
1250	56.39	0.000657	4.032
1150	43.40	0.000703	3.770
1150	43.60	0.000703	3.775
1050	30.72	0.000756	3.425
1050	30.84	0.000756	3.429

### LP2-OL-18

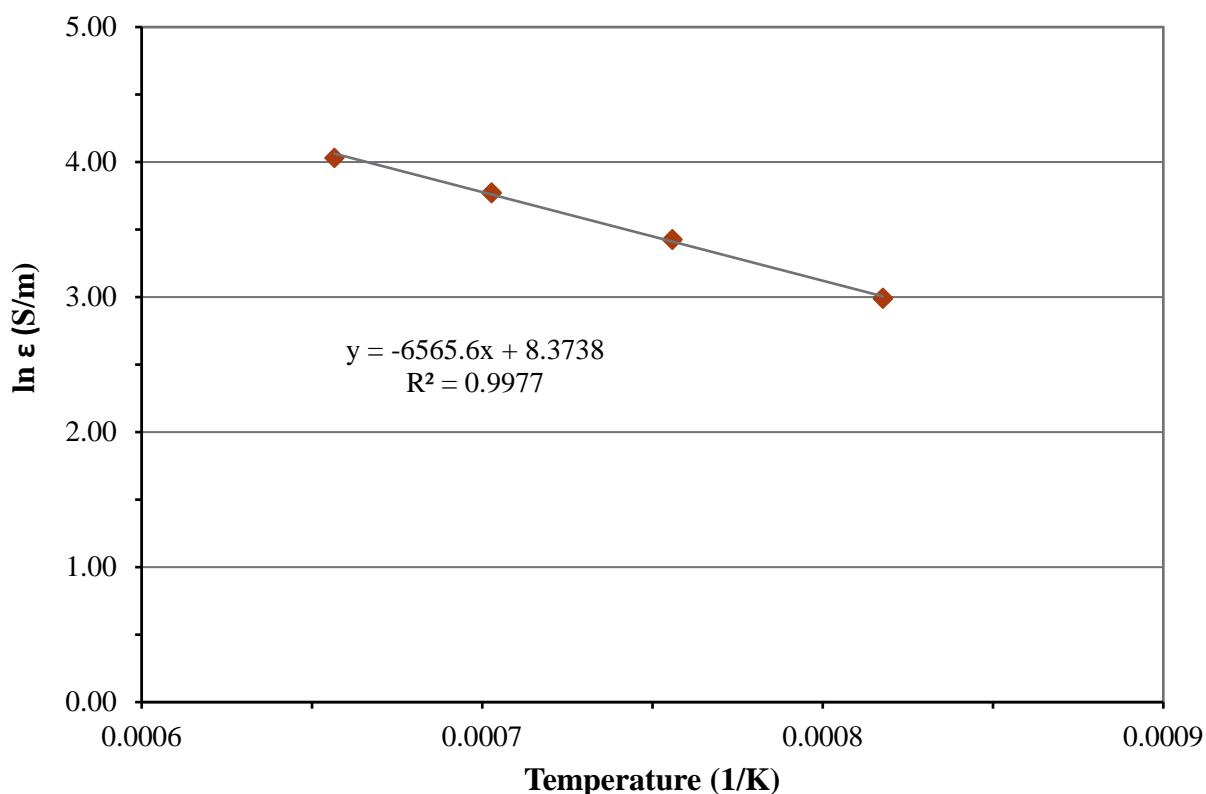


Figure D.34. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-18

### D.35 Glass LP2-OL-19 Electrical Conductivity Data

Table D.35. Electrical Conductivity Data for Glass LP2-OL-19

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	21.75	0.000818	3.080
950	21.89	0.000818	3.086
1250	57.18	0.000657	4.046
1250	57.16	0.000657	4.046
1150	45.11	0.000703	3.809
1150	45.25	0.000703	3.812
1050	32.79	0.000756	3.490
1050	32.91	0.000756	3.494

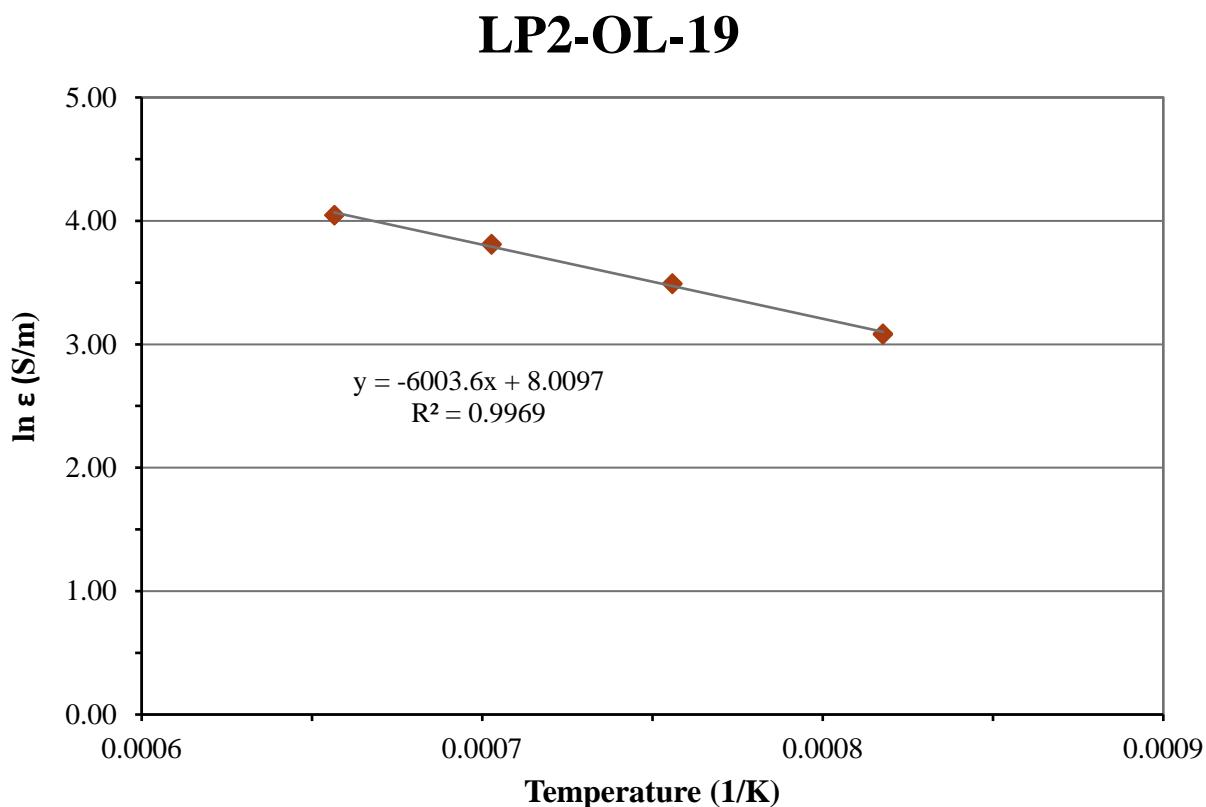


Figure D.35. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-19

## D.36 Glass LP2-OL-20 Electrical Conductivity Data

Table D.36. Electrical Conductivity Data for Glass LP2-OL-20

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	29.06	0.000818	3.369
950	29.23	0.000818	3.375
1250	66.15	0.000657	4.192
1250	65.95	0.000657	4.189
1150	54.17	0.000703	3.992
1150	54.30	0.000703	3.994
1050	41.49	0.000756	3.725
1050	41.61	0.000756	3.728

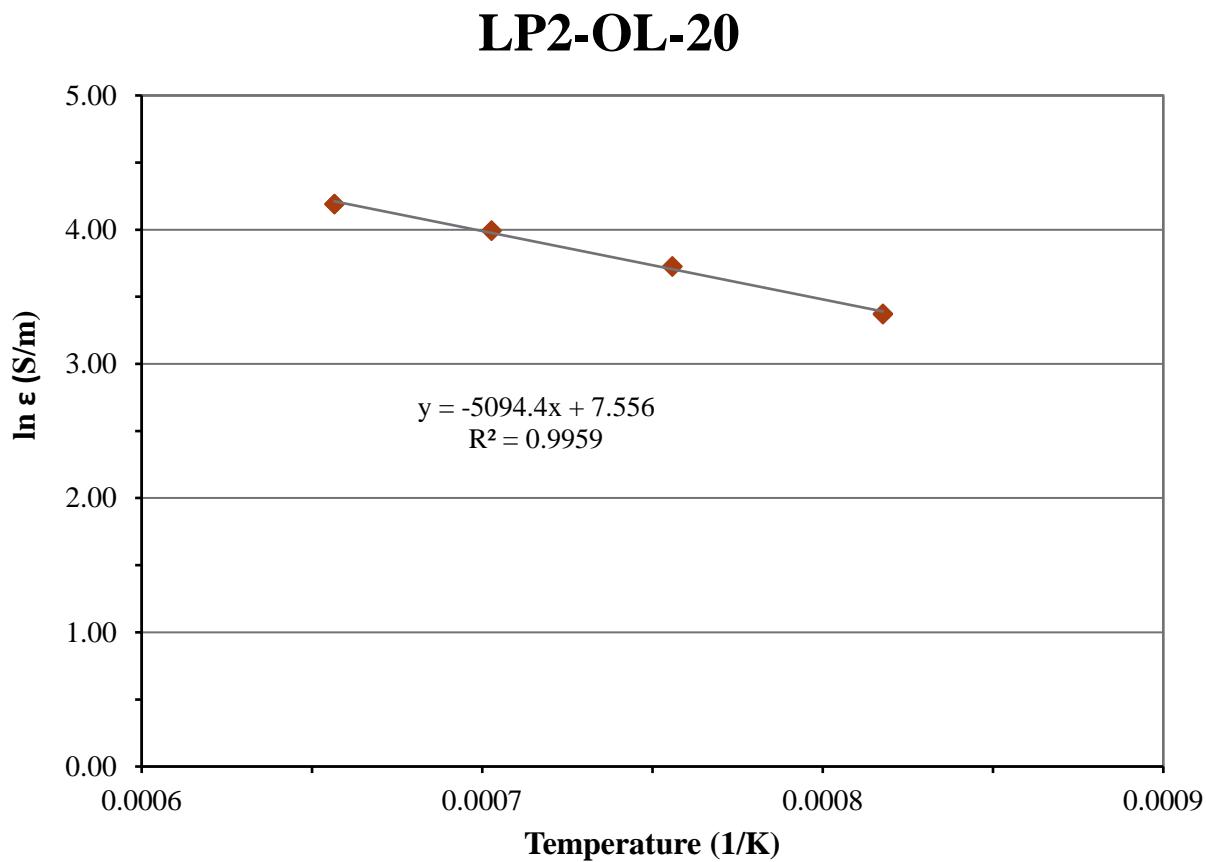


Figure D.36. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-20

### D.37 Glass LP2-OL-21 Electrical Conductivity Data

Table D.37. Electrical Conductivity Data for Glass LP2-OL-21

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	25.05	0.000818	3.221
950	25.22	0.000818	3.228
1250	62.49	0.000657	4.135
1150	49.87	0.000703	3.909
1150	50.00	0.000703	3.912
1050	37.03	0.000756	3.612
1050	37.18	0.000756	3.616

### LP2-OL-21

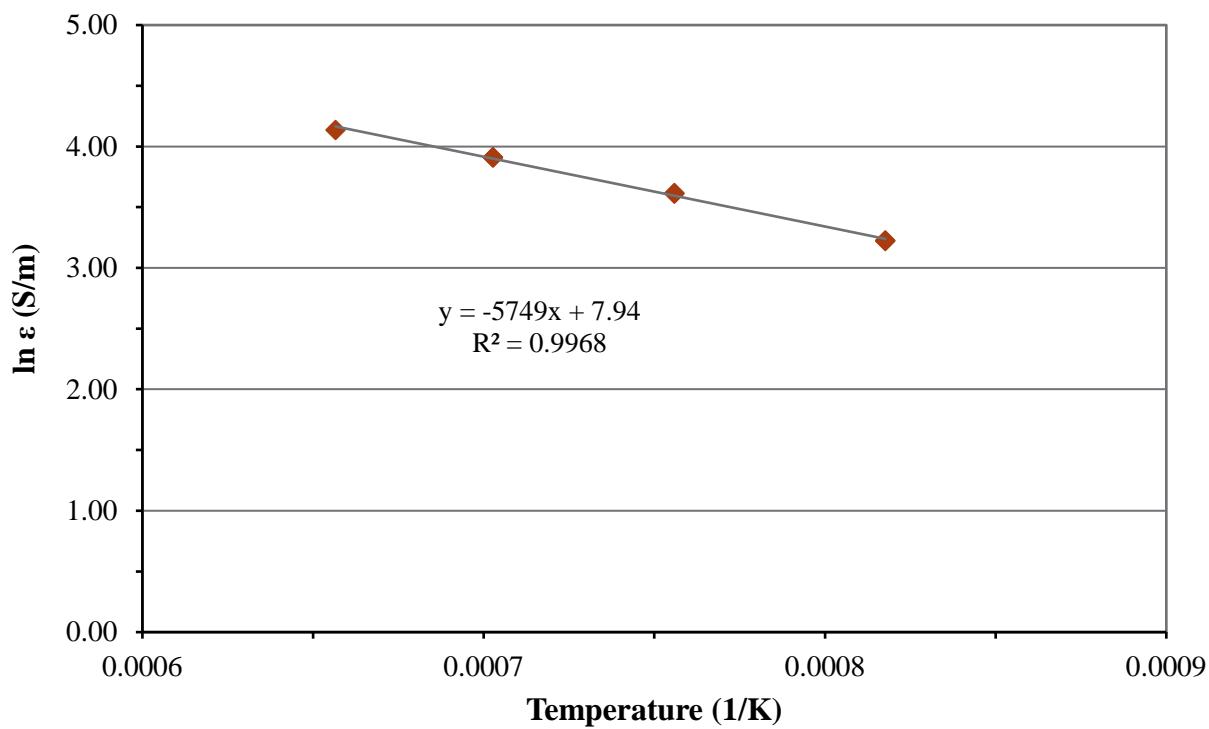


Figure D.37. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-21

### D.38 Glass LP2-OL-22 Electrical Conductivity Data

Table D.38. Electrical Conductivity Data for Glass LP2-OL-22

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	17.60	0.000818	2.868
950	17.74	0.000818	2.876
1250	53.76	0.000657	3.985
1150	40.65	0.000703	3.705
1150	40.75	0.000703	3.707
1050	28.18	0.000756	3.338
1050	28.33	0.000756	3.344

### LP2-OL-22

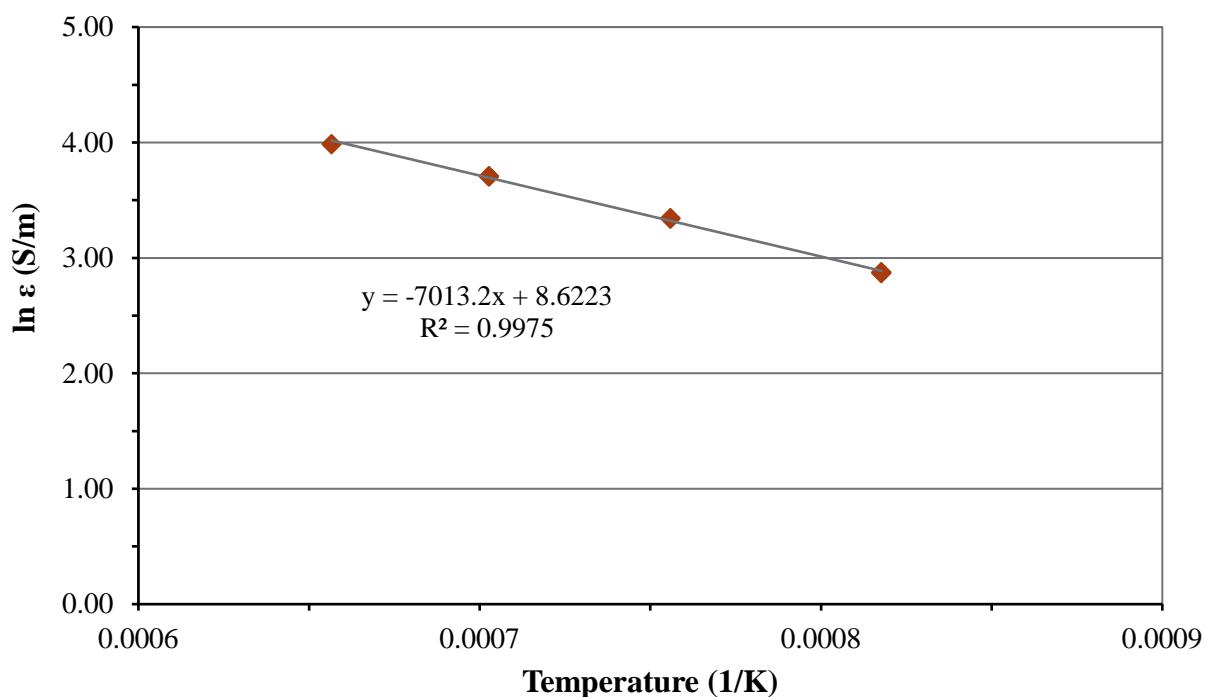


Figure D.38. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-22

### D.39 Glass LP2-OL-23 Electrical Conductivity Data

Table D.39. Electrical Conductivity Data for Glass LP2-OL-23

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	18.38	0.000818	2.911
950	18.52	0.000818	2.919
1250	55.99	0.000657	4.025
1250	55.78	0.000657	4.022
1150	42.51	0.000703	3.750
1150	42.64	0.000703	3.753
1050	29.49	0.000756	3.384
1050	29.63	0.000756	3.389

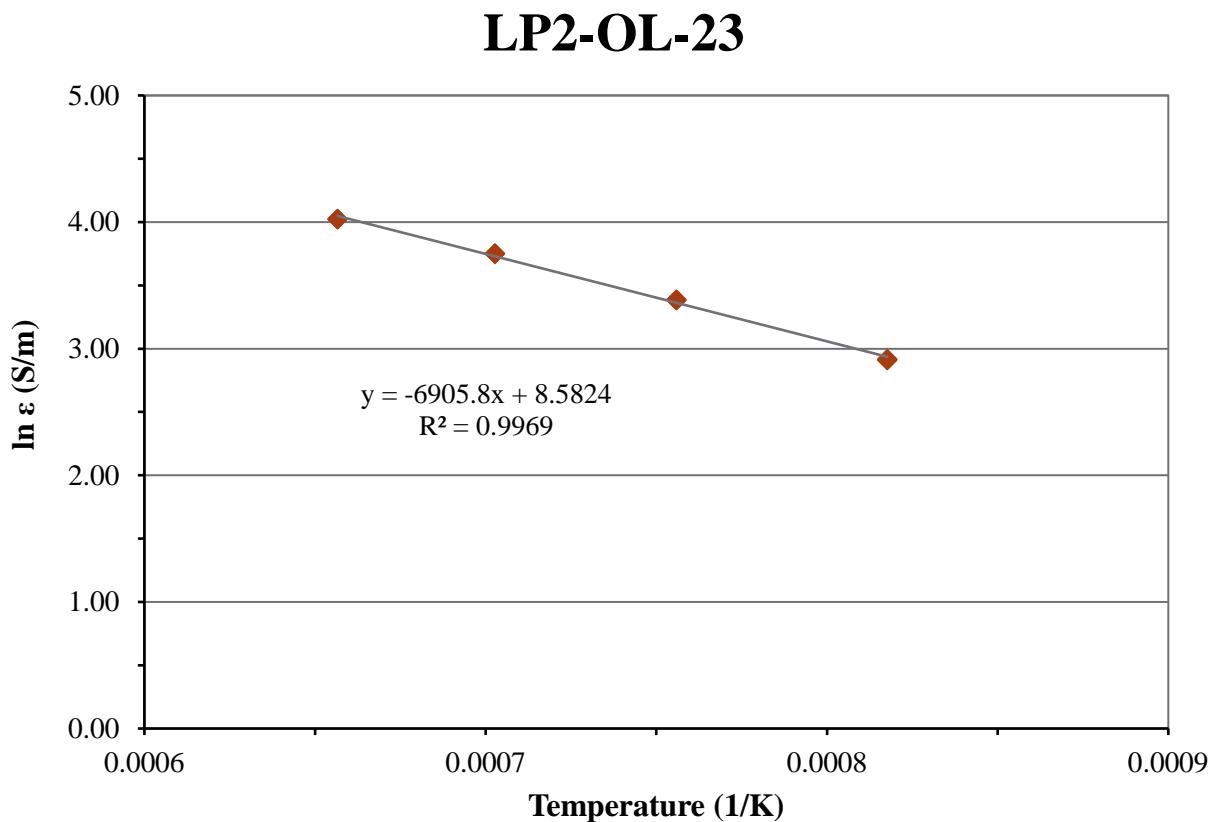


Figure D.39. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-23

## D.40 Glass LP2-OL-24 Electrical Conductivity Data

Table D.40. Electrical Conductivity Data for Glass LP2-OL-24

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	27.96	0.000818	3.331
950	28.13	0.000818	3.337
1250	64.54	0.000657	4.167
1250	64.38	0.000657	4.165
1150	52.60	0.000703	3.963
1150	52.73	0.000703	3.965
1050	40.06	0.000756	3.690
1050	40.24	0.000756	3.695

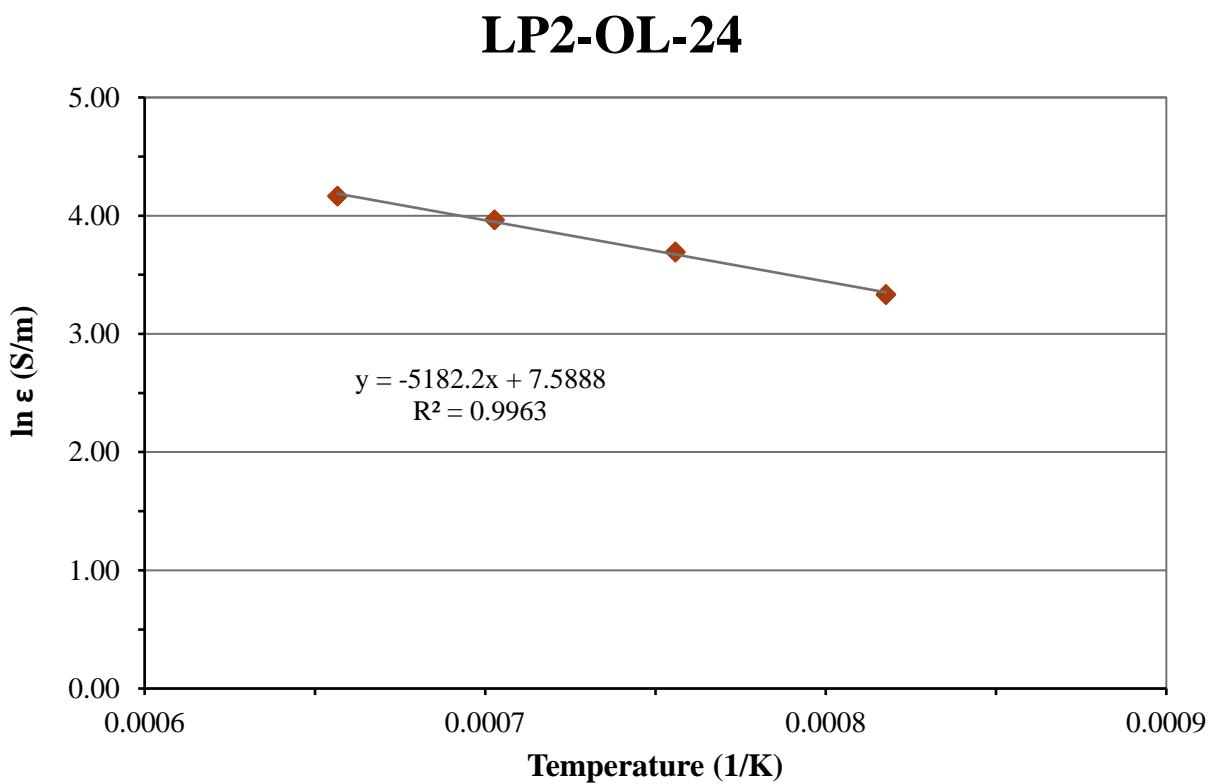


Figure D.40. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-24

## D.41 Glass LP2-OL-25 Electrical Conductivity Data

Table D.41. Electrical Conductivity Data for Glass LP2-OL-25

Temperature, °C	Conductivity, S/m	1/T, K <sup>-1</sup>	ln (ε, S/m)
950	29.42	0.000818	3.382
950	29.61	0.000818	3.388
1250	68.78	0.000657	4.231
1250	68.64	0.000657	4.229
1150	55.78	0.000703	4.021
1150	55.88	0.000703	4.023
1050	42.20	0.000756	3.742
1050	42.30	0.000756	3.745

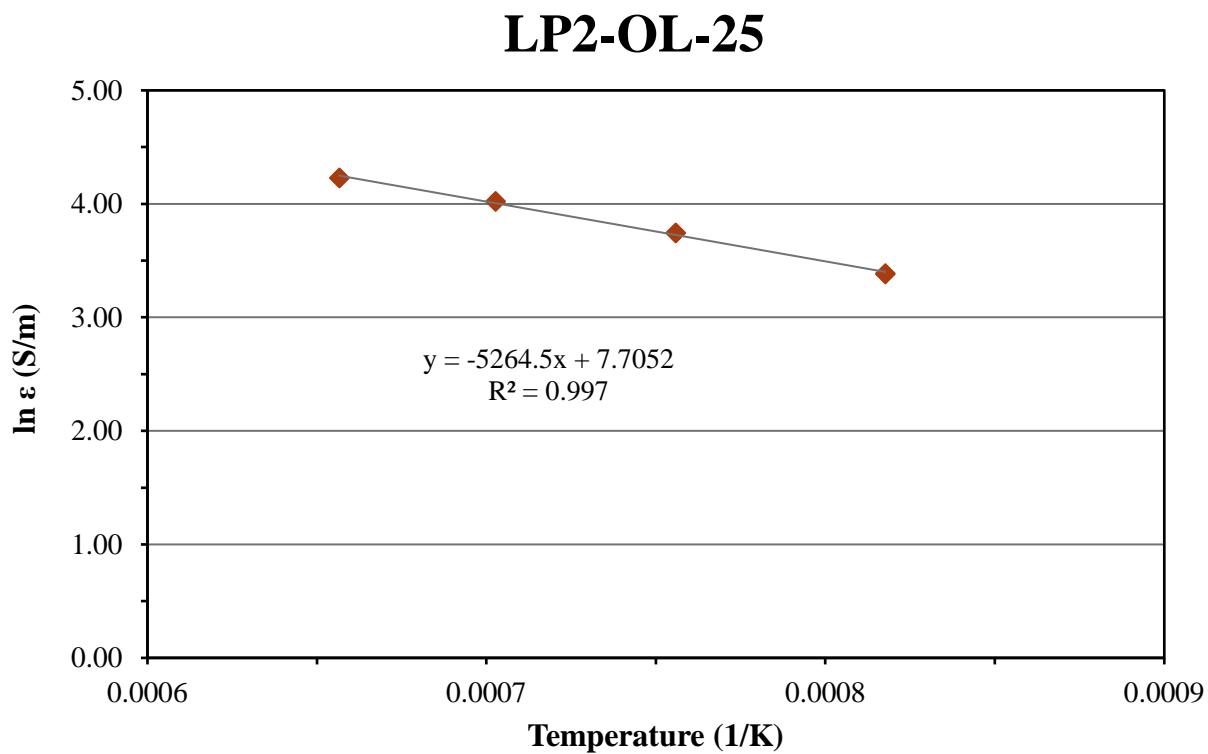


Figure D.41. Electrical Conductivity-Temperature Data and Arrhenius Equation Fit for Glass LP2-OL-25

## Appendix E – Crystal Fraction (CF) of Heat-Treated Glasses Photographs

This appendix contains photos of Phase 2 enhanced LAW glasses after they were heat-treated at 950°C for 24 hours (CF Heat-Treatment). Each showed different responses to the heat-treatment as indicated by these photos. No photo was taken of glass LP2-IL-01.

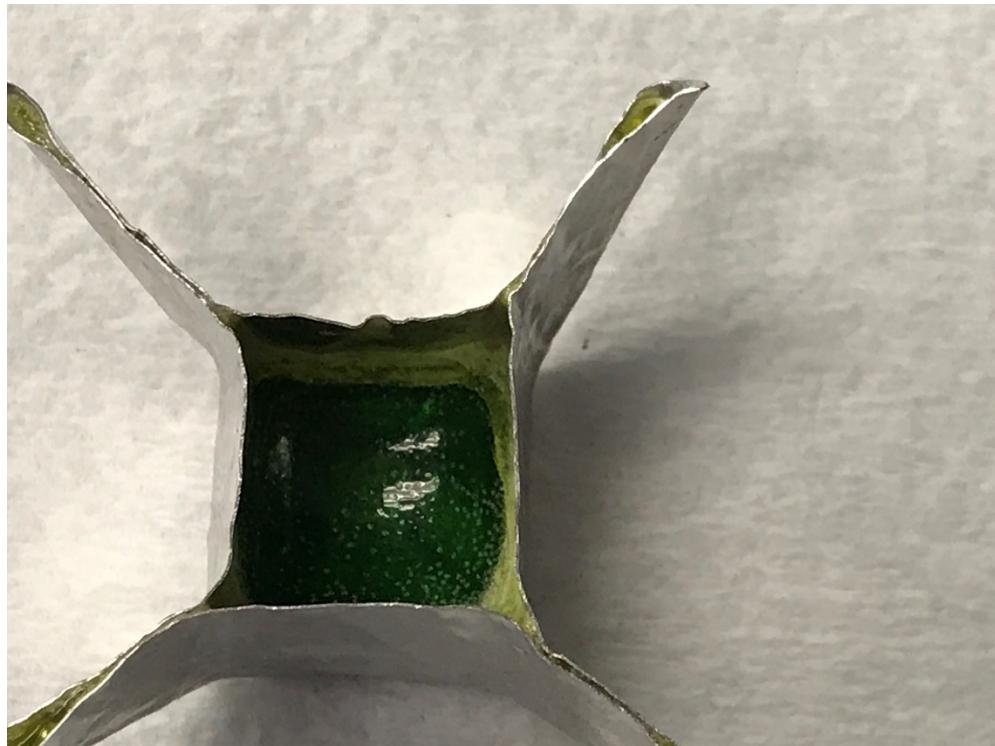


Figure E.1. Glass LP2-IL-02 after CF Heat Treatment at 950°C for 24 h

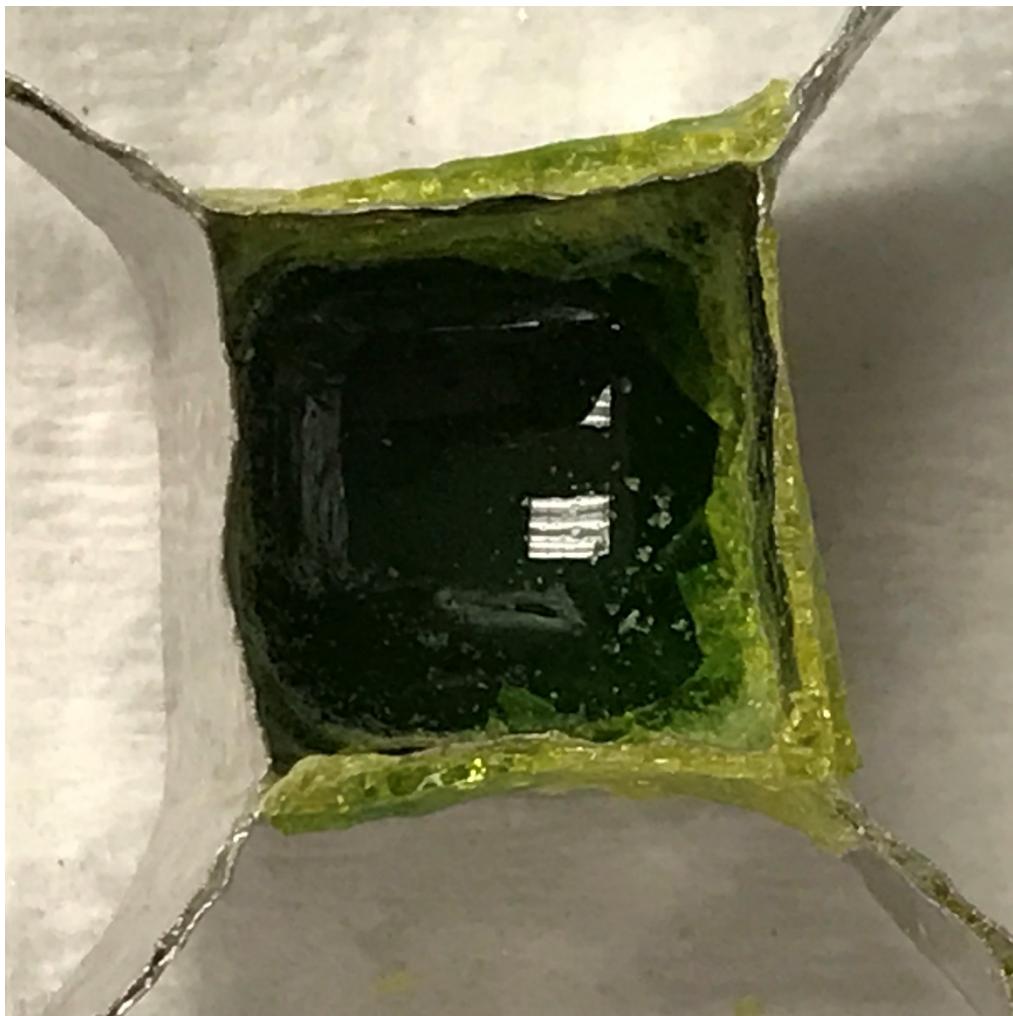


Figure E.2. Glass LP2-IL-03 after CF Heat Treatment at 950°C for 24 h

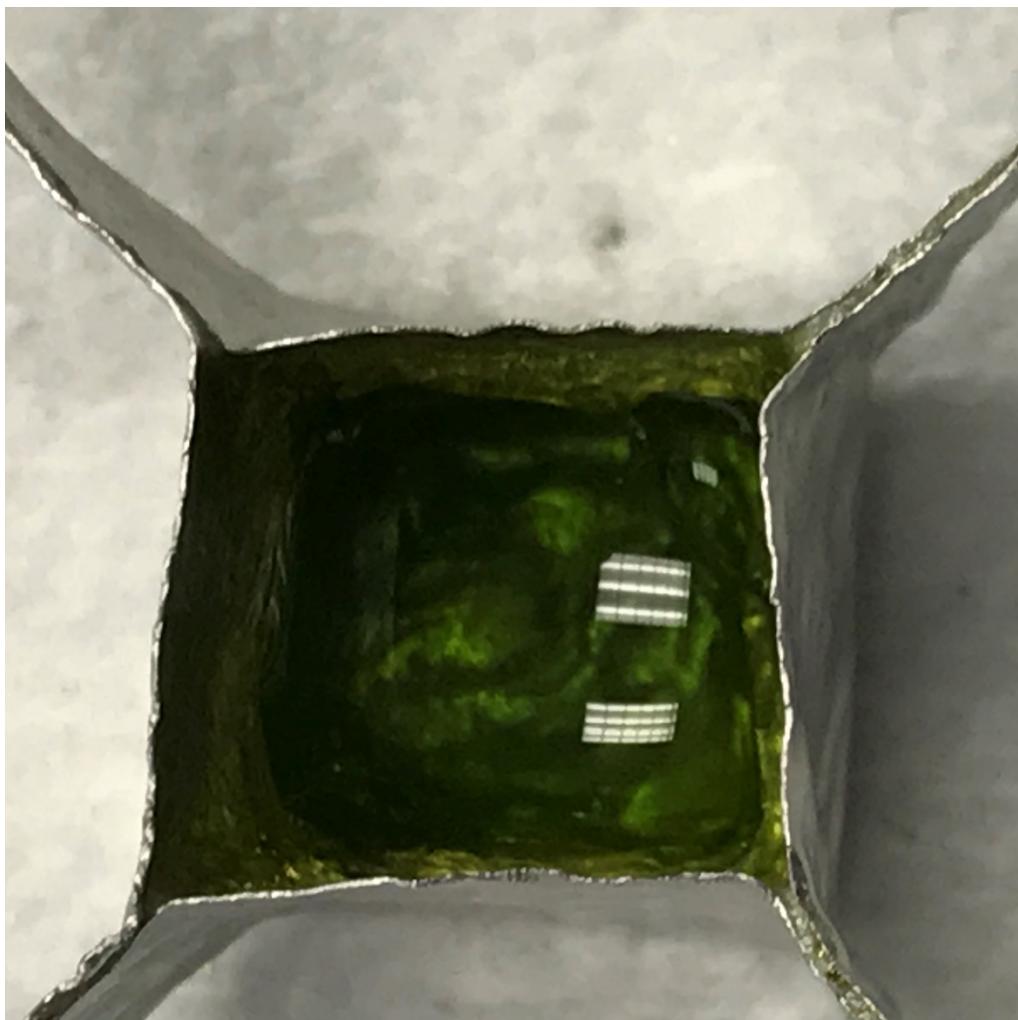


Figure E.3. Glass LP2-IL-04 after CF Heat Treatment at 950°C for 24 h

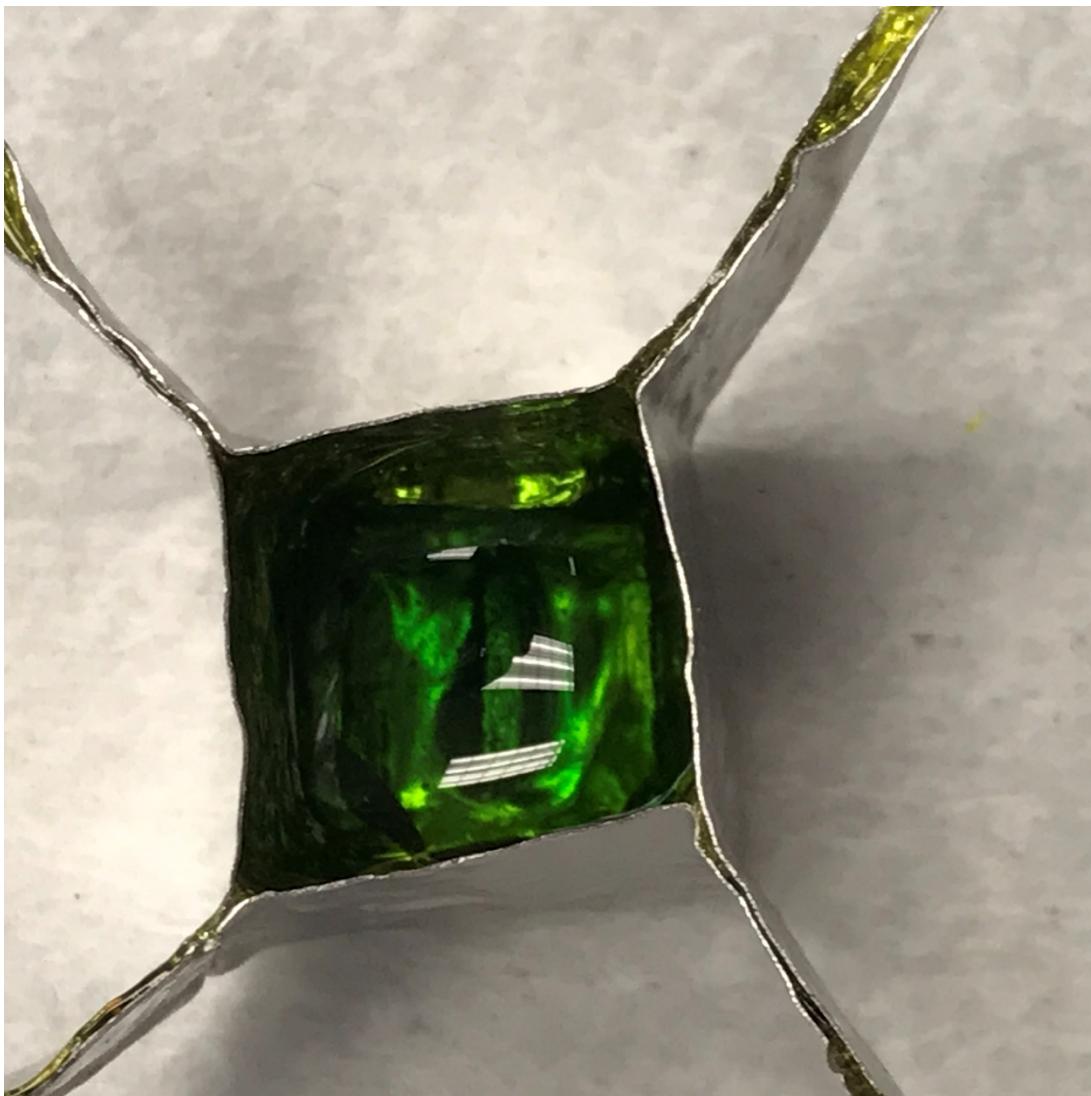


Figure E.4. Glass LP2-IL-05 after CF Heat Treatment at 950°C for 24 h



Figure E.5. Glass LP2-IL-06 after CF Heat Treatment at 950°C for 24 h both in Crucible (left) and Magnified 100X (right)



Figure E.6. Glass LP2-IL-07 after CF Heat Treatment at 950°C for 24 h Magnified 20X



Figure E.7. Glass LP2-IL-08 after CF Heat Treatment at 950°C for 24 h both in Crucible (left) and Magnified 150X (right)

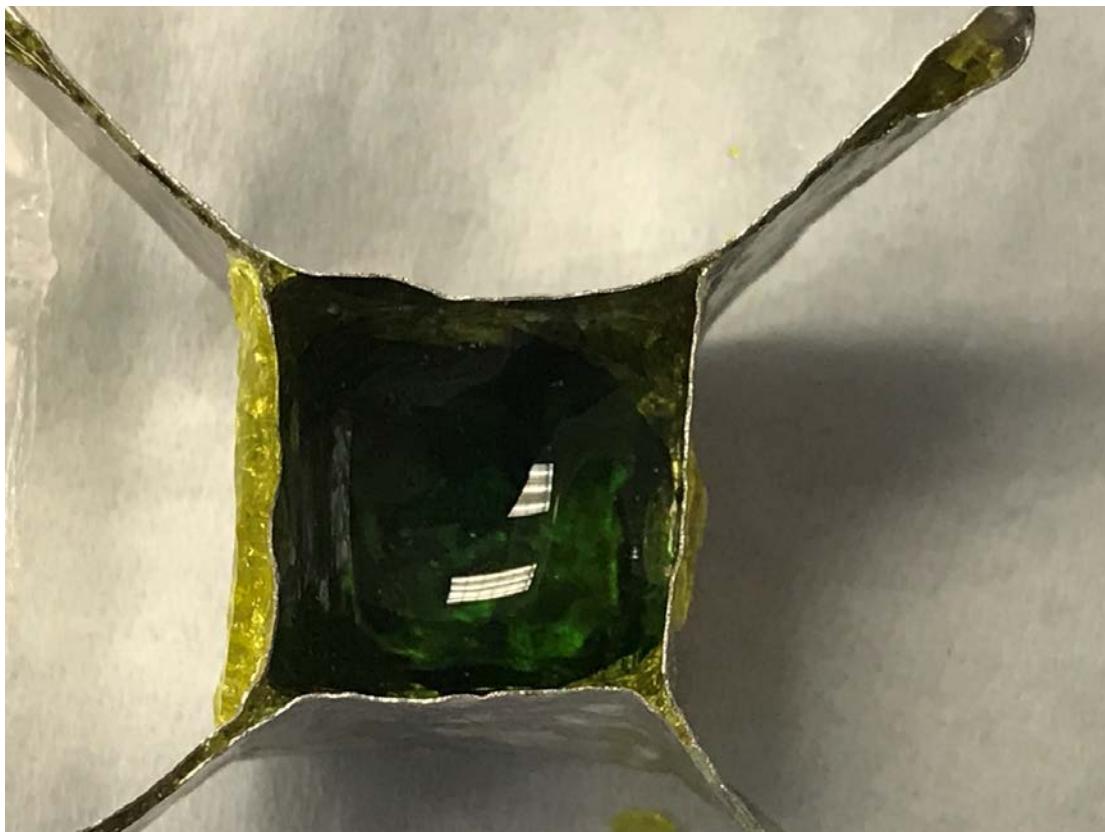


Figure E.8. Glass LP2-IL-09 after CF Heat Treatment at 950°C for 24 h

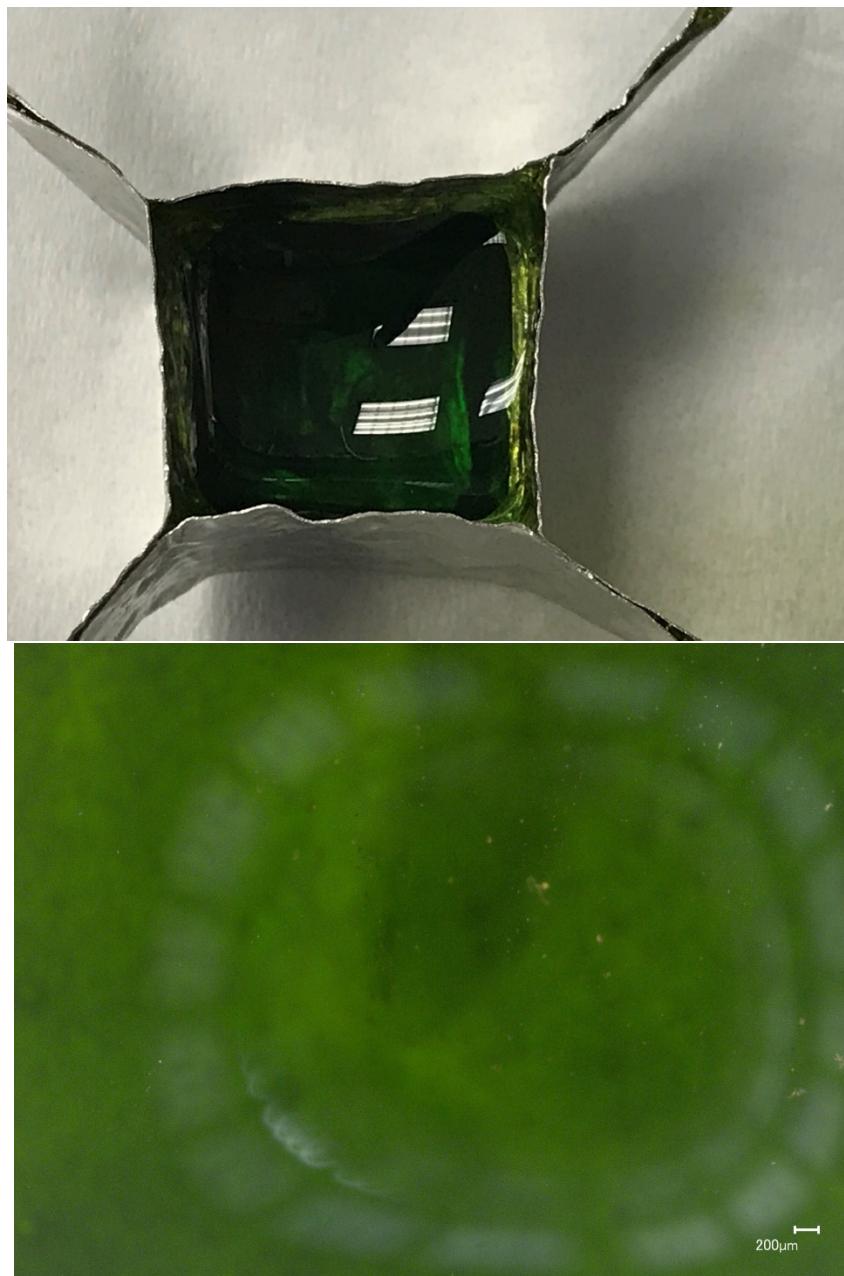


Figure E.9. Glass LP2-JL-10 after CF Heat Treatment at 950°C for 24 h both in Crucible (left) and Magnified 50X (right)



Figure E.10. Glass LP2-IL-11 after CF Heat Treatment at 950°C for 24 h both in Crucible (left) and Magnified 200X (right)



Figure E.11. Glass LP2-IL-12 after CF Heat Treatment at 950°C for 24 h Magnified 20X

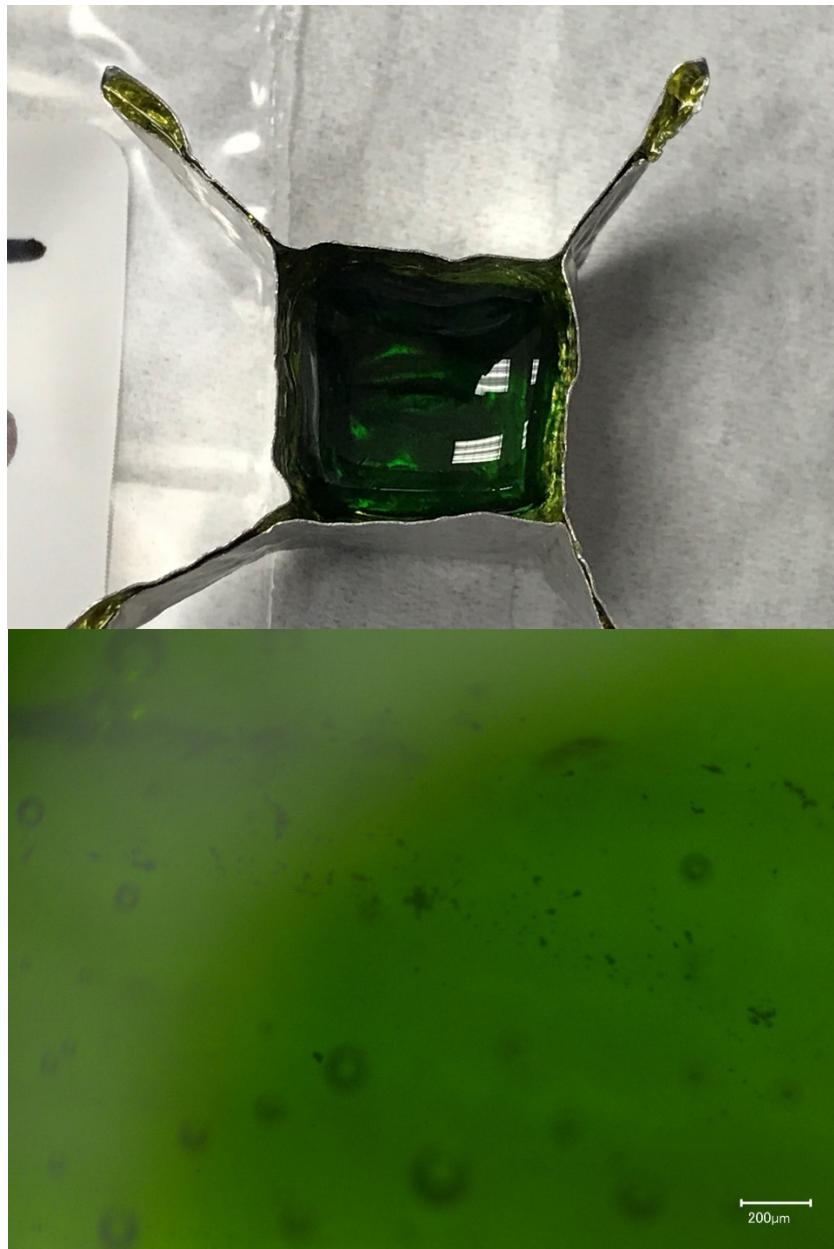


Figure E.12. Glass LP2-IL-13 after CF Heat Treatment at 950°C for 24 h both in Crucible (left) and Magnified 150X (right)

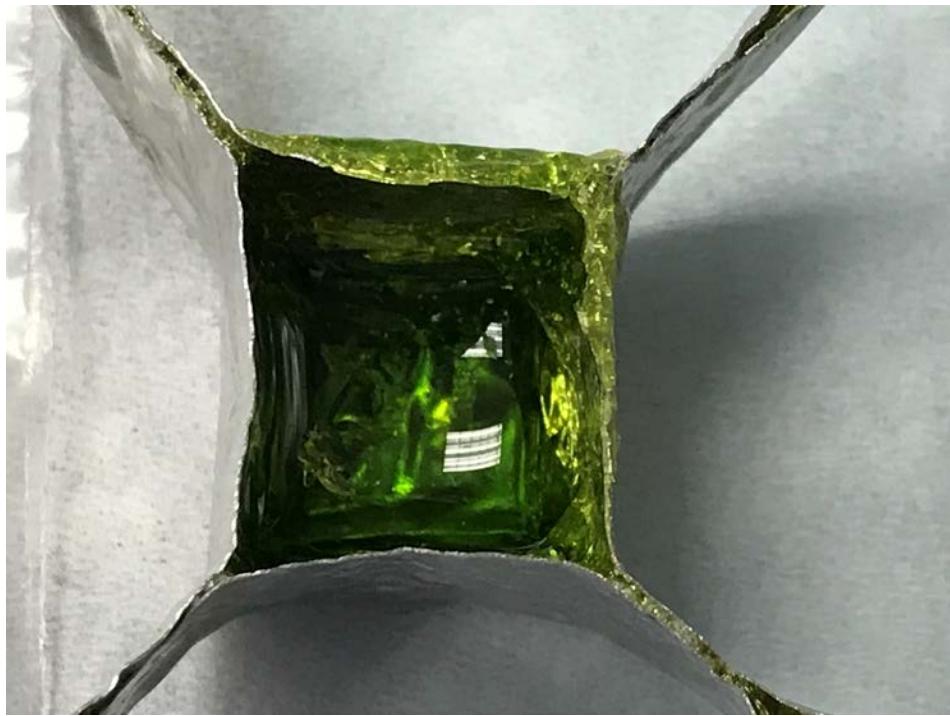


Figure E.13. Glass LP2-IL-14 after CF Heat Treatment at 950°C for 24 h

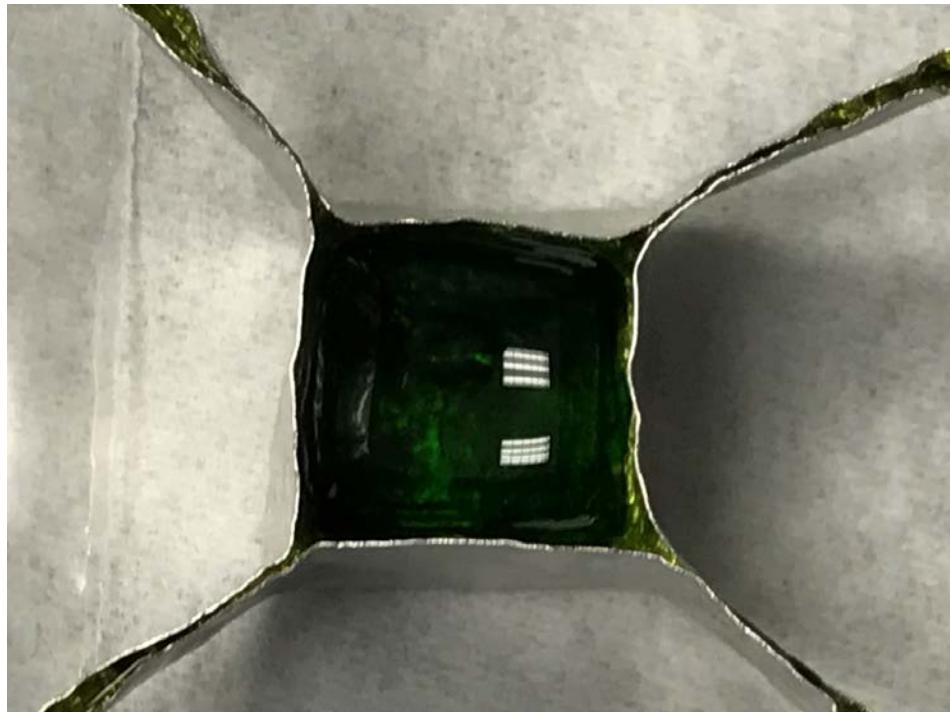


Figure E.14. Glass LP2-IL-15 after CF Heat Treatment at 950°C for 24 h

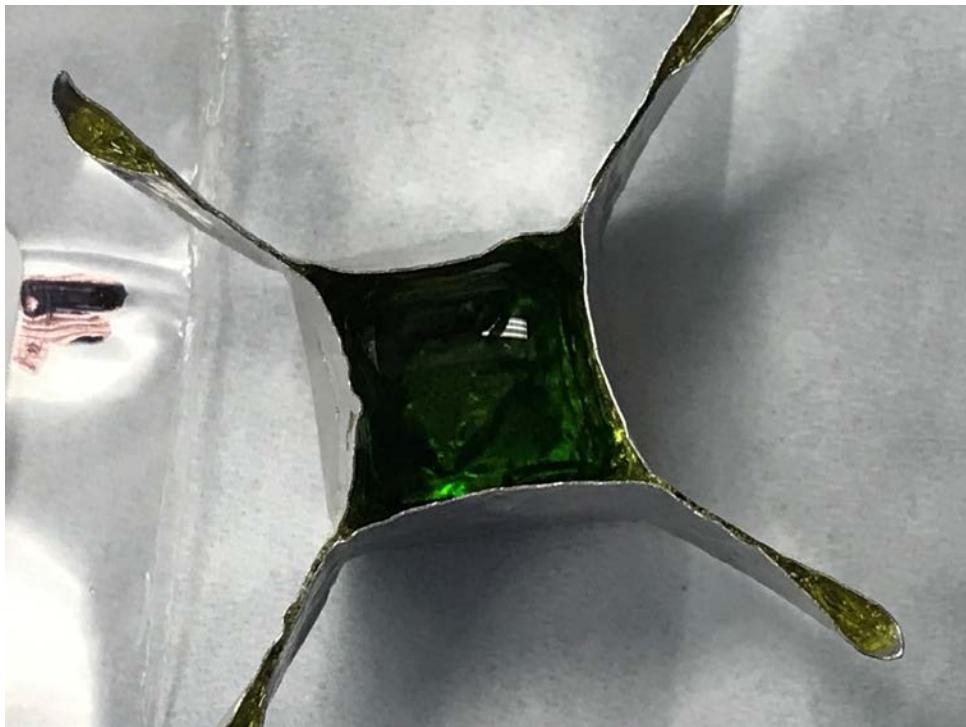


Figure E.15. Glass LP2-IL-16 after CF Heat Treatment at 950°C for 24 h



Figure E.16. Glass LP2-IL-17 after CF Heat Treatment at 950°C for 24 h

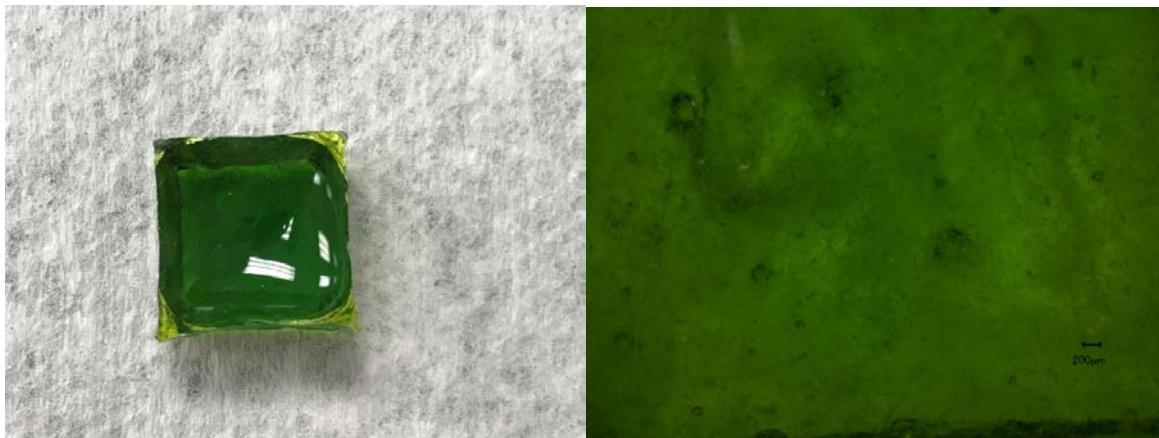


Figure E.17. Glass LP2-OL-01-3 after CF Heat Treatment at 950°C for 24 h both Glass (left) and Magnified 50X (right)

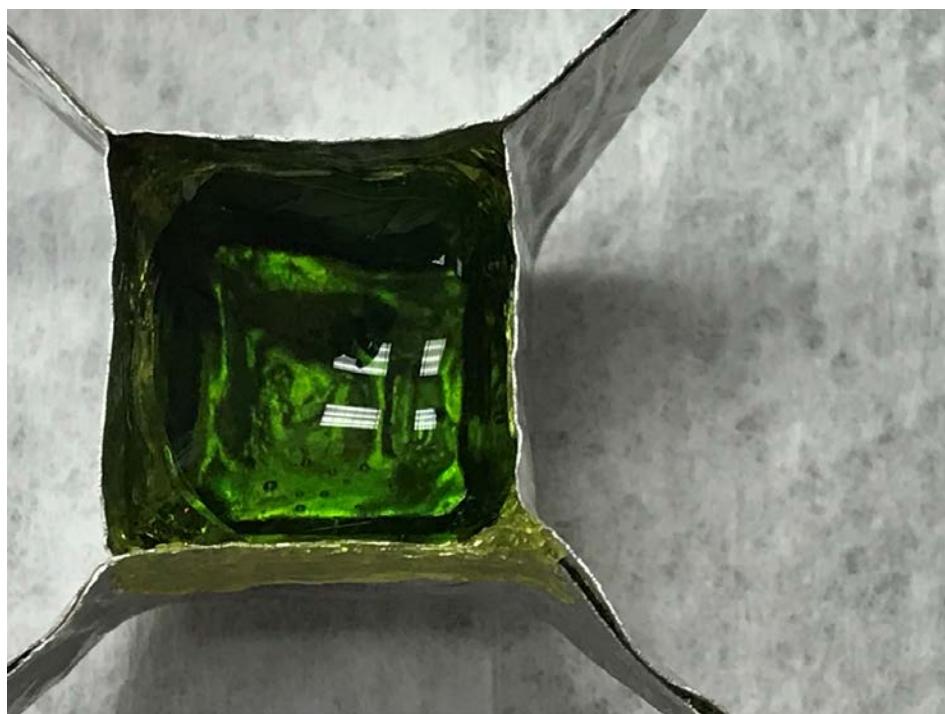


Figure E.18. Glass LP2-OL-02-1 after CF Heat Treatment at 950°C for 24 h



Figure E.19. Glass LP2-OL-03 MOD2 after CF Heat Treatment at 950°C for 24 h



Figure E.20. Glass LP2-OL-04-1 after CF Heat Treatment at 950°C for 24 h both in Crucible (left) and Magnified 30X (right)



Figure E.21. Glass LP2-OL-05 after CF Heat Treatment at 950°C for 24 h both in crucible (left) and magnified 20X (right)



Figure E.22. Glass LP2-OL-07-1 after CF Heat Treatment at 950°C for 24 h

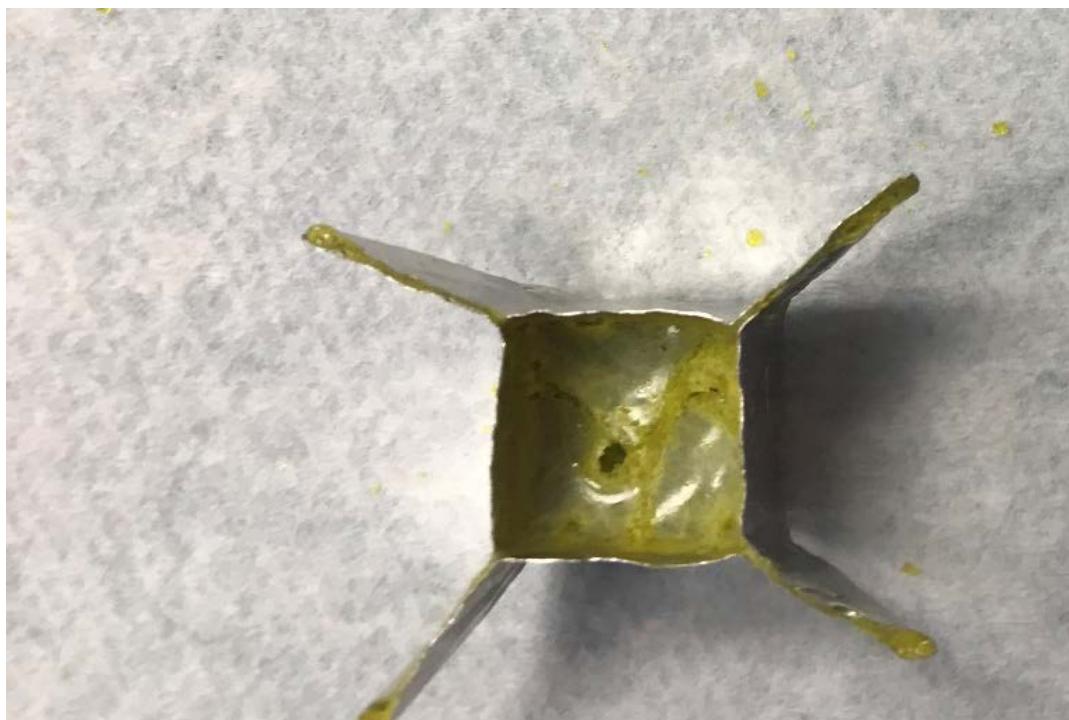


Figure E.23. Glass LP2-OL-08 MOD after CF Heat Treatment at 950°C for 24 h

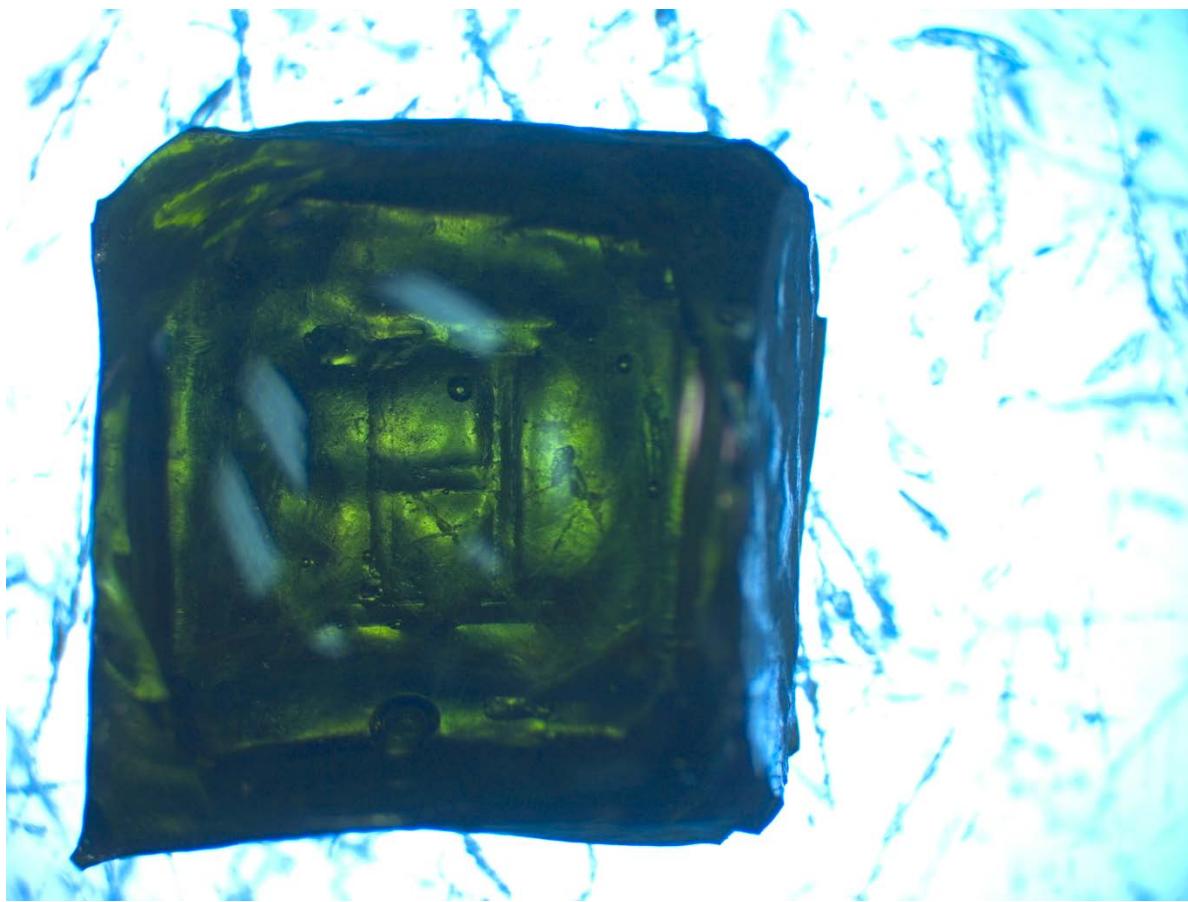


Figure E.24. Glass LP2-OL-09-1 after CF Heat Treatment at 950°C for 24 h



Figure E.25. Glass LP2-OL-10 MOD after CF Heat Treatment at 950°C for 24 h

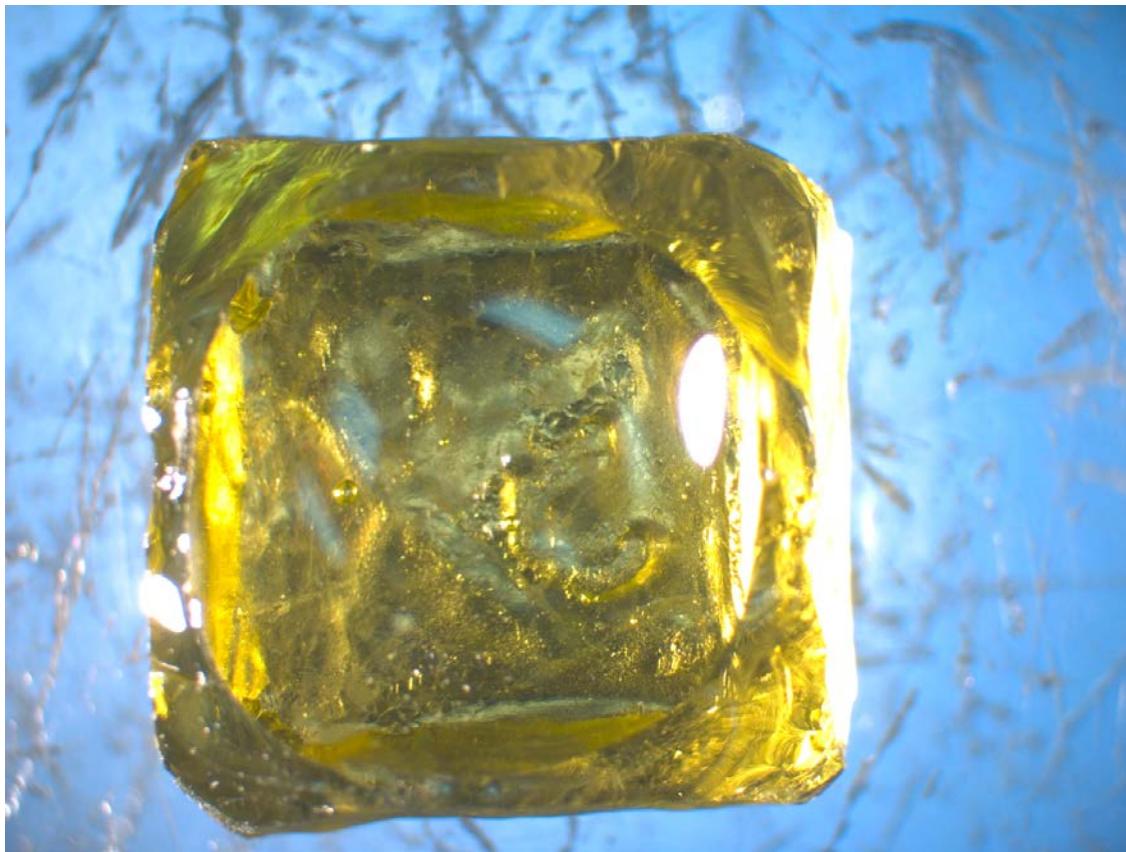


Figure E.26. Glass LP2-OL-11 after CF Heat Treatment at 950°C for 24 h



Figure E.27. Glass LP2-OL-12 after CF Heat Treatment at 950°C for 24 h

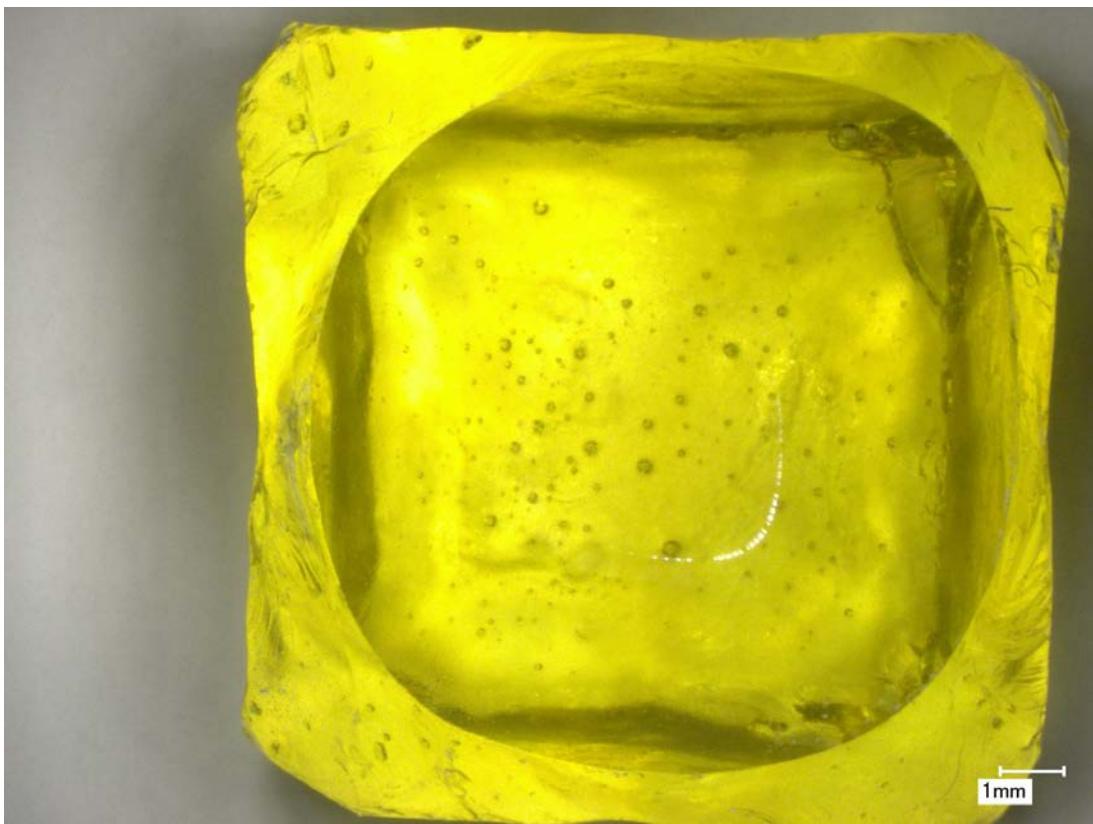


Figure E.28. Glass LP2-OL-13 after CF Heat Treatment at 950°C for 24 h Magnified 20X



Figure E.29. Glass LP2-OL-14 after CF Heat Treatment at 950°C for 24 h

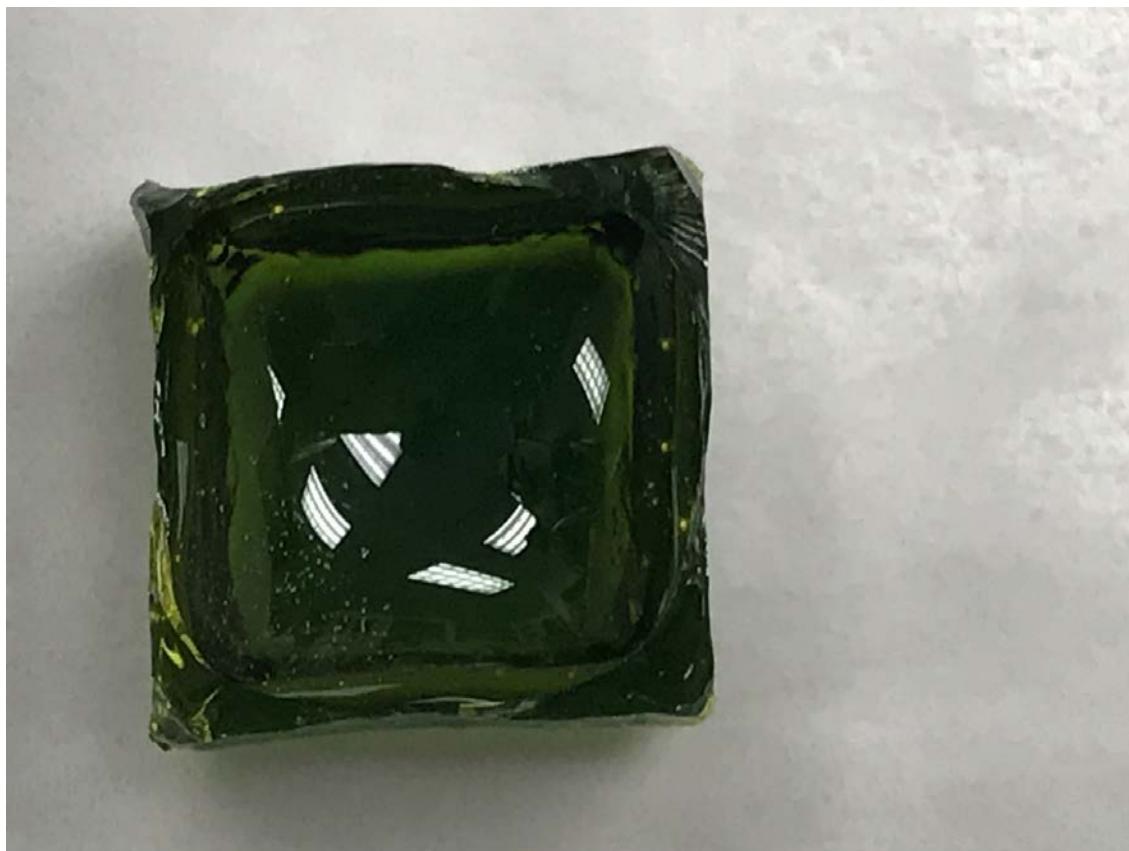


Figure E.30. Glass LP2-OL-15 after CF Heat Treatment at 950°C for 24 h



Figure E.31. Glass LP2-OL-16 MOD after CF Heat Treatment at 950°C for 24 h

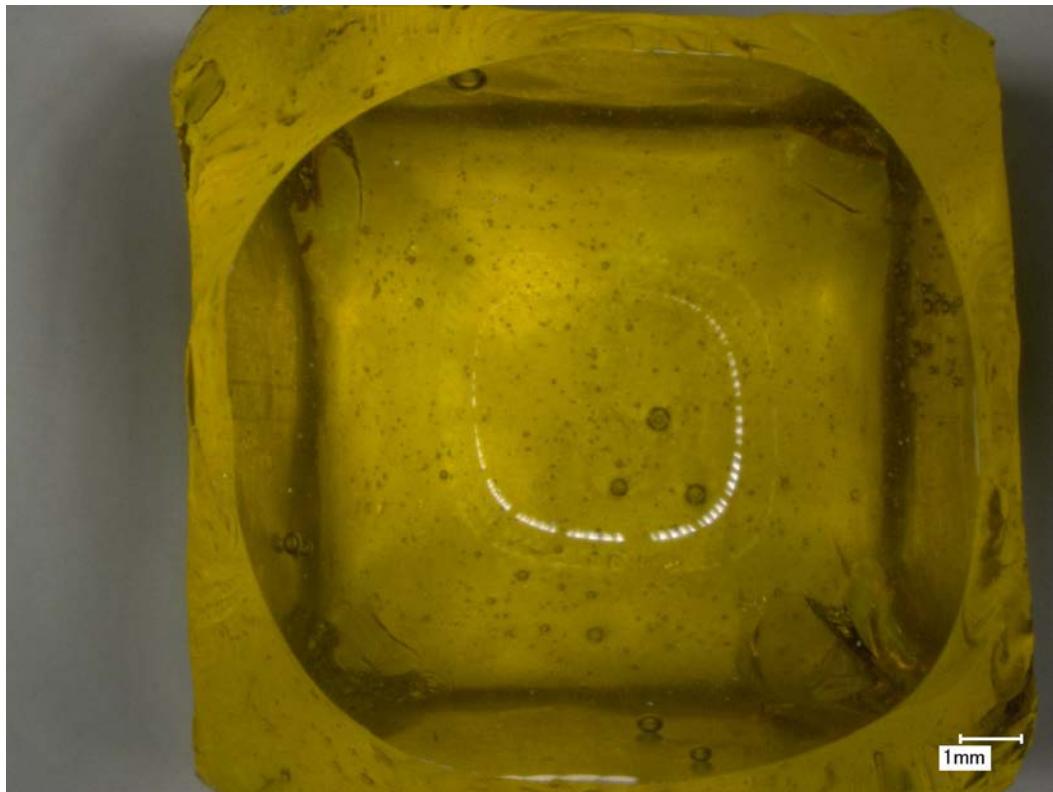


Figure E.32. Glass LP2-OL-17 after CF Heat Treatment at 950°C for 24 h Magnified 20X



Figure E.33. Glass LP2-OL-18 after CF Heat Treatment at 950°C for 24 h

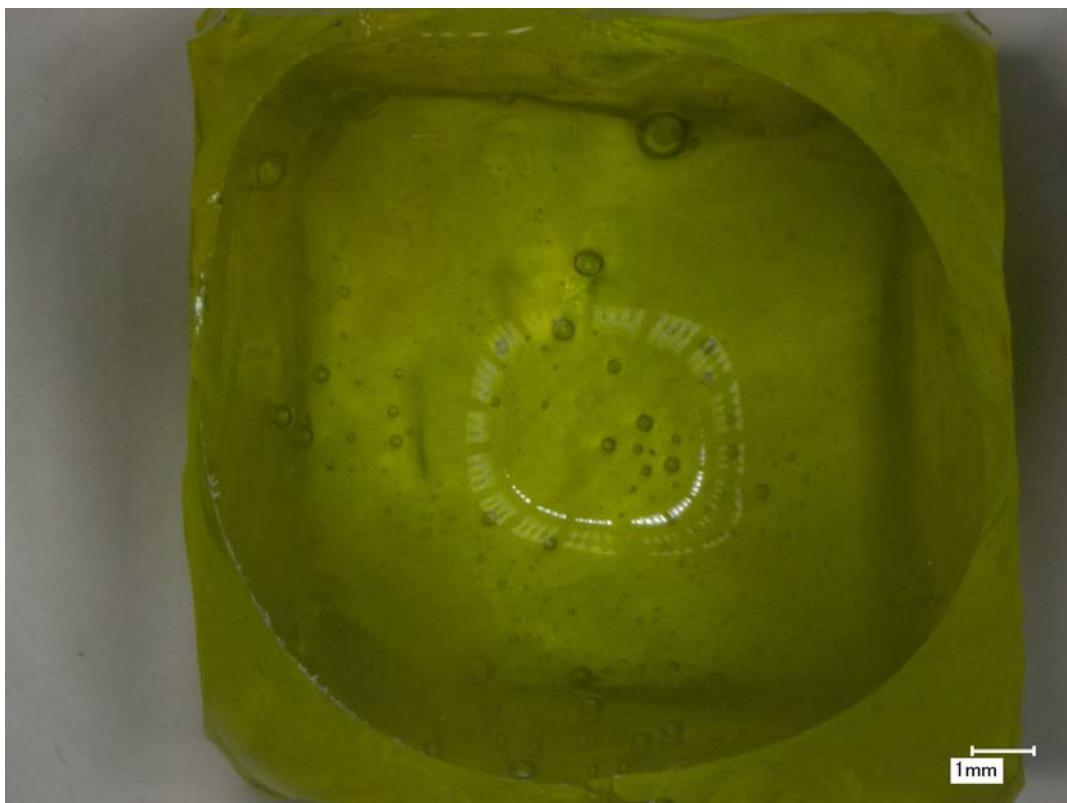


Figure E.34. Glass LP2-OL-19 after CF Heat Treatment at 950°C for 24 h Magnified 20X

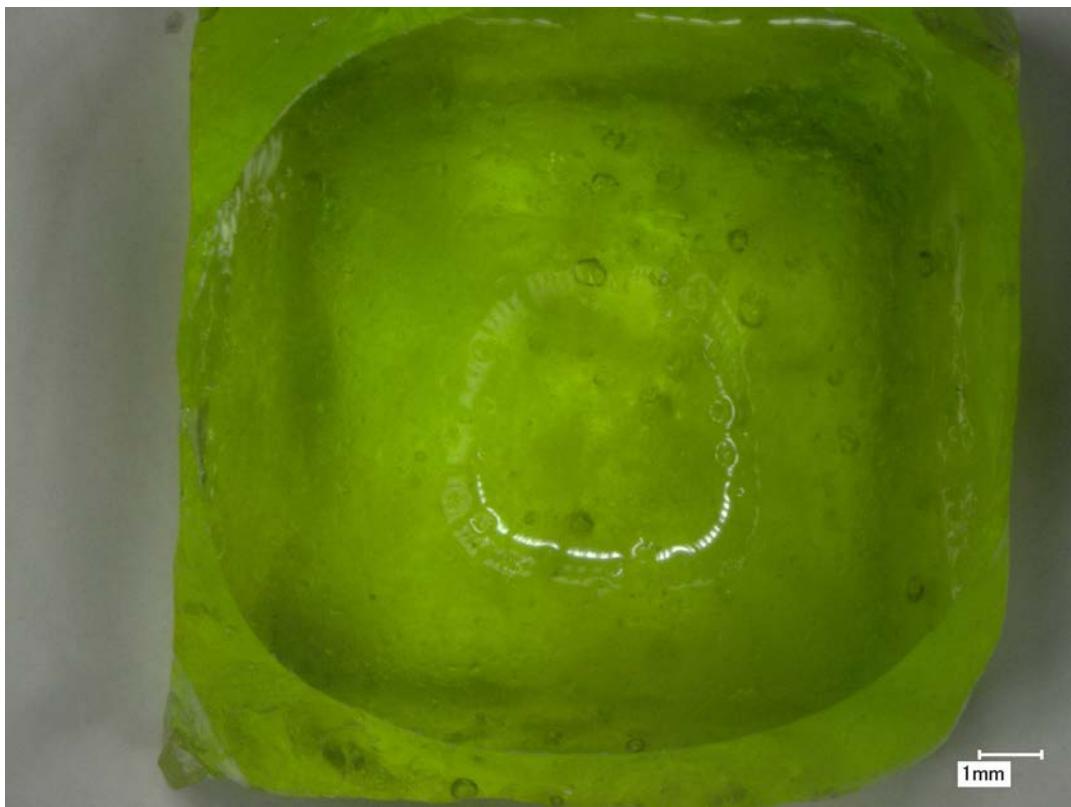


Figure E.35. Glass LP2-OL-20 after CF Heat Treatment at 950°C for 24 h Magnified 20X



Figure E.36. Glass LP2-OL-21 after CF Heat Treatment at 950°C for 24 h



Figure E.37. Glass LP2-OL-22 after CF Heat Treatment at 950°C for 24 h

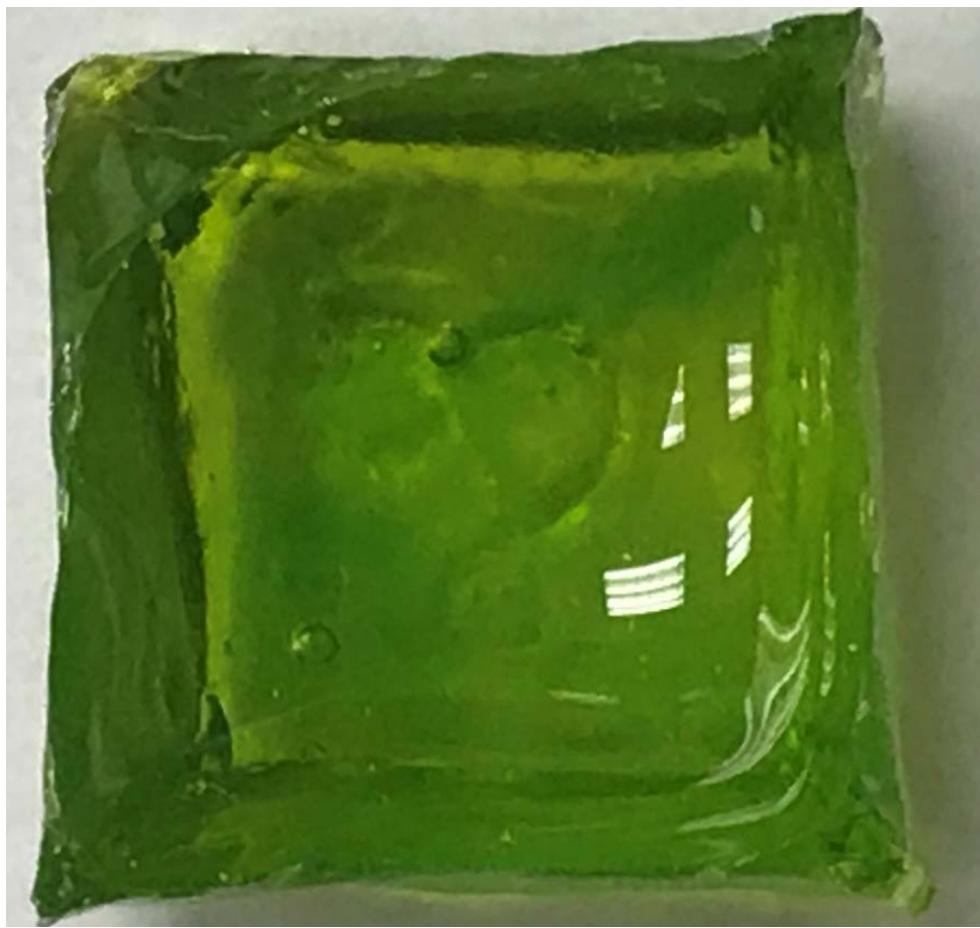


Figure E.38. Glass LP2-OL-23 after CF Heat Treatment at 950°C for 24 h



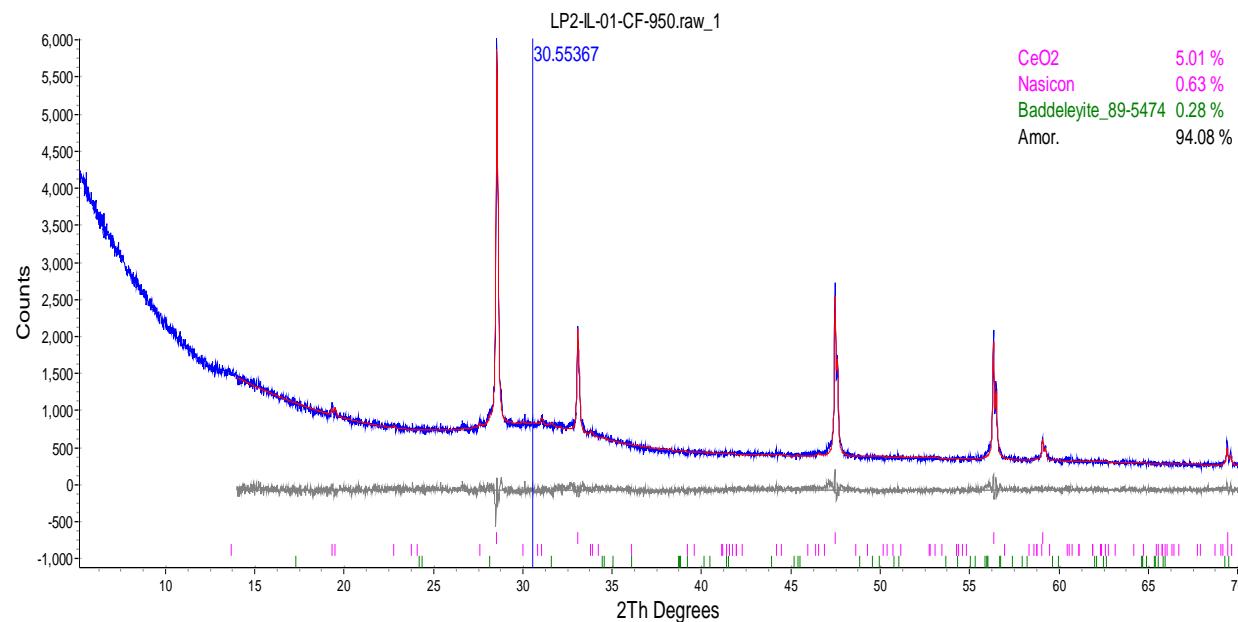
Figure E.39. Glass LP2-OL-24 after CF Heat Treatment at 950°C for 24 h



Figure E.40. Glass LP2-OL-25 after CF Heat Treatment at 950°C for 24 h

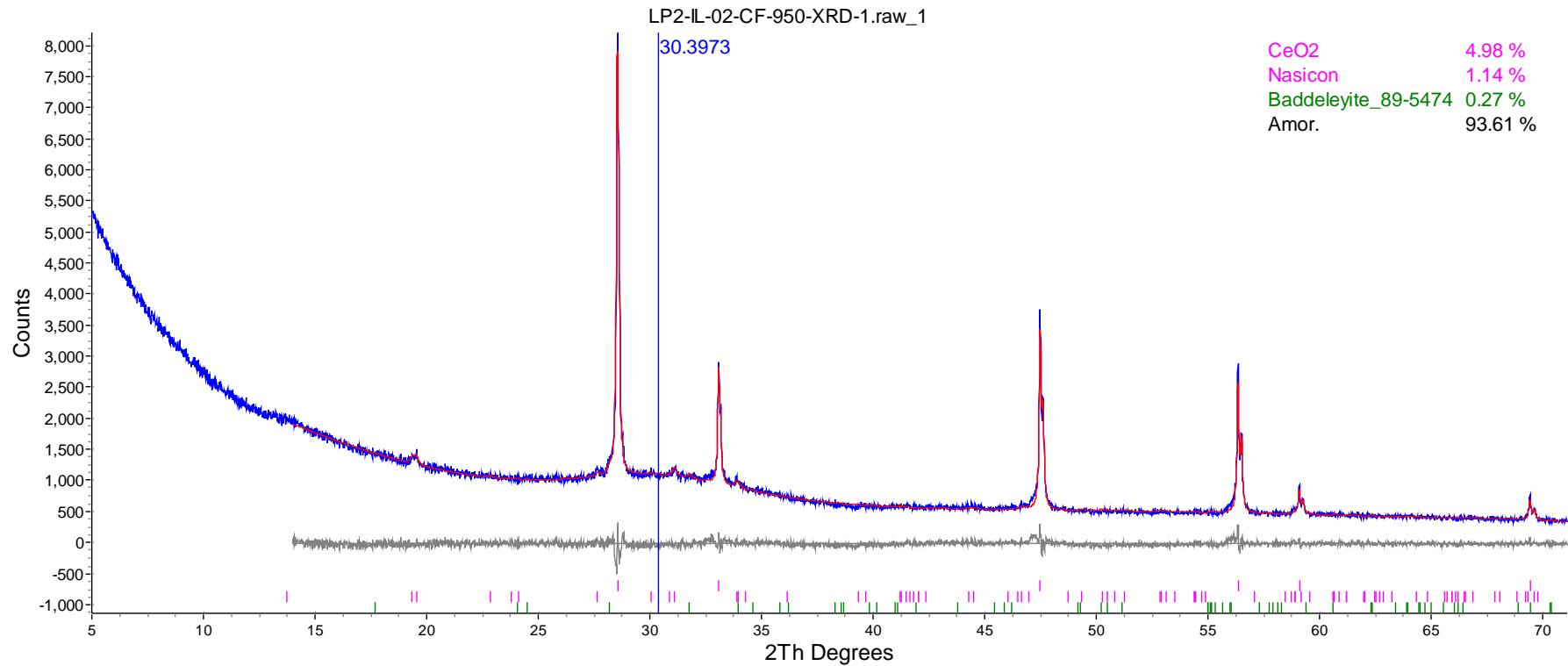
## Appendix F – XRD of Heat-Treated Glasses to Determine Crystal Fraction (CF)

This appendix shows the XRD plots of several Phase 2 enhanced LAW glasses after heat-treating (24 hours at 950°C). These glasses all responded very differently to the heat-treatment from remaining amorphous to developing quite a few crystals of various kinds as shown by the following plots. Some glasses did not contain enough crystals to perform XRD and therefore aren't included here. They were LP2-IL-07, LP2-IL-09, LP2-IL-12, LP2-IL-13, LP2-IL-14, LP2-IL-15, LP2-IL-16, LP2-IL-17, LP2-OL-02-1, LP2-OL-09-1, LP2-OL-11, LP2-OL-12, LP2-OL-14, LP2-OL-15, LP2-OL-21, and LP2-OL-23.



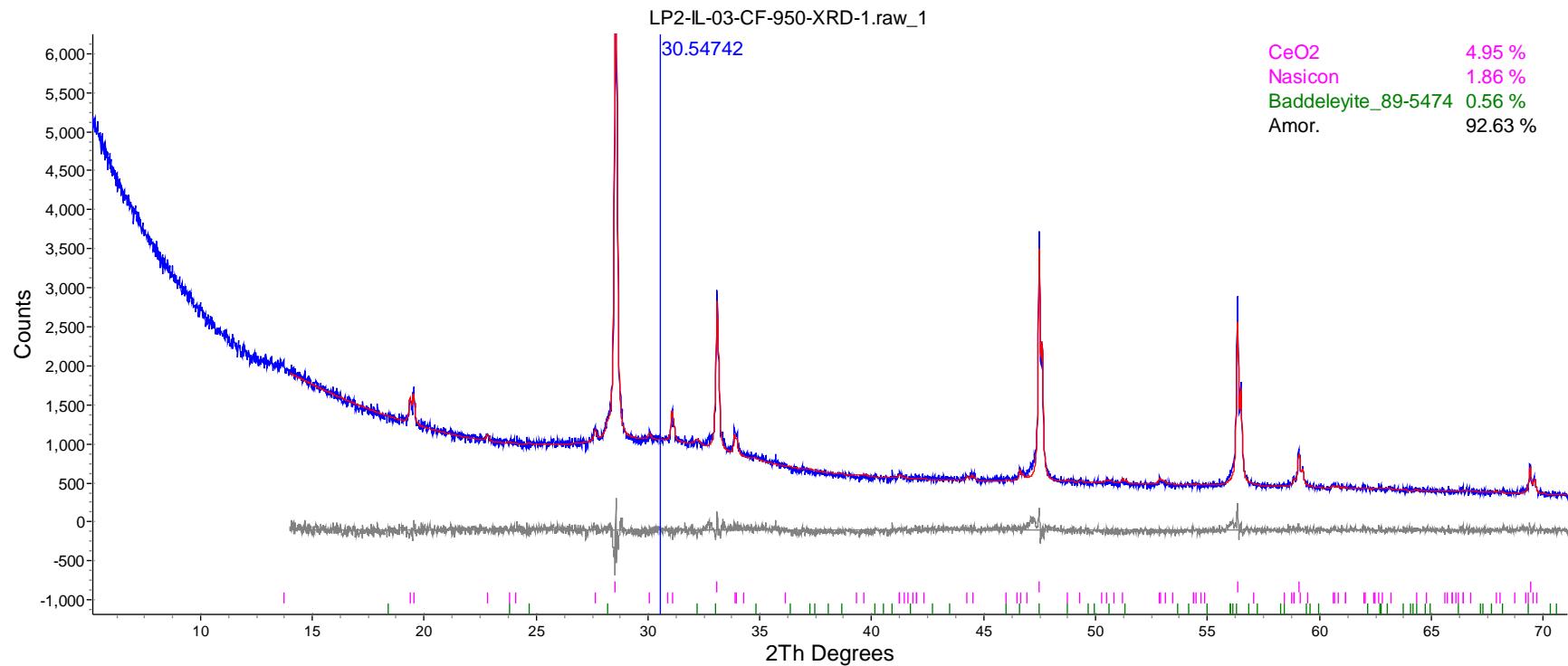
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.007	5.007	0
Nasicon	0	0.632	0.665
Baddeleyite	0	0.279	0.294

Figure F.1. XRD Spectrum of Heat-Treated Glass LP2-IL-01



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.976	4.976	0
Nasicon	0	1.14	1.199
Baddeleyite	0	0.272	0.286

Figure F.2. XRD Spectrum of Heat-Treated Glass LP2-IL-02



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.98	4.98	0
Nasicon	0	1.859	1.956
Baddeleyite	0	0.557	0.586

Figure F.3. XRD Spectrum of Heat-Treated Glass LP2-IL-03

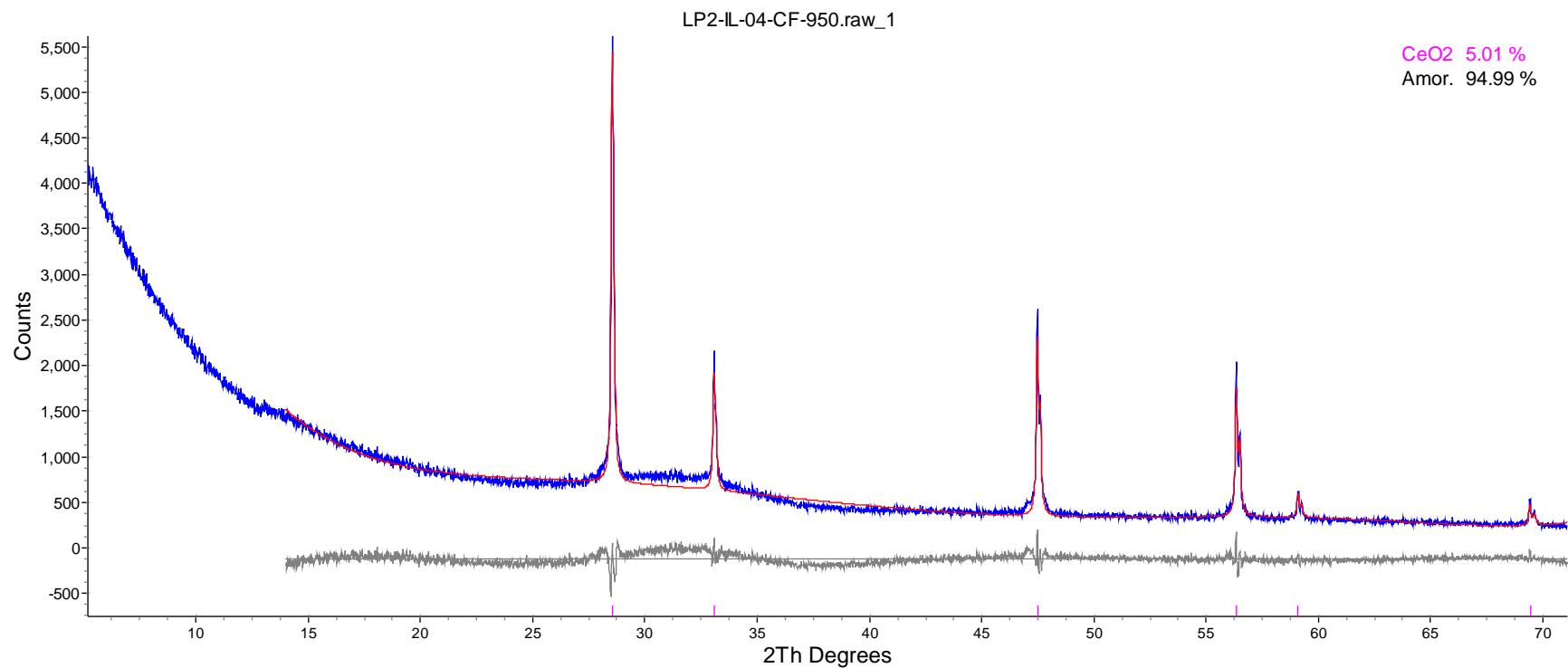


Figure F.4. XRD Spectrum of Heat-Treated Glass LP2-IL-04

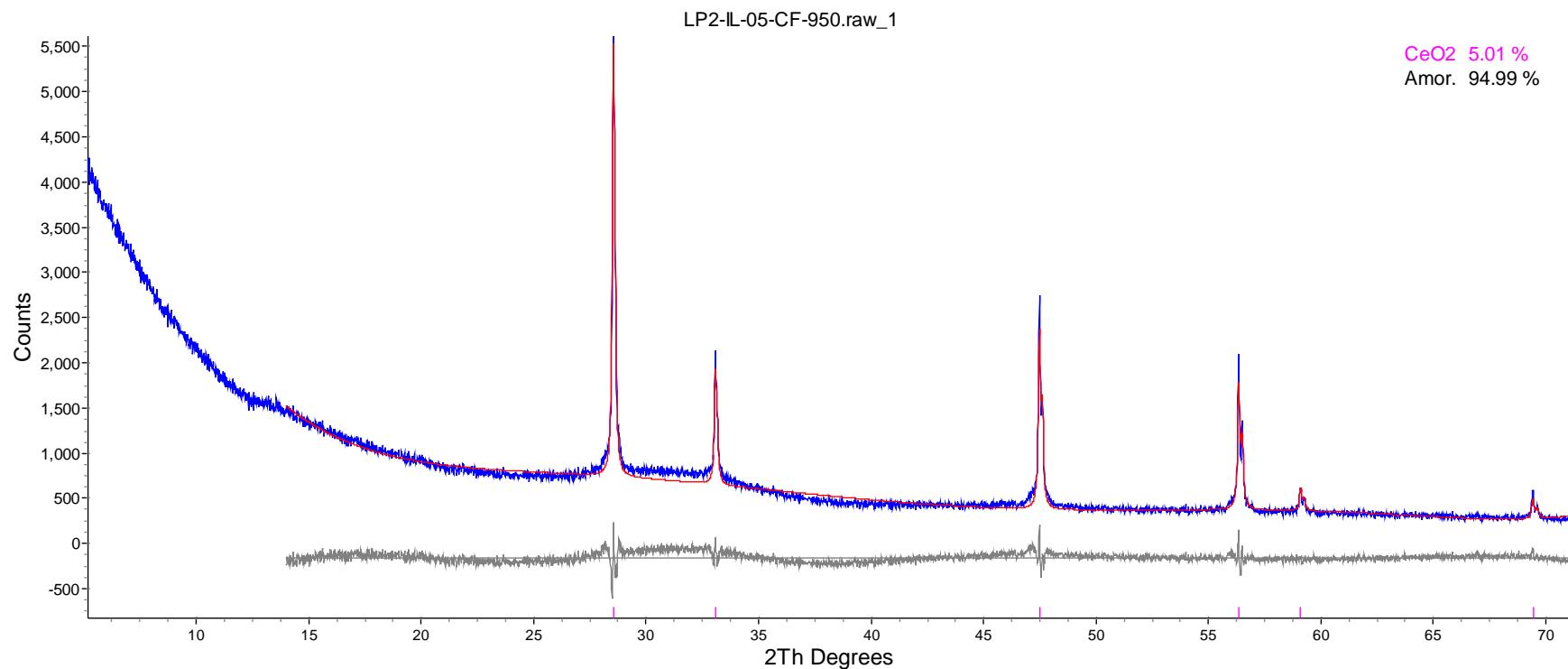


Figure F.5. XRD Spectrum of Heat-Treated Glass LP2-IL-05

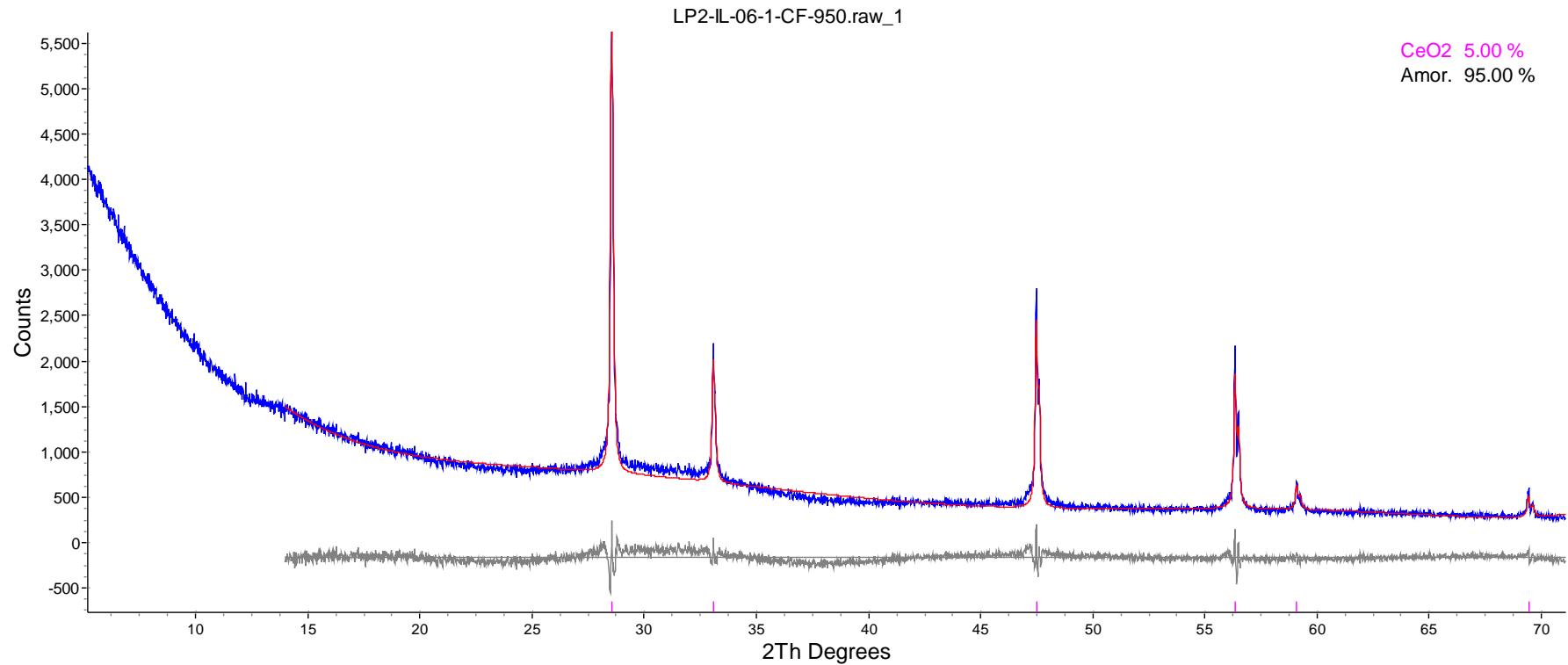


Figure F.6. XRD Spectrum of Heat-Treated Glass LP2-IL-06

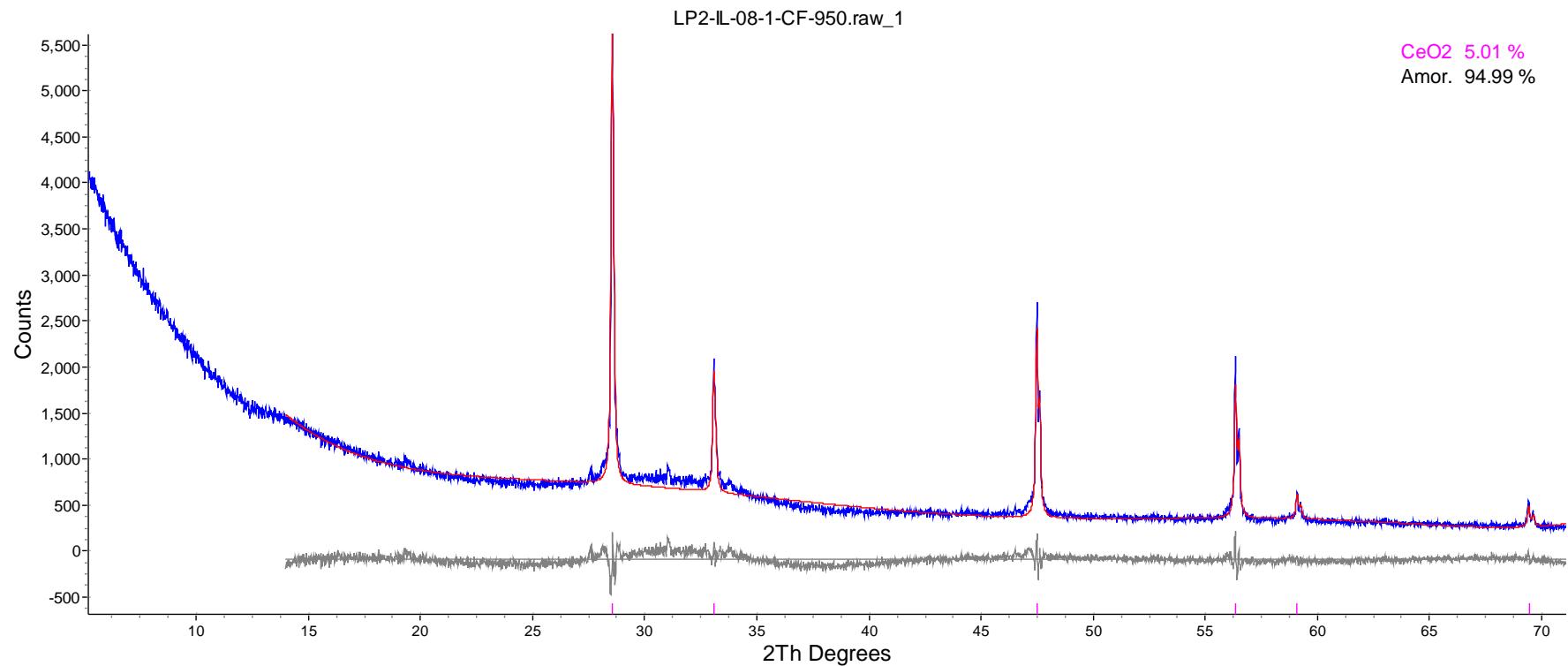


Figure F.7. XRD Spectrum of Heat-Treated Glass LP2-IL-08

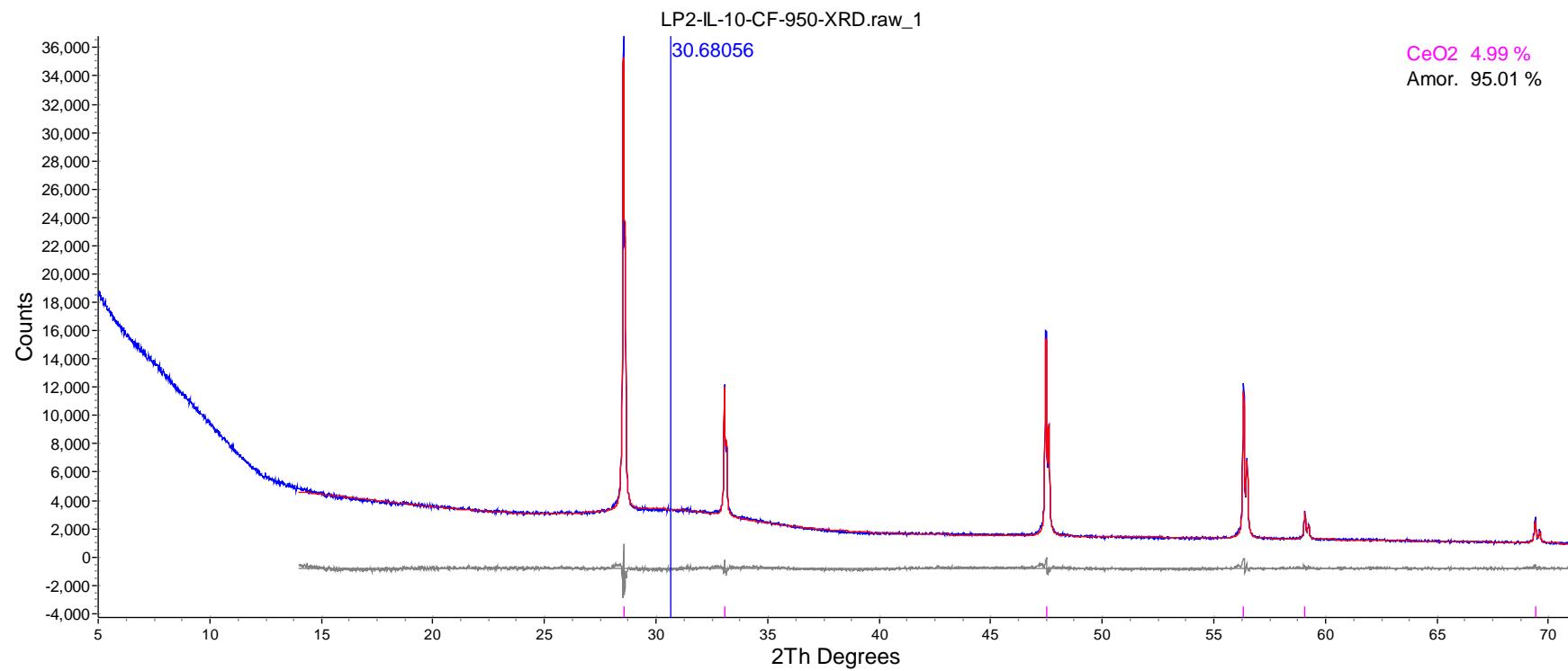
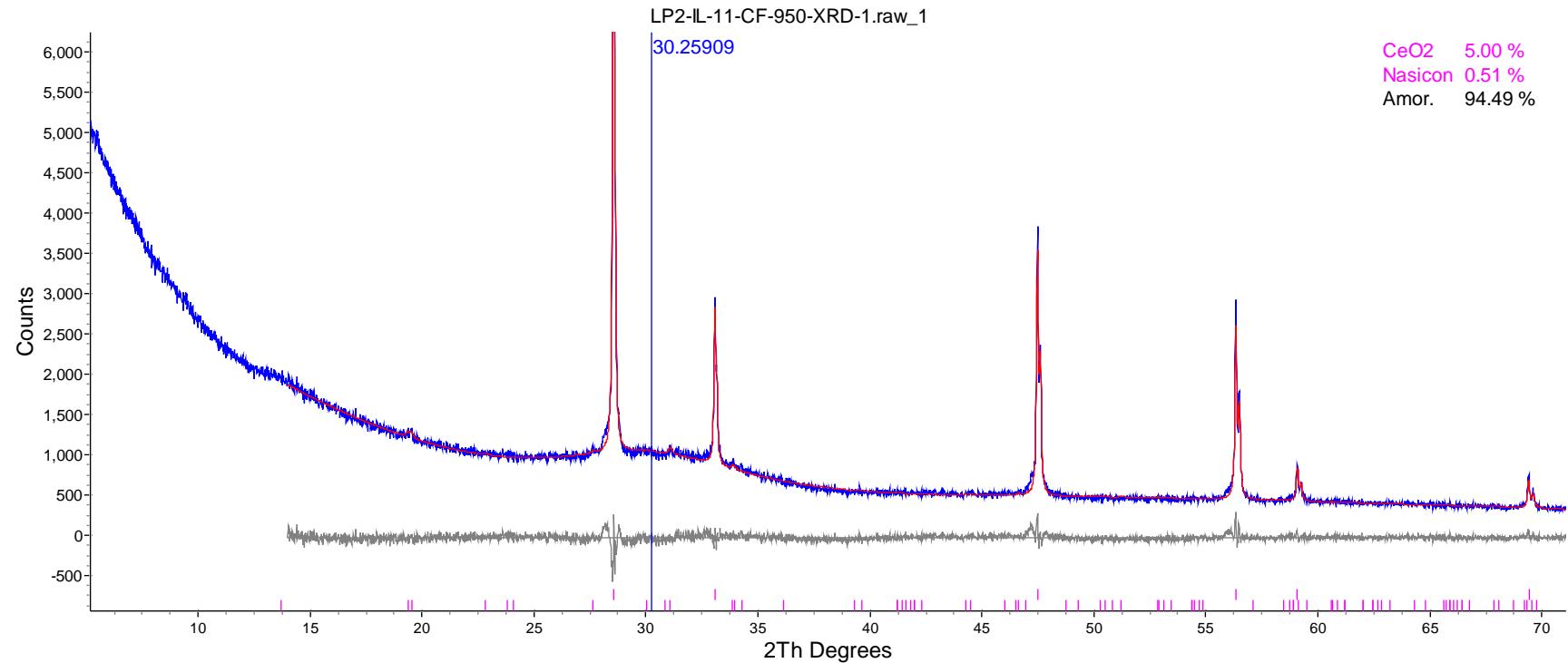


Figure F.8. XRD Spectrum of Heat-Treated Glass LP2-IL-10



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.999	4.999	0
Nasicon	0	0.512	0.539

Figure F.9. XRD Spectrum of Heat-Treated Glass LP2-IL-11

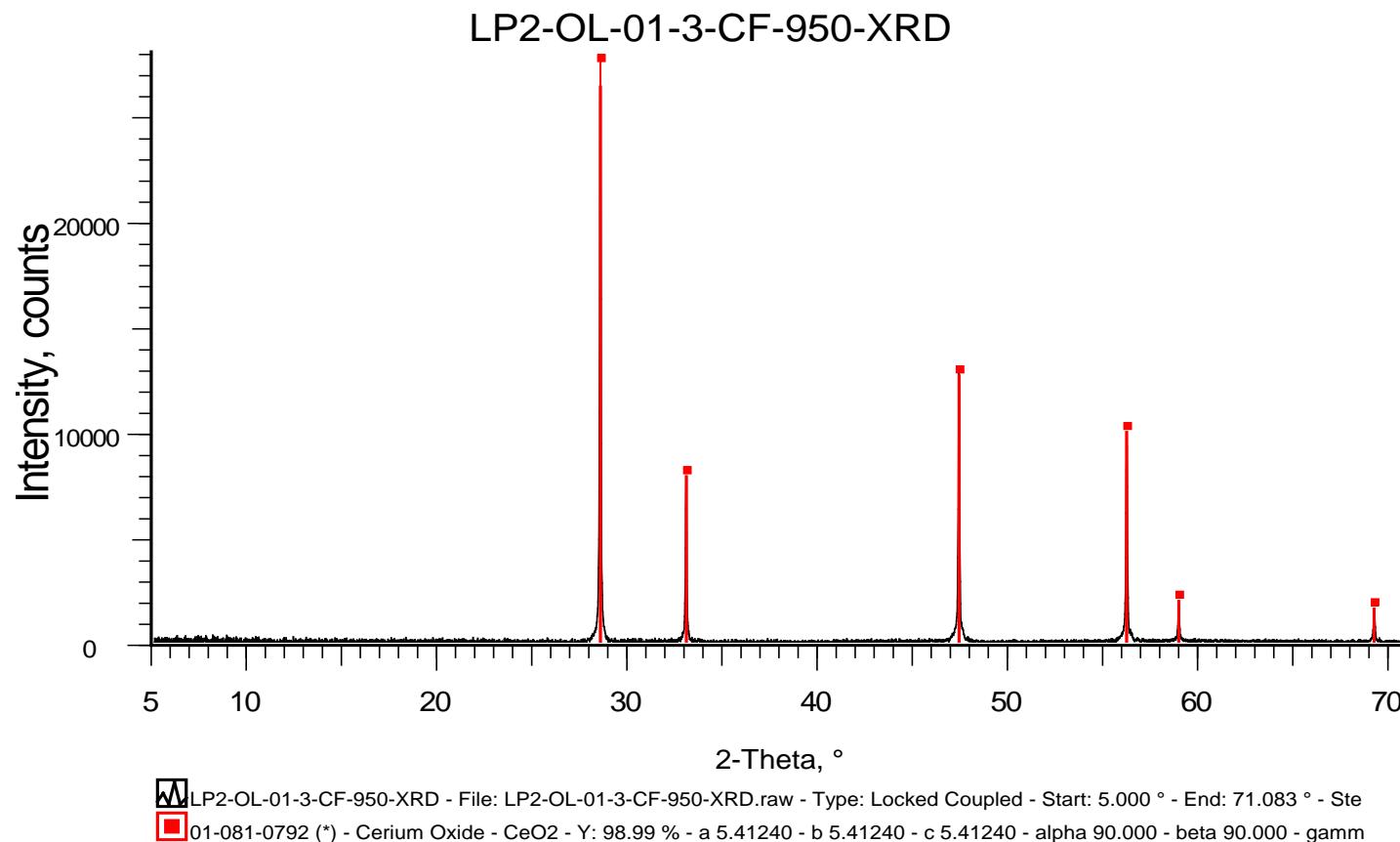
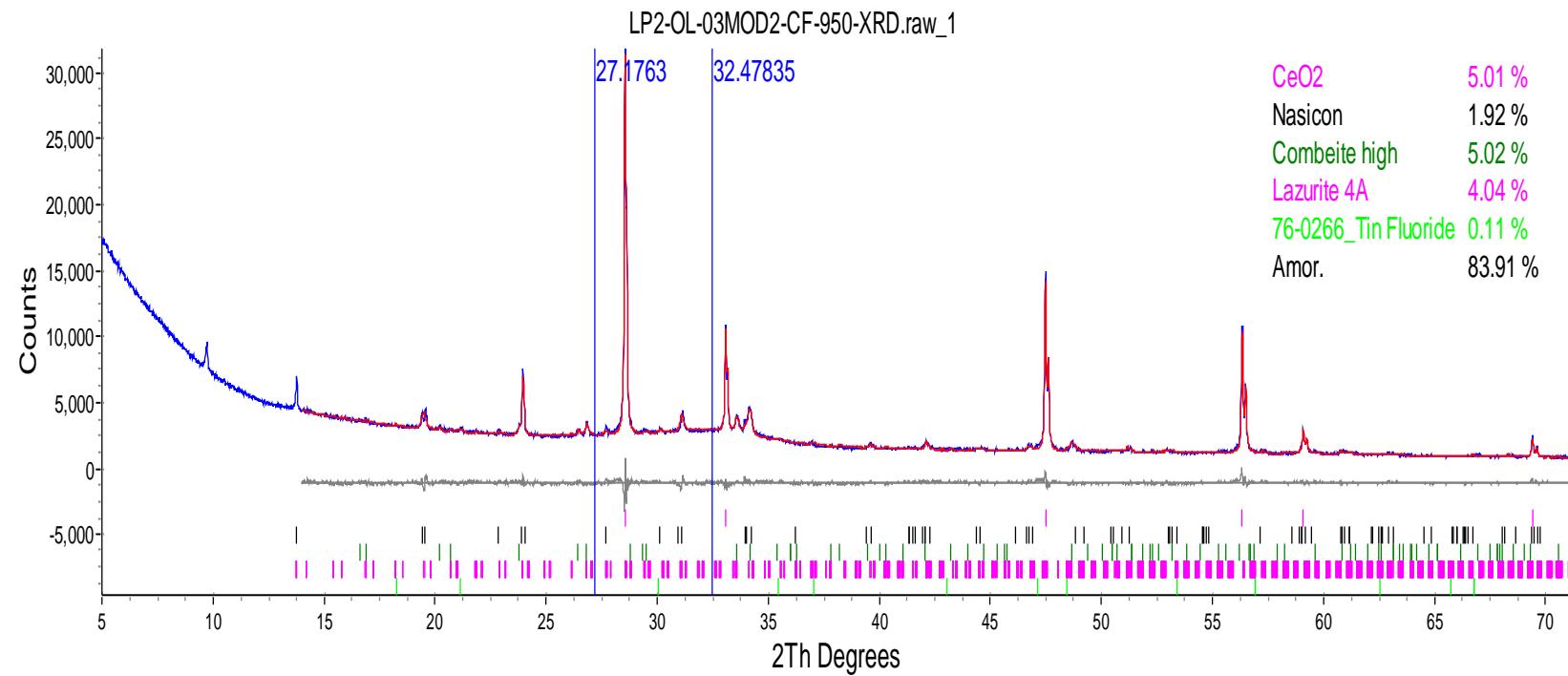
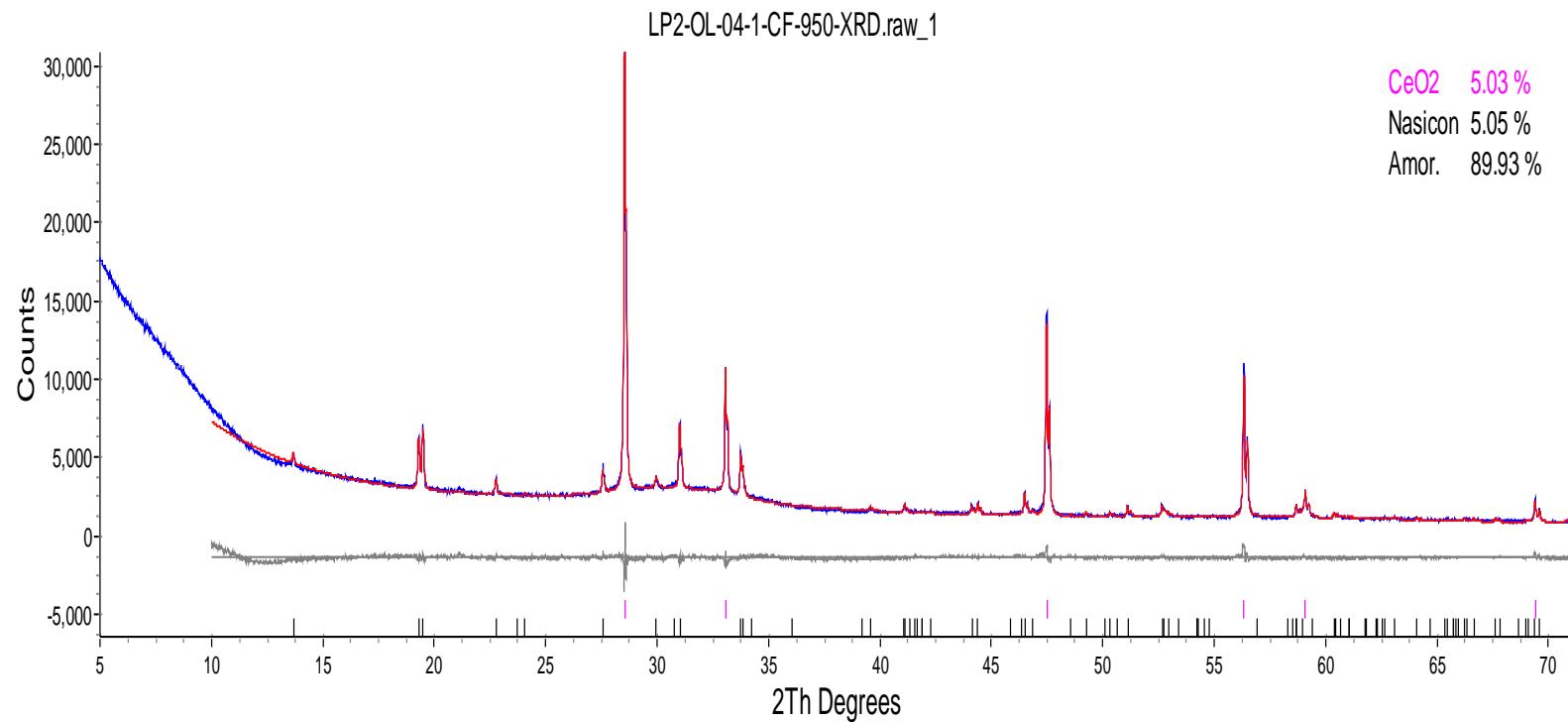


Figure F.10. XRD Spectrum of Heat-Treated Glass LP2-OL-01-3



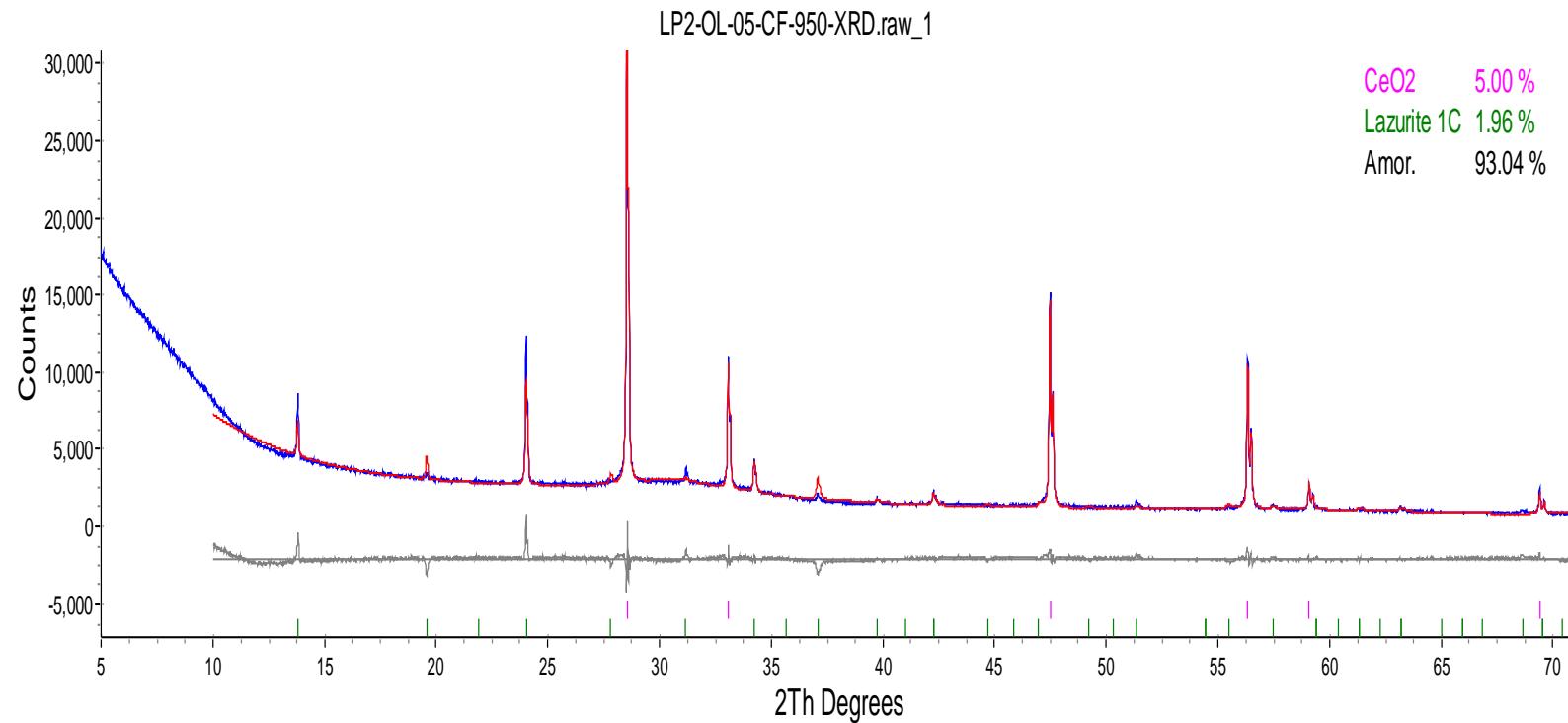
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.011	5.011	0
Nasicon	0	1.916	2.017
Combeite high	0	5.023	5.288
Lazurite 4A	0	4.036	4.248
Tin Fluoride	0	0.109	0.114

Figure F.11. XRD Spectrum of Heat-Treated Glass LP2-OL-03-MOD2



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.025	5.025	0
Nasicon	0	5.047	5.314

Figure F.12. XRD Spectrum of Heat-Treated Glass LP2-OL-04-1



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.001	5.001	0
Lazurite 1C	0	1.961	2.065

Figure F.13. XRD Spectrum of Heat-Treated Glass LP2-OL-05

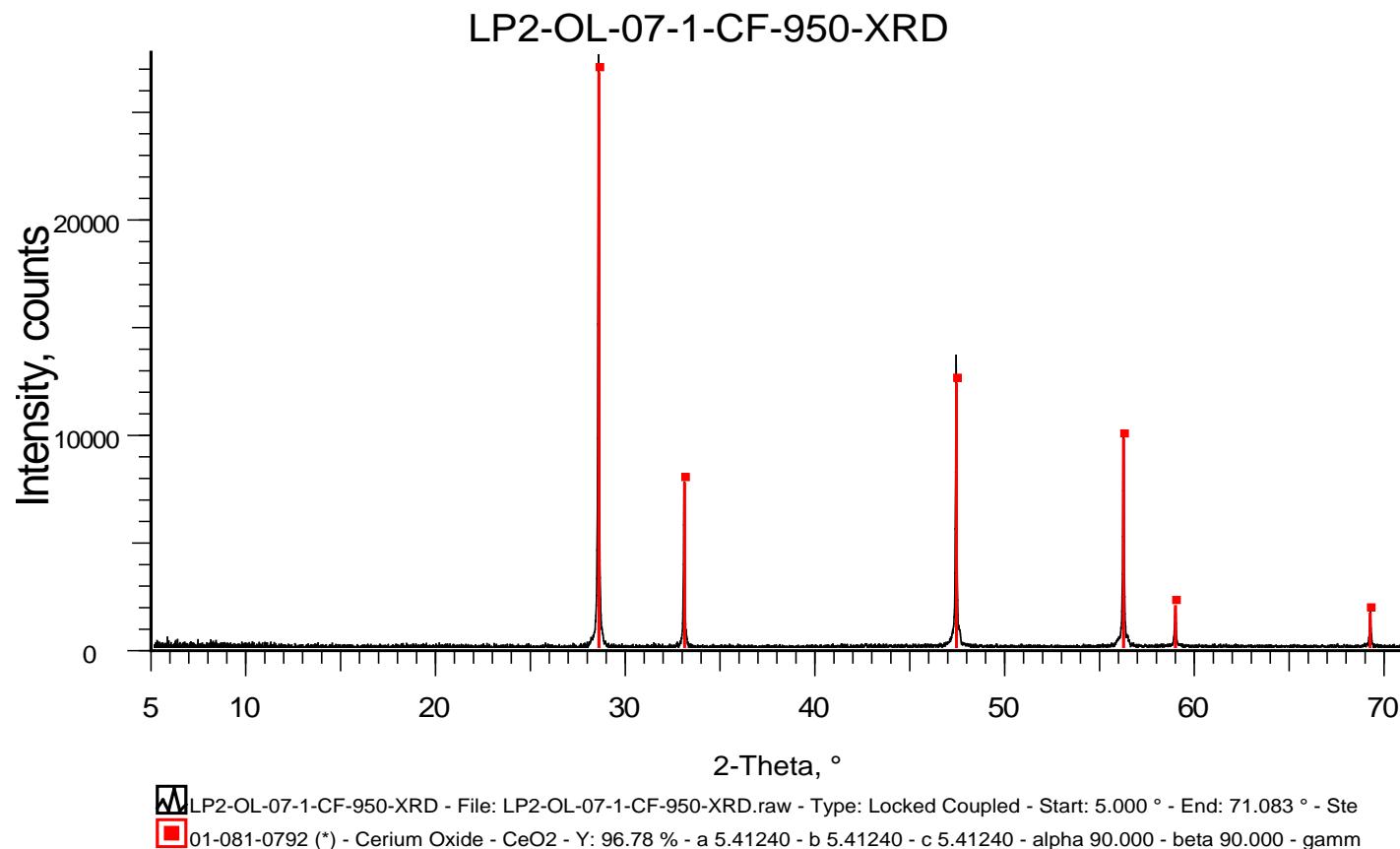
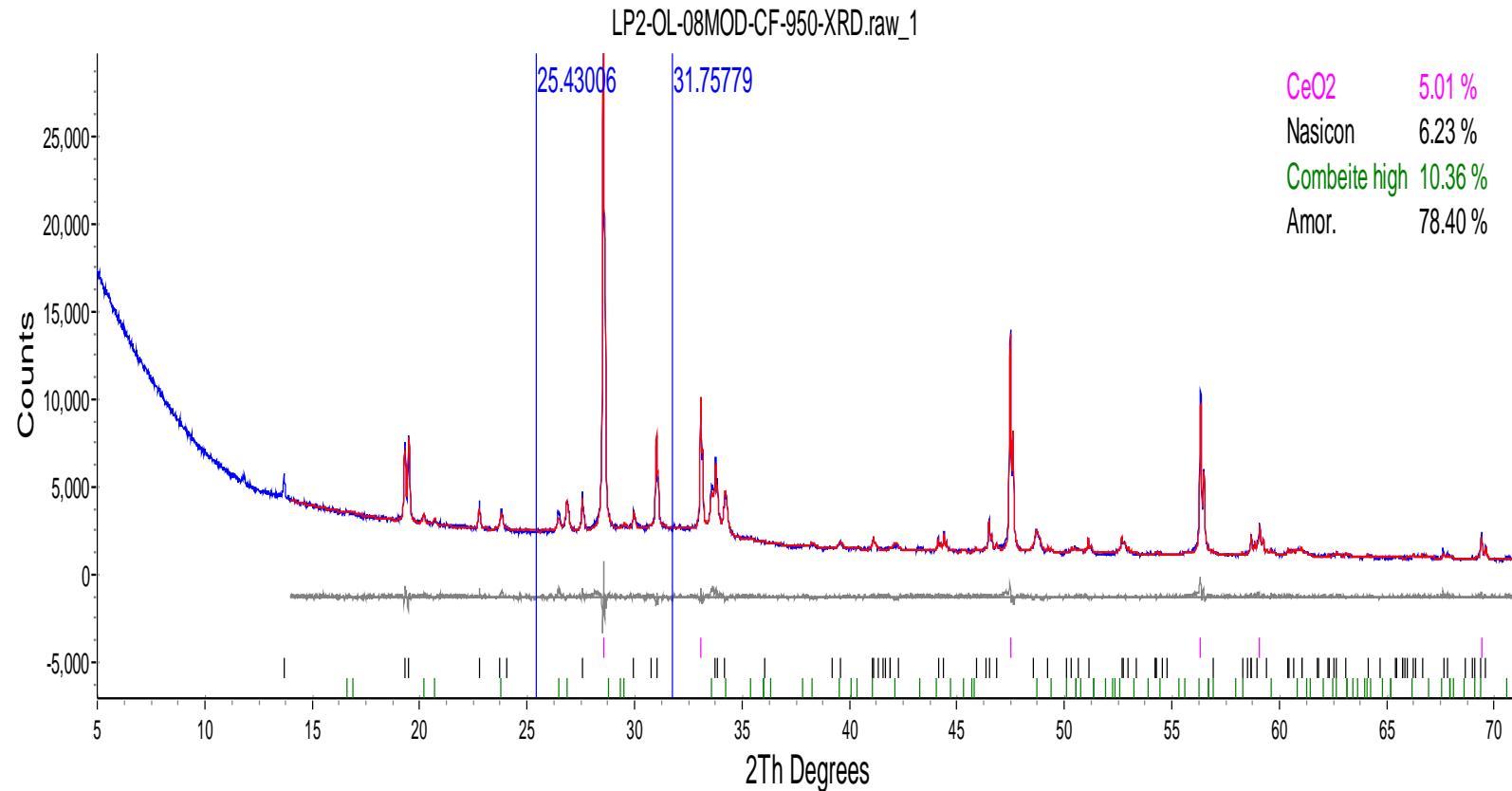
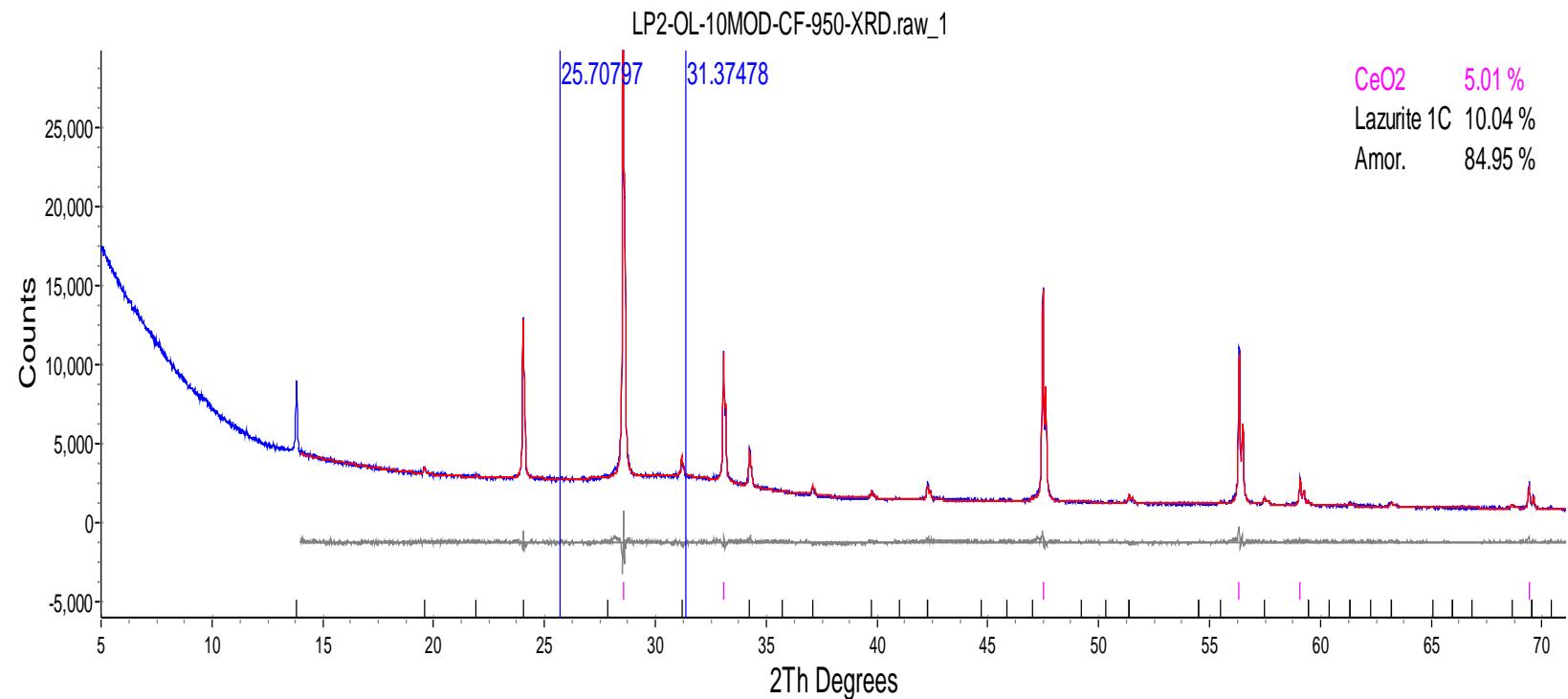


Figure F.14. XRD Spectrum of Heat-Treated Glass LP2-OL-07-1



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.011	5.011	0
Nasicon	0	6.231	6.560
Combeite high	0	10.357	10.903

Figure F.15. XRD Spectrum of Heat-Treated Glass LP2-OL-08 MOD



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.006	5.006	0
Lazurite 1C	0	10.040	10.569

Figure F.16. XRD Spectrum of Heat-Treated Glass LP2-OL-10 MOD

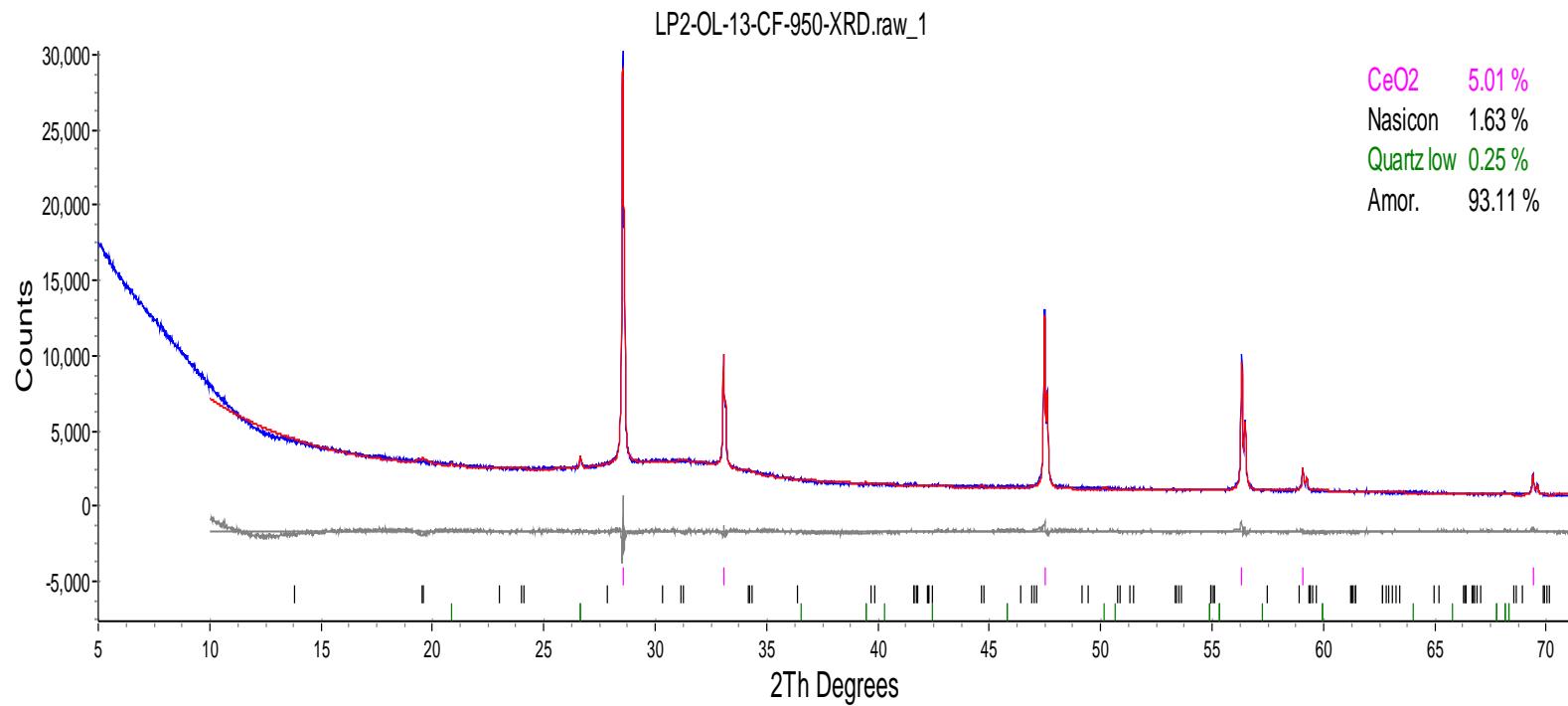


Figure F.17. XRD Spectrum of Heat-Treated Glass LP2-OL-13

### LP2-OL-16MOD-CF-950-XRD

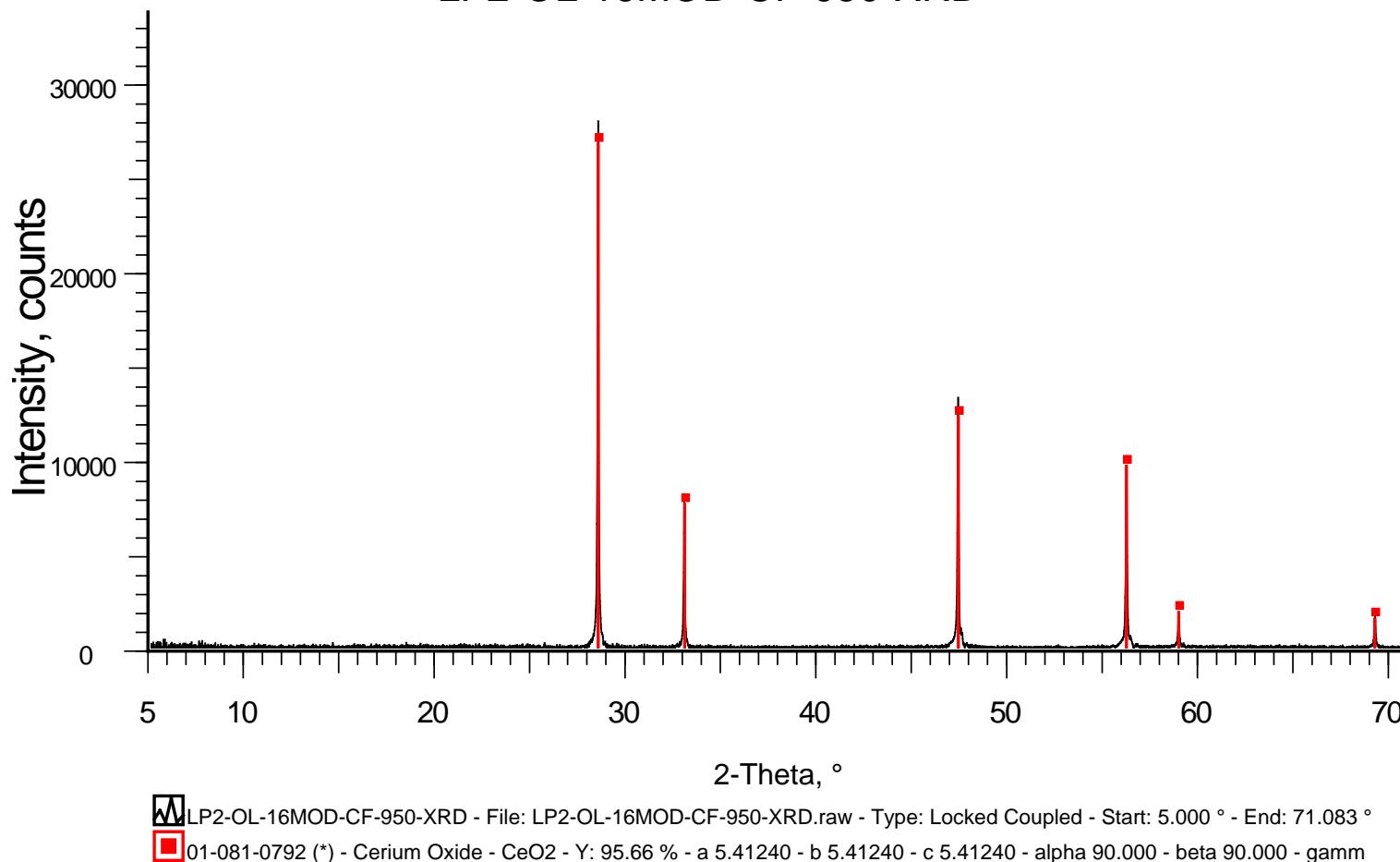


Figure F.18. XRD Spectrum of Heat-Treated Glass LP2-OL-16 MOD

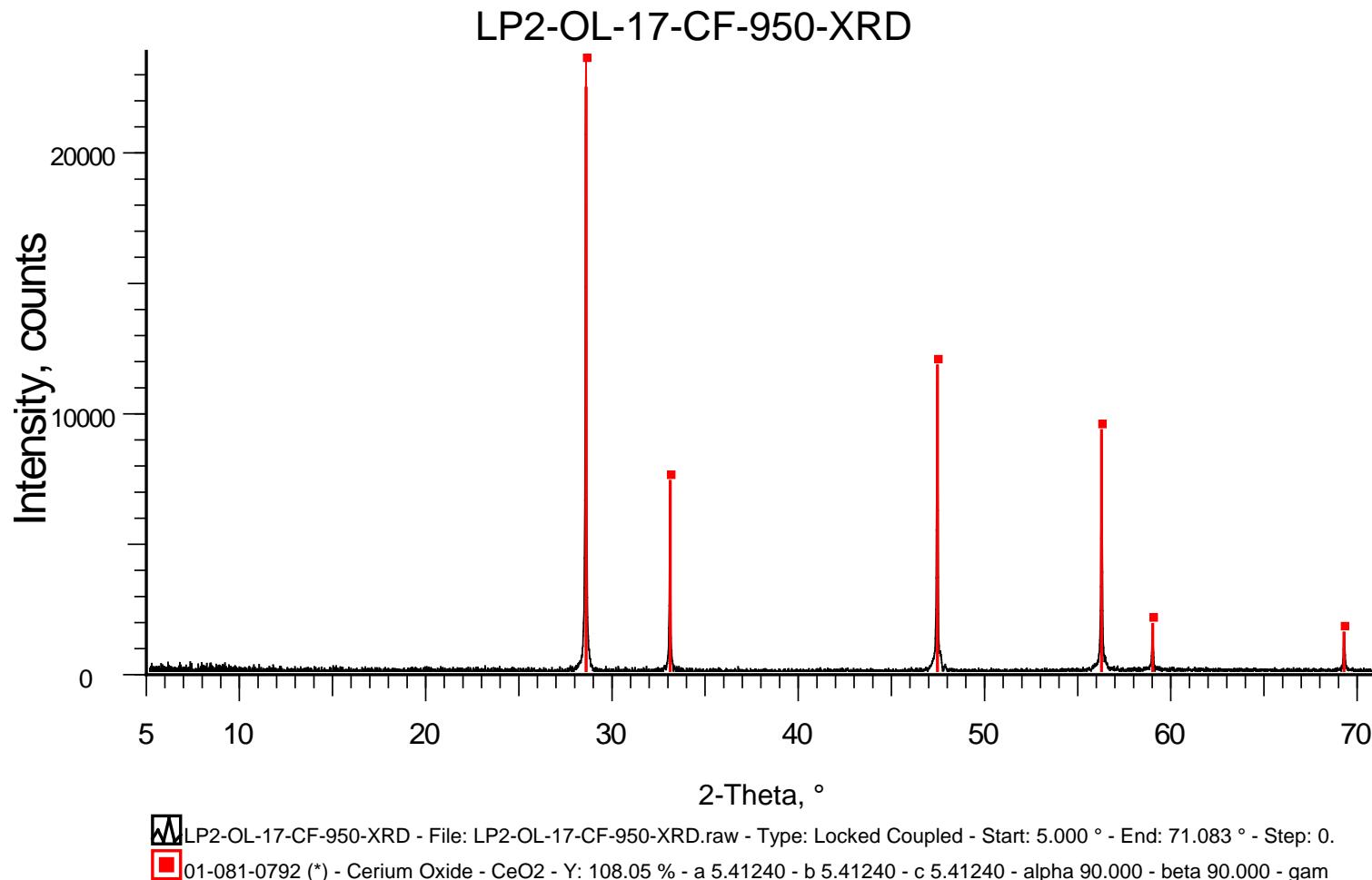
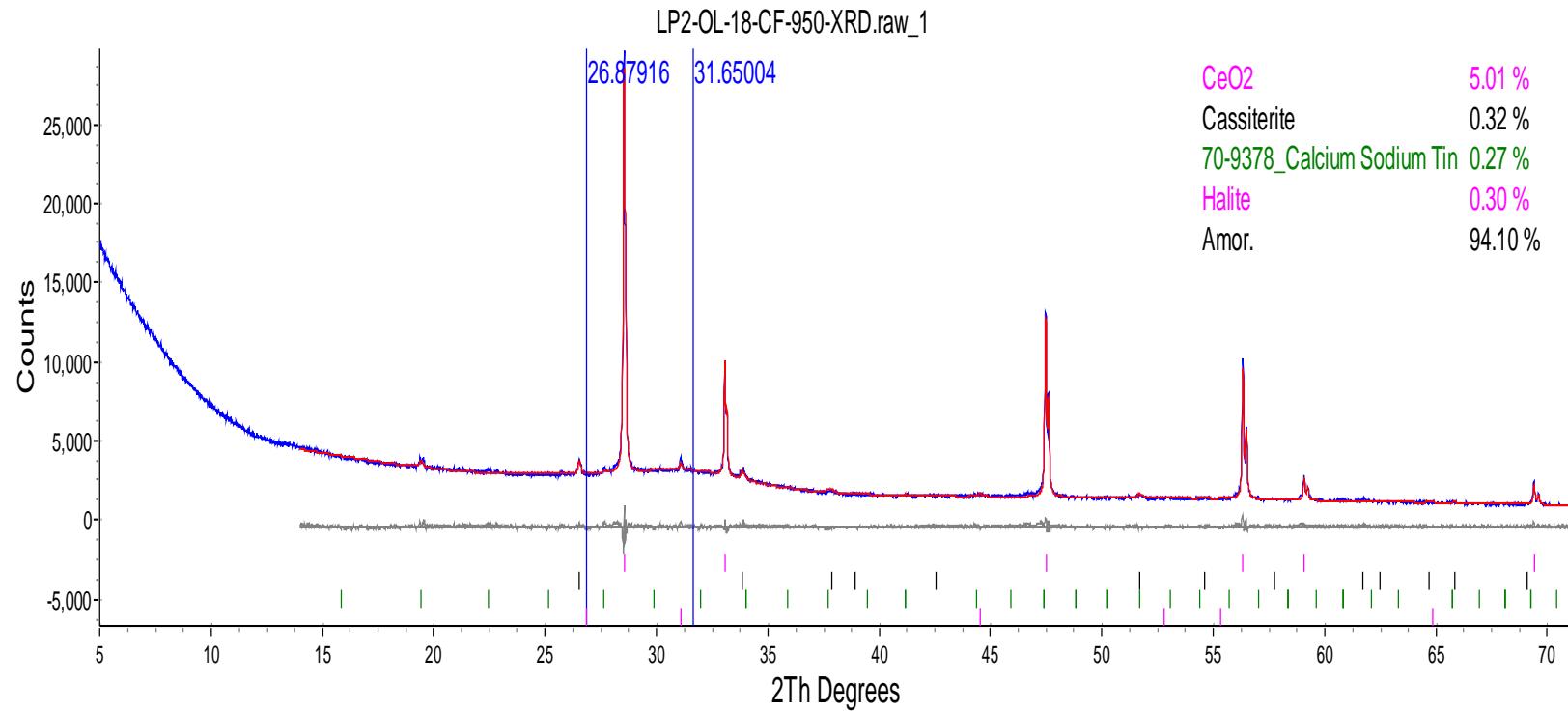


Figure F.19. XRD Spectrum of Heat-Treated Glass LP2-OL-17



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.010	5.010	0
Cassiterite	0	0.319	0.336
Calcium Sodium Tin	0	0.272	0.287
Halite	0	0.297	0.313

Figure F.20. XRD Spectrum of Heat-Treated Glass LP2-OL-18

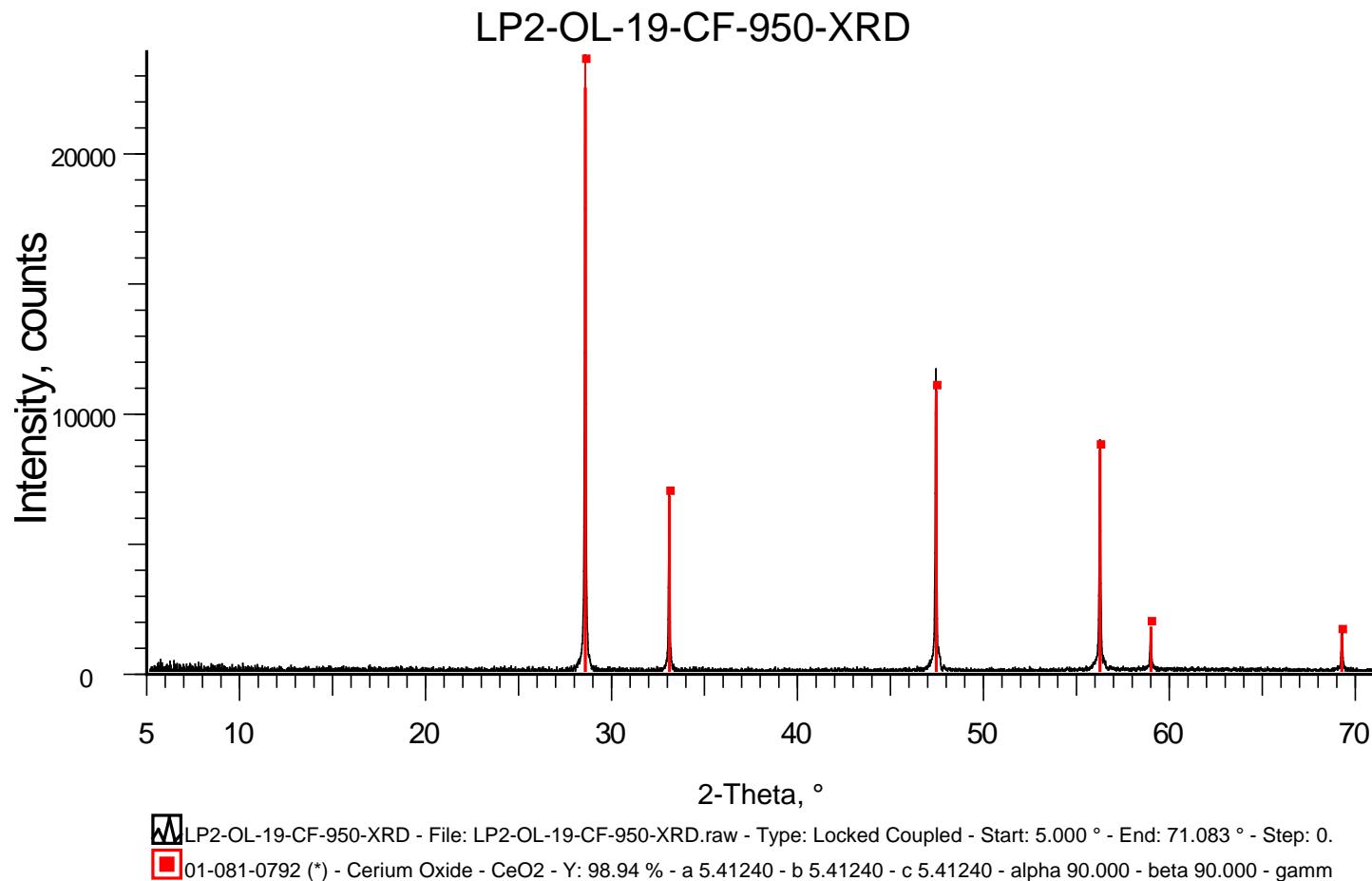
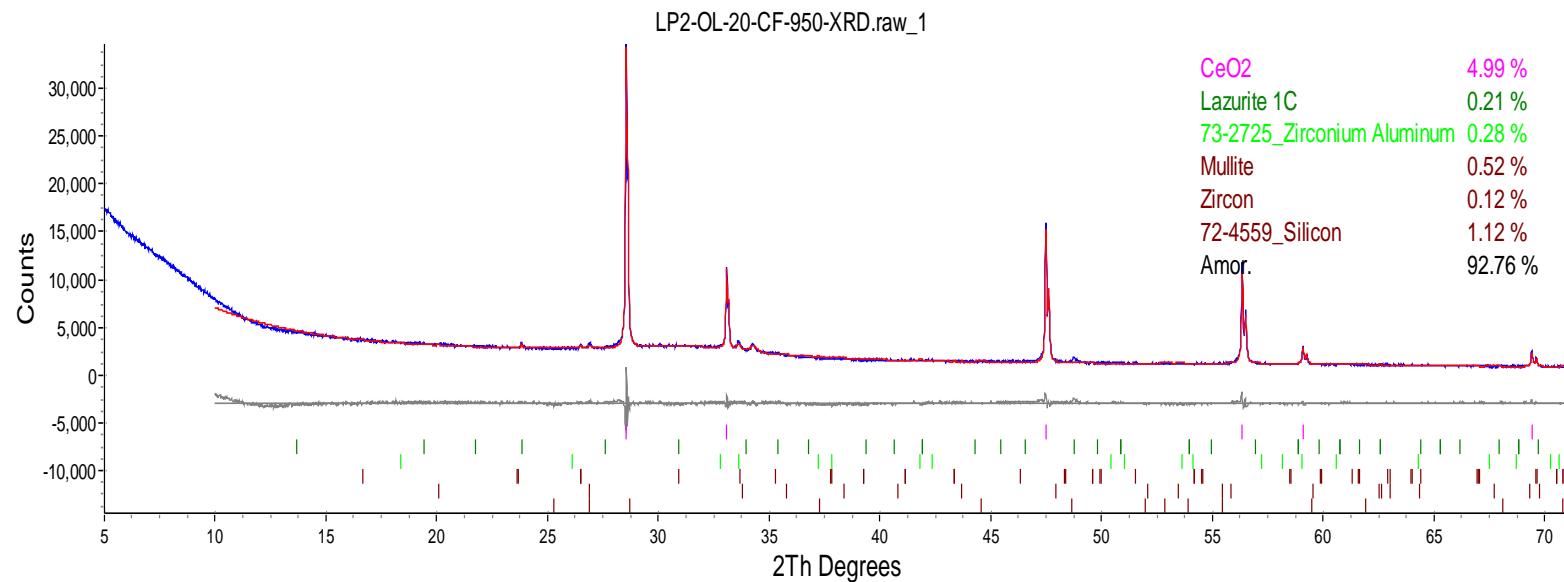
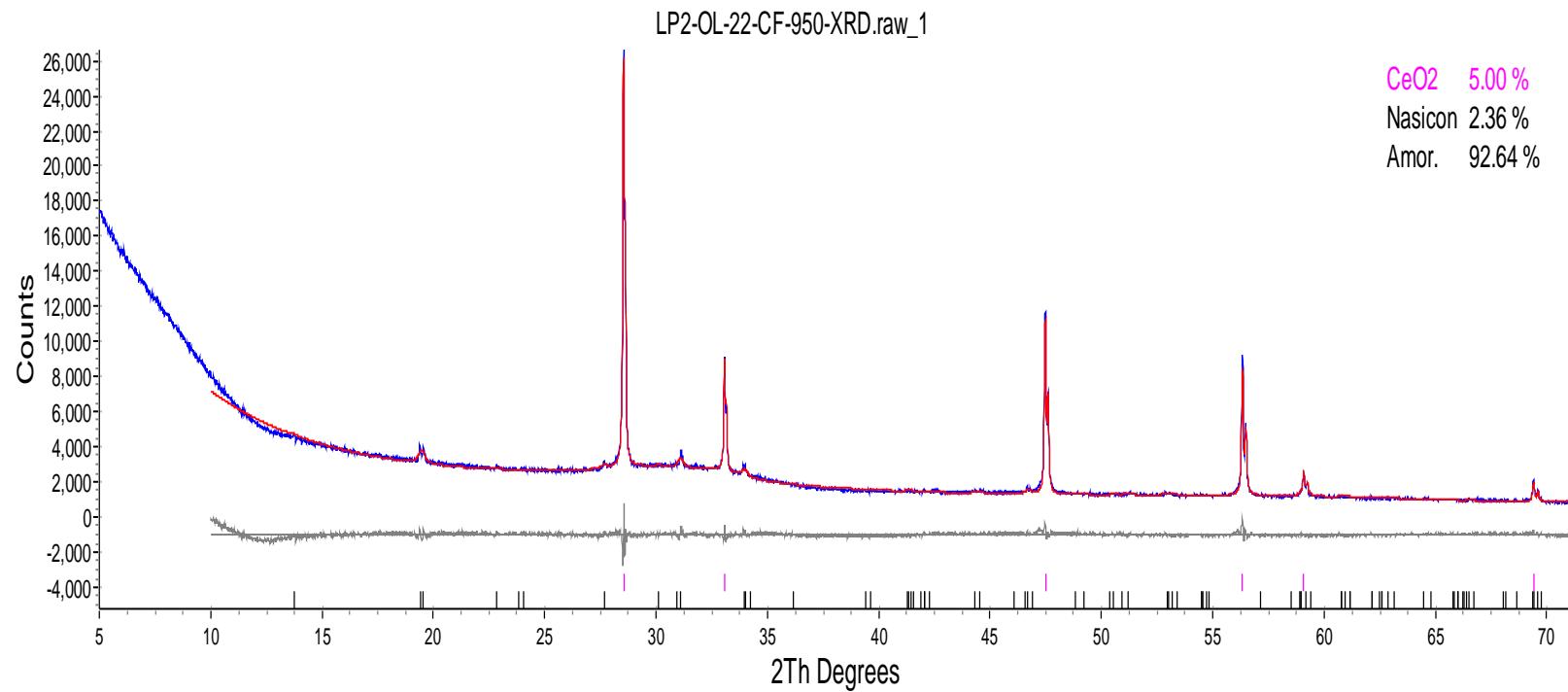


Figure F.21. XRD Spectrum of Heat-Treated Glass LP2-OL-19



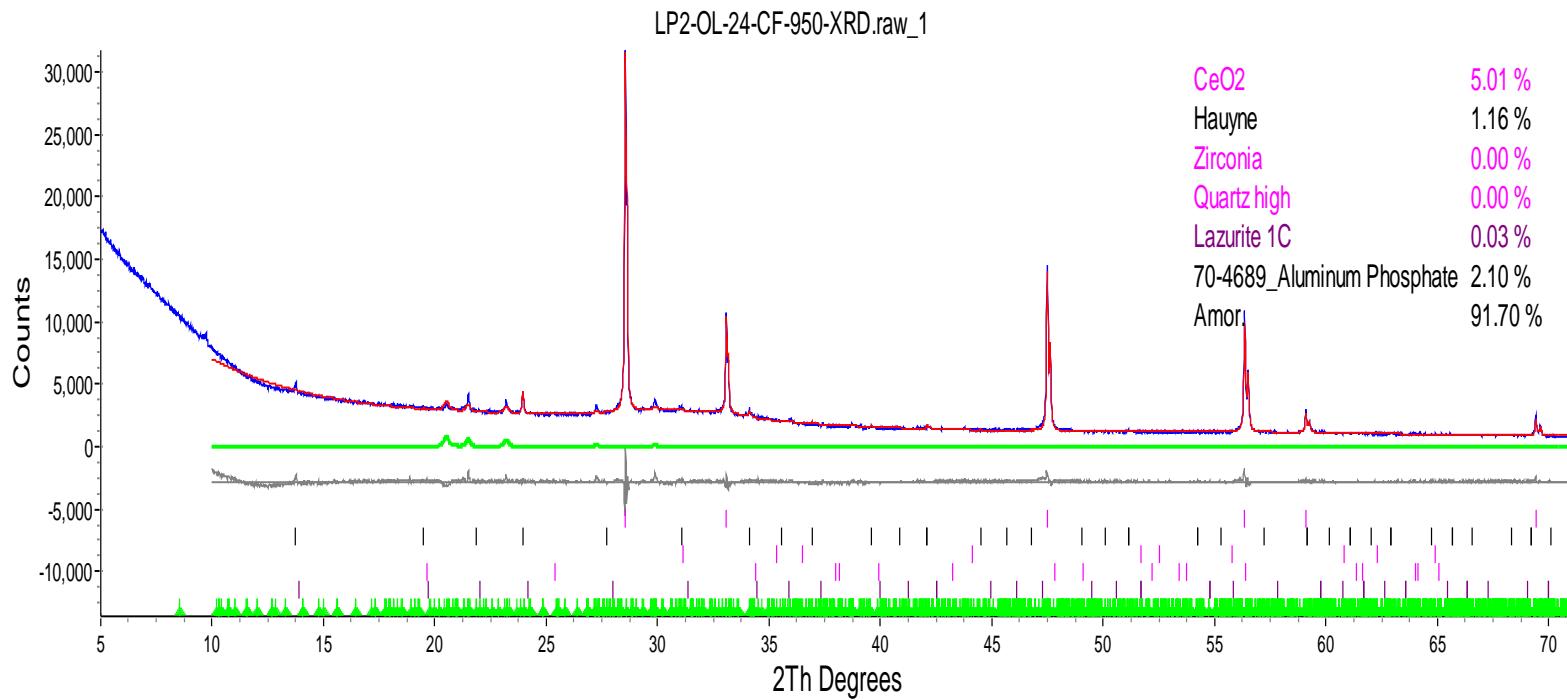
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.985	4.985	0
Lazurite 1C	0	0.213	0.224
Zirconium Aluminum	0	0.277	0.292
Mullite	0	0.517	0.544
Zircon	0	0.125	0.131
Silicon	0	1.121	1.180

Figure F.22. XRD Spectrum of Heat-Treated Glass LP2-OL-20



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.004	5.004	0
Nasicon	0	2.358	2.483

Figure F.23. XRD Spectrum of Heat-Treated Glass LP2-OL-22



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.007	5.007	0
Hauyne	0	1.157	1.218
Lazurite 1C	0	0.031	0.033
Aluminum Phosphate	0	2.105	2.216

Figure F.24. XRD Spectrum of Heat-Treated Glass LP2-OL-24

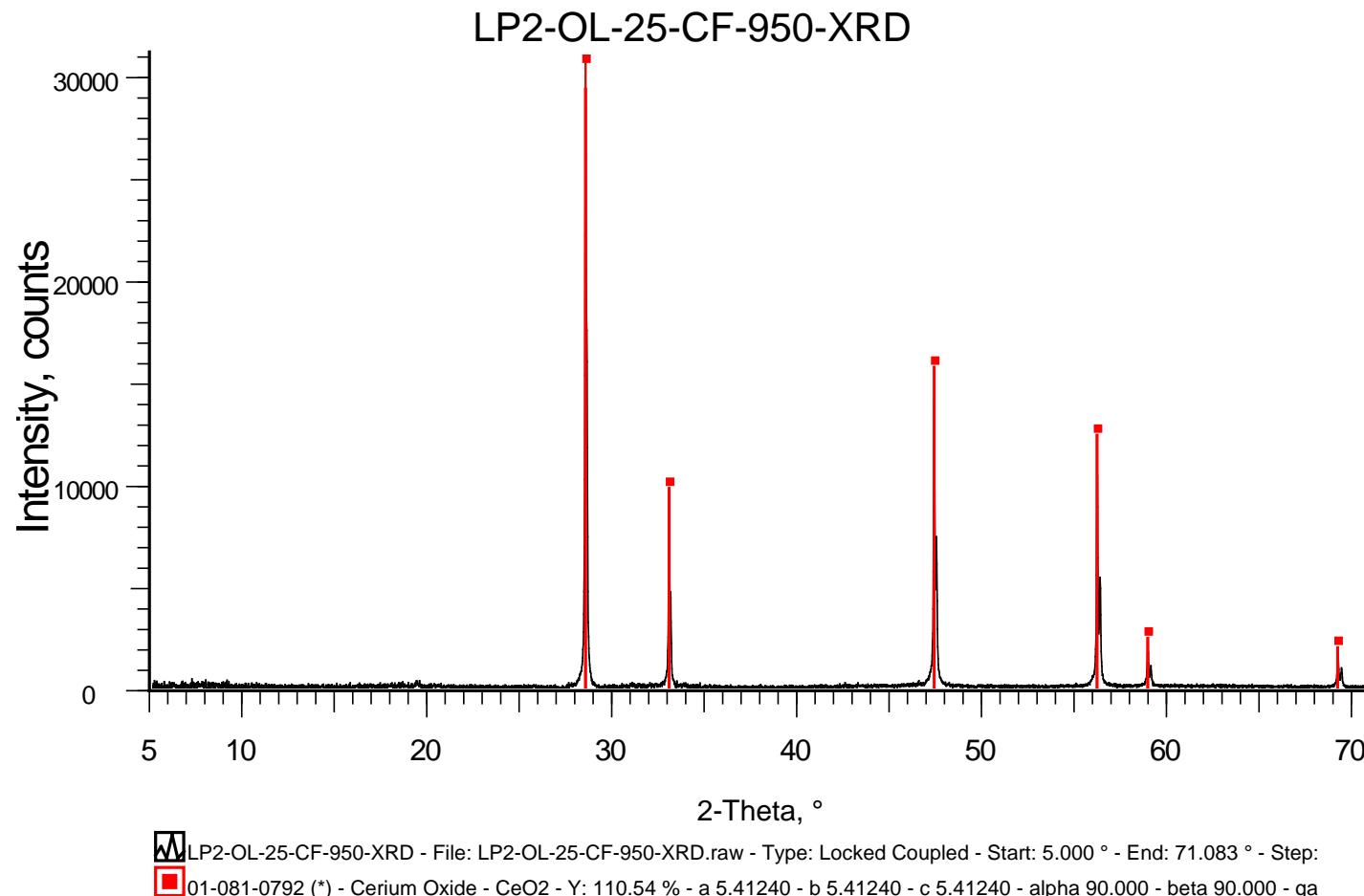


Figure F.25. XRD Spectrum of Heat-Treated Glass LP2-OL-25

## Appendix G – Canister Centerline Cooling (CCC) Glass Photographs

This appendix contains photos of Phase 2 enhanced LAW glasses after they were CCC heat-treated beginning at the glass melting temperature, which is indicated in the picture title. Each showed different responses to the CCC heat-treatment as indicated by these photos.



Figure G.1. Glass LP2-IL-01 after CCC Beginning at 1150°C both Glass (left) and Magnified 50X (right)



Figure G.2. Glass LP2-IL-02 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)



Figure G.3. Glass LP2-IL-03 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

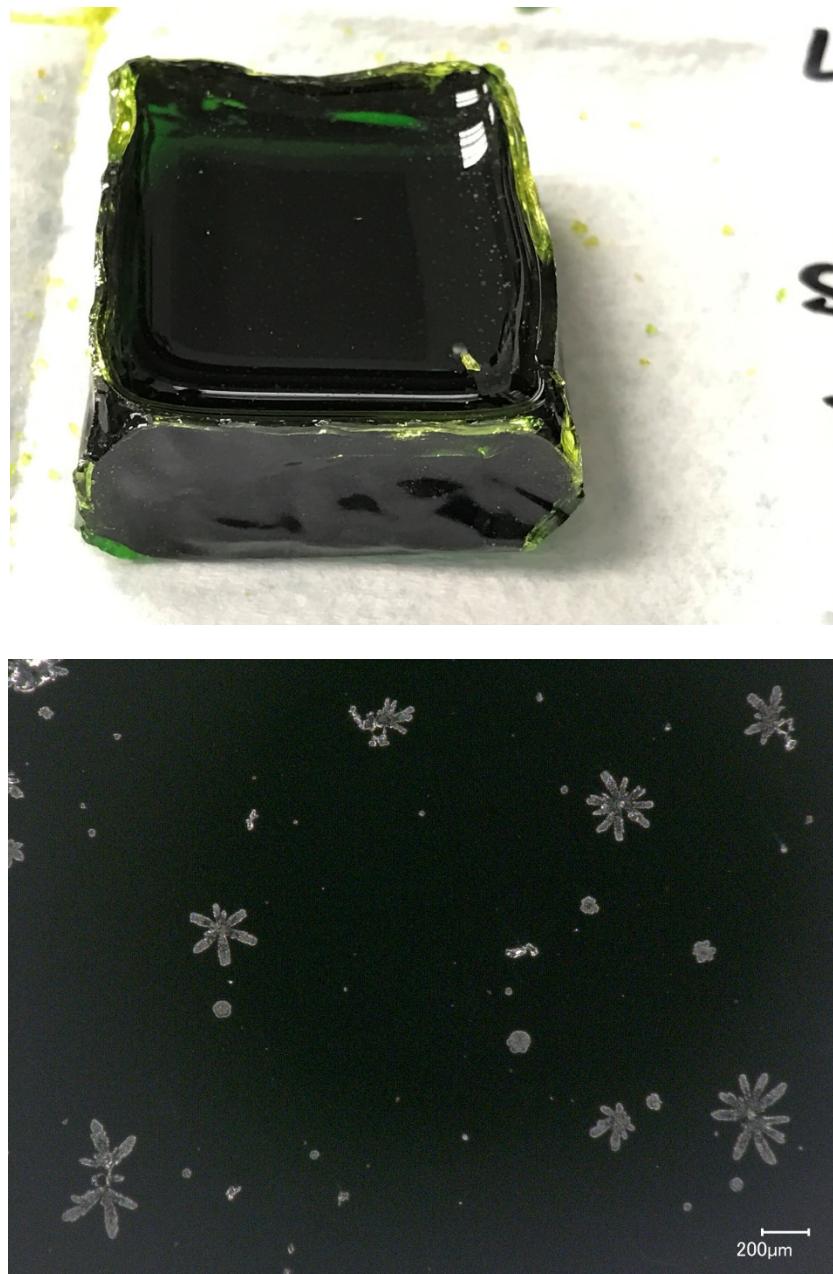


Figure G.4. Glass LP2-IL-04 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

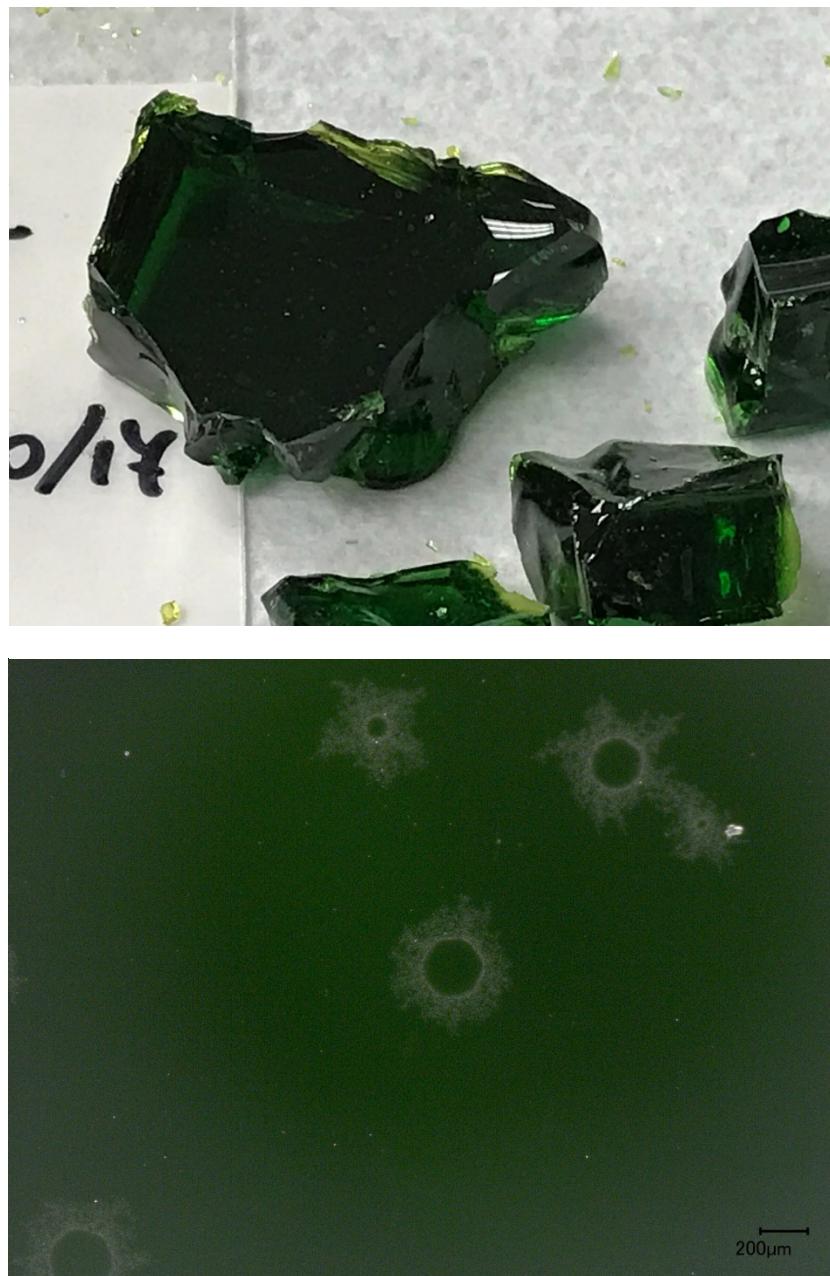


Figure G.5. Glass LP2-IL-05 CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

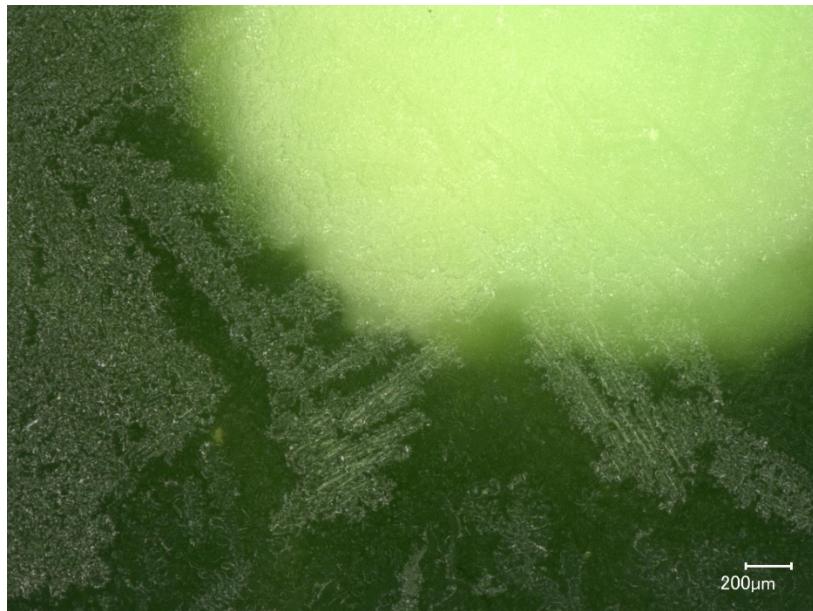
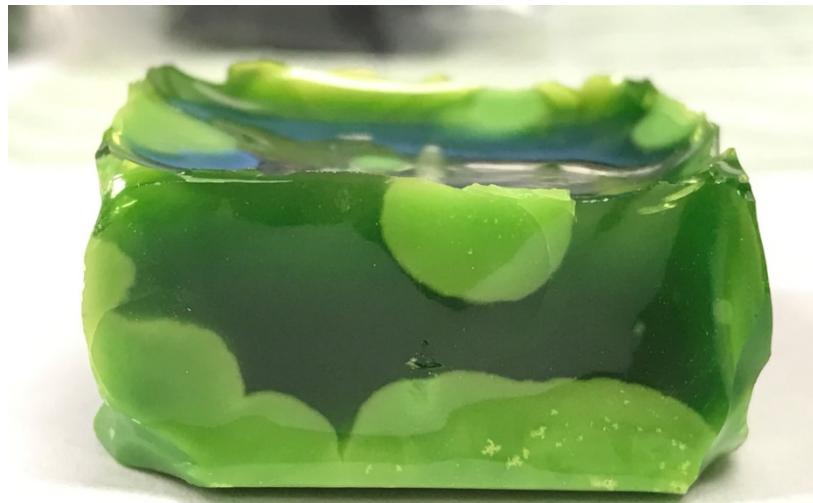


Figure G.6. Glass LP2-IL-06 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

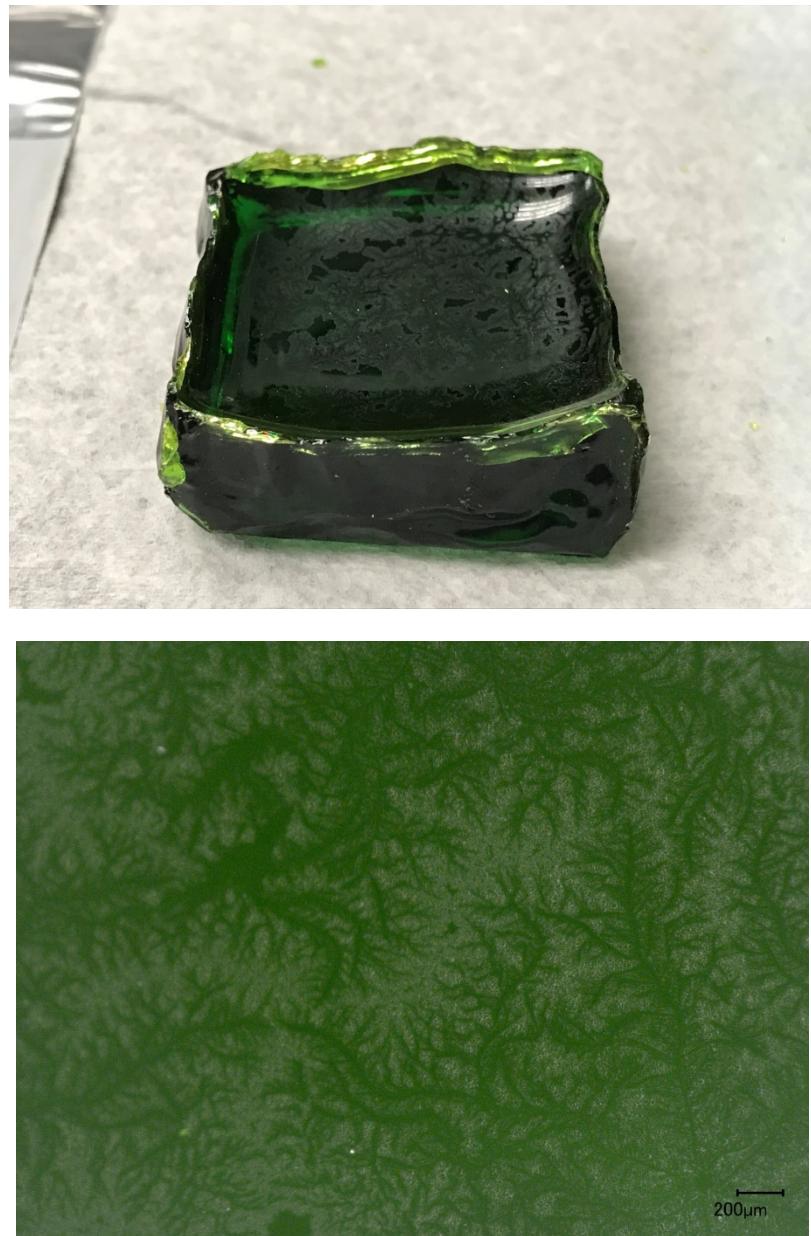


Figure G.7. Glass LP2-IL-07 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

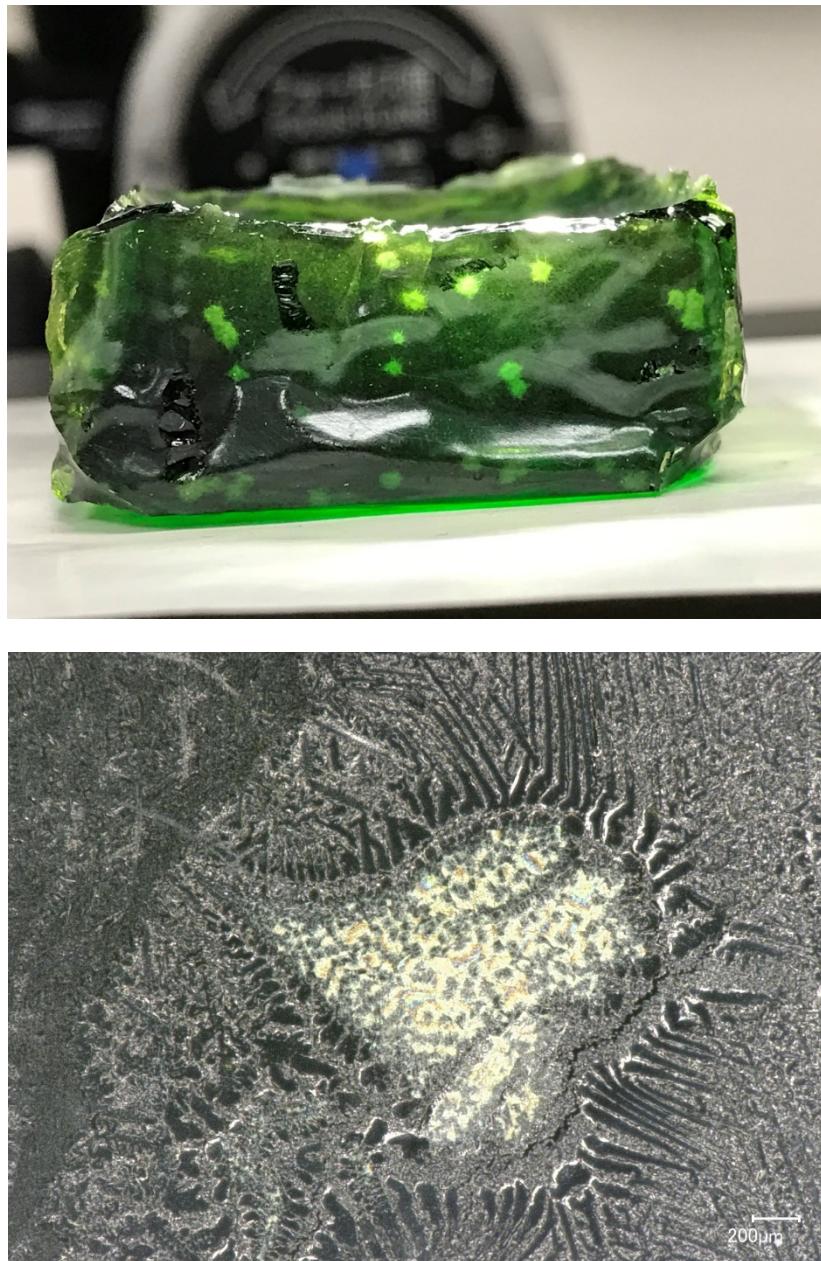


Figure G.8. Glass LP2-IL-08 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

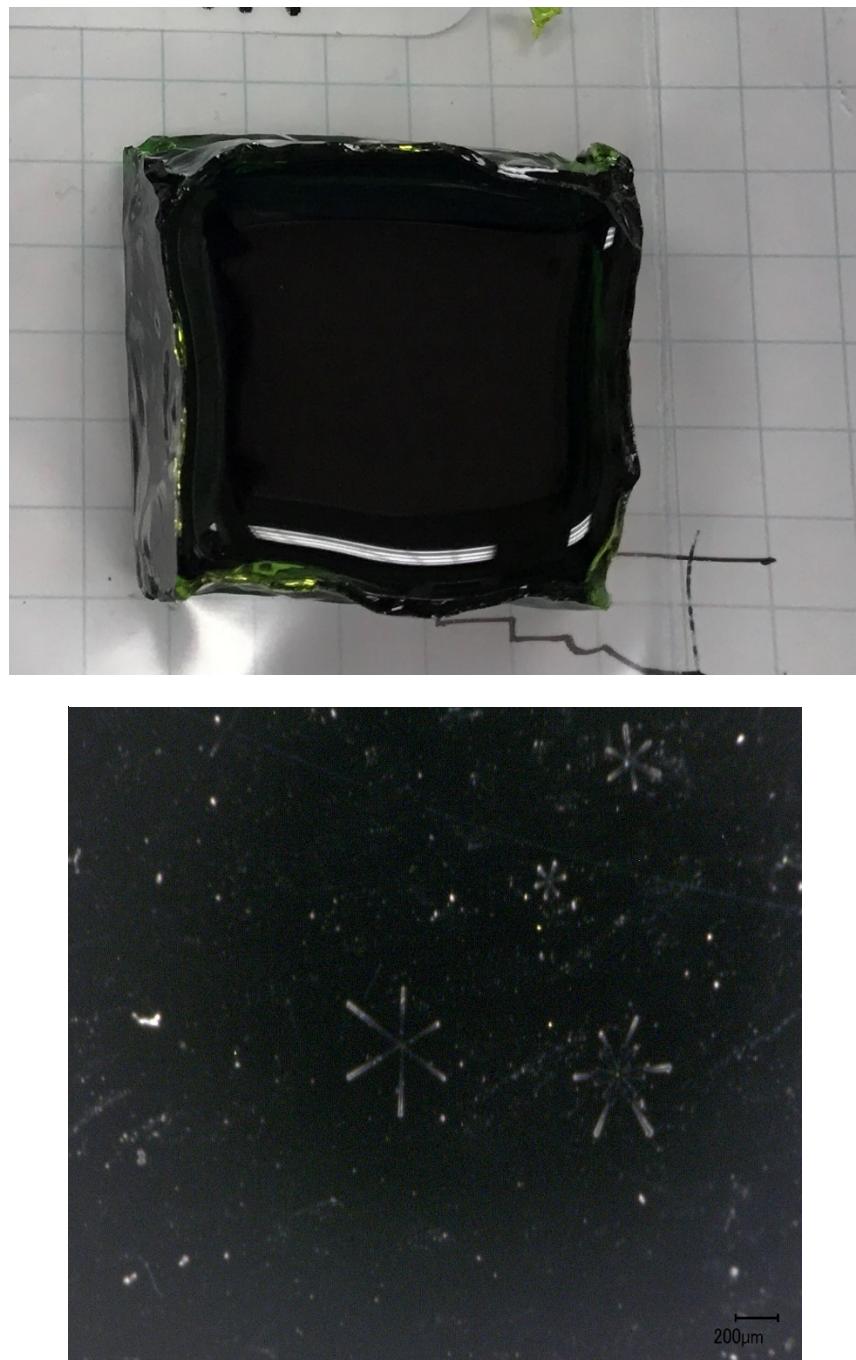


Figure G.9. Glass LP2-IL-09 after CCC Beginning at 1150°C both Glass (left) and Magnified 100X (right)

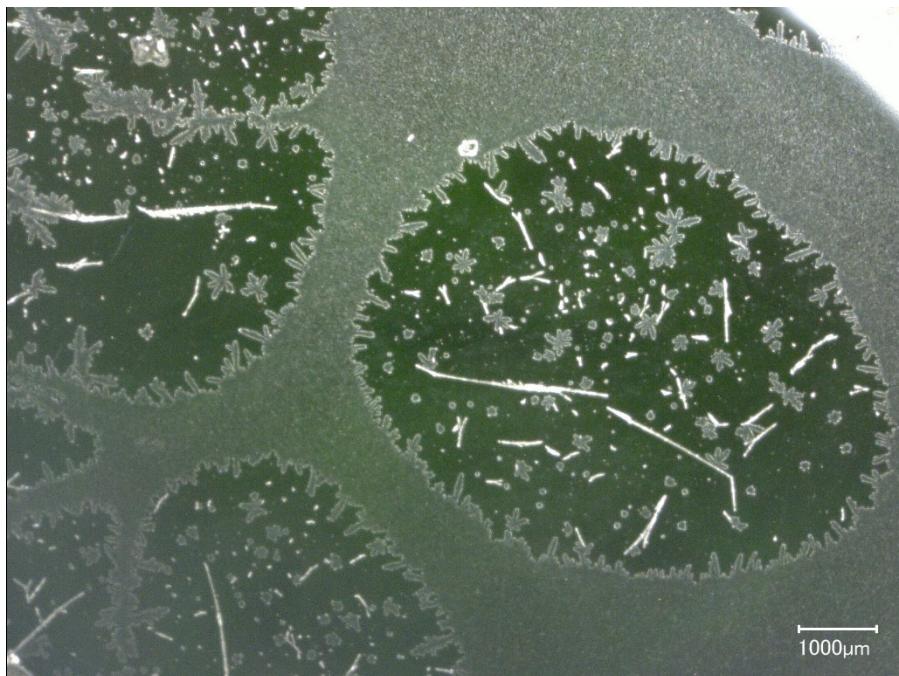
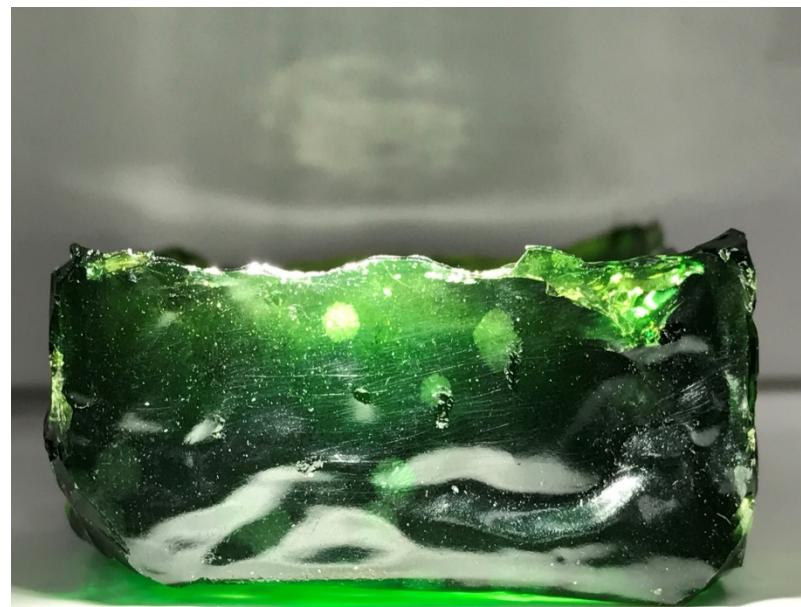


Figure G.10. Glass LP2-IL-10 CCC Beginning at 1150°C both Glass (left) and Magnified 30X (right)

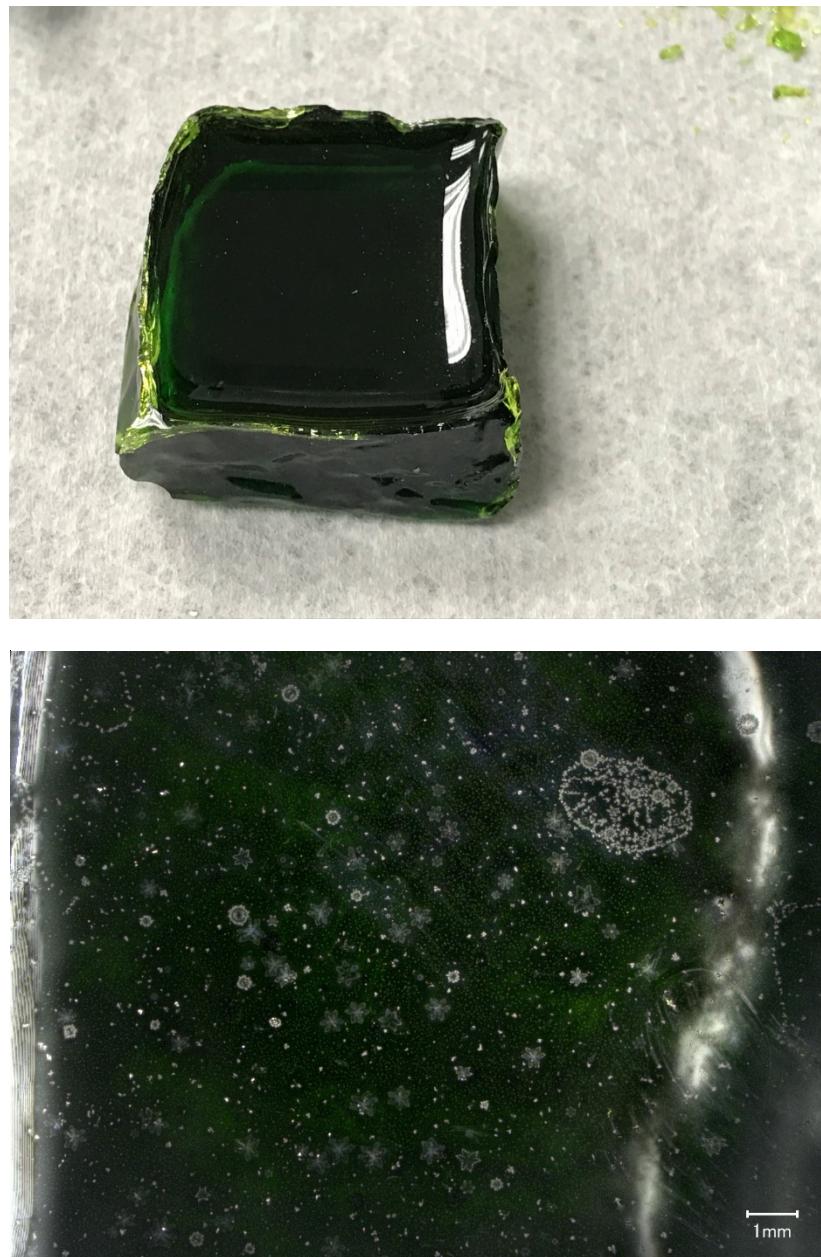


Figure G.11. Glass LP2-JL-11 CCC Beginning at 1150°C both Glass (left) and Magnified 20X (right)



Figure G.12. Glass LP2-IL-12 after CCC Beginning at 1150°C both Glass (left) and Magnified 50X (right)



Figure G.13. Glass LP2-IL-13 after CCC Beginning at 1150°C both Glass (left) and Magnified 50X (right)

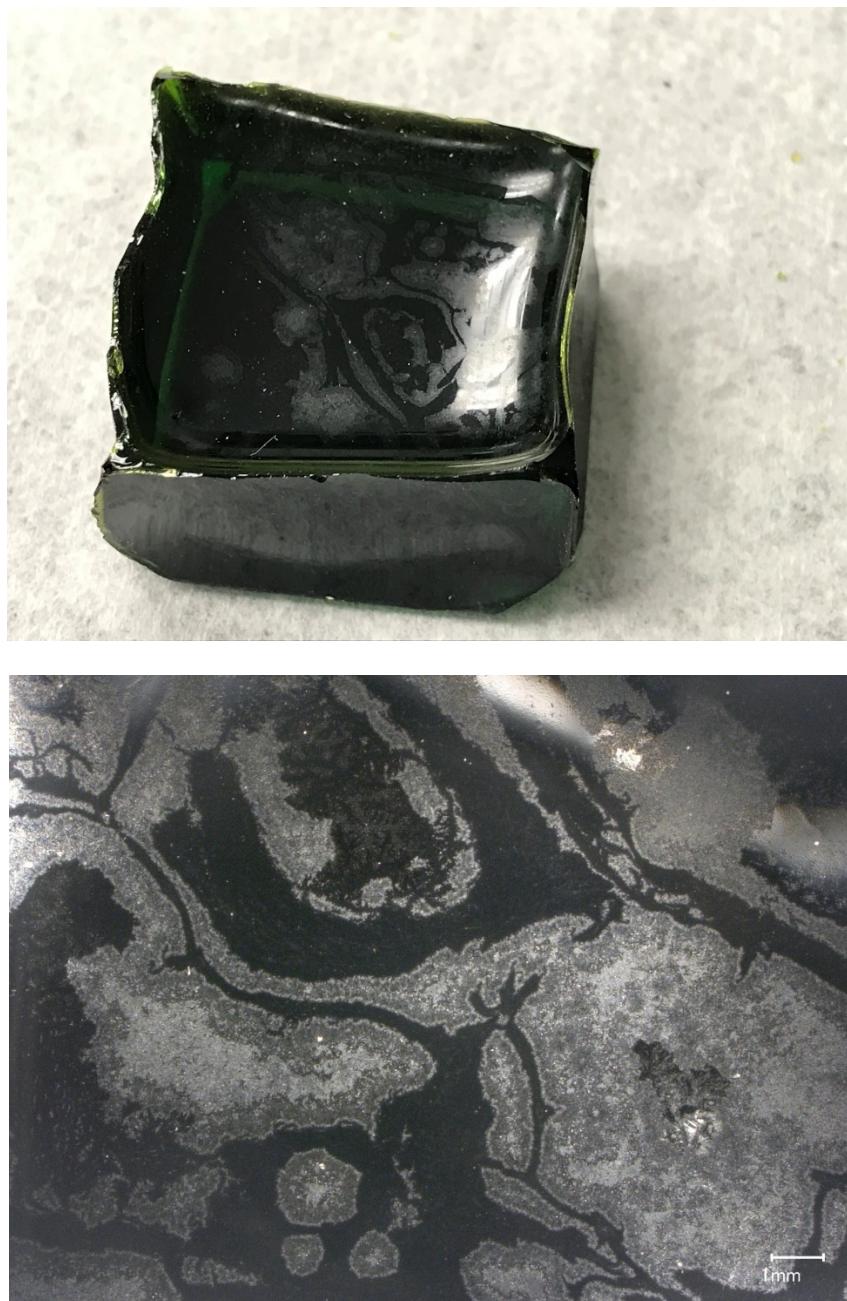


Figure G.14. Glass LP2-IL-14 after CCC Beginning at 1150°C both Glass (left) and Magnified 20X (right)

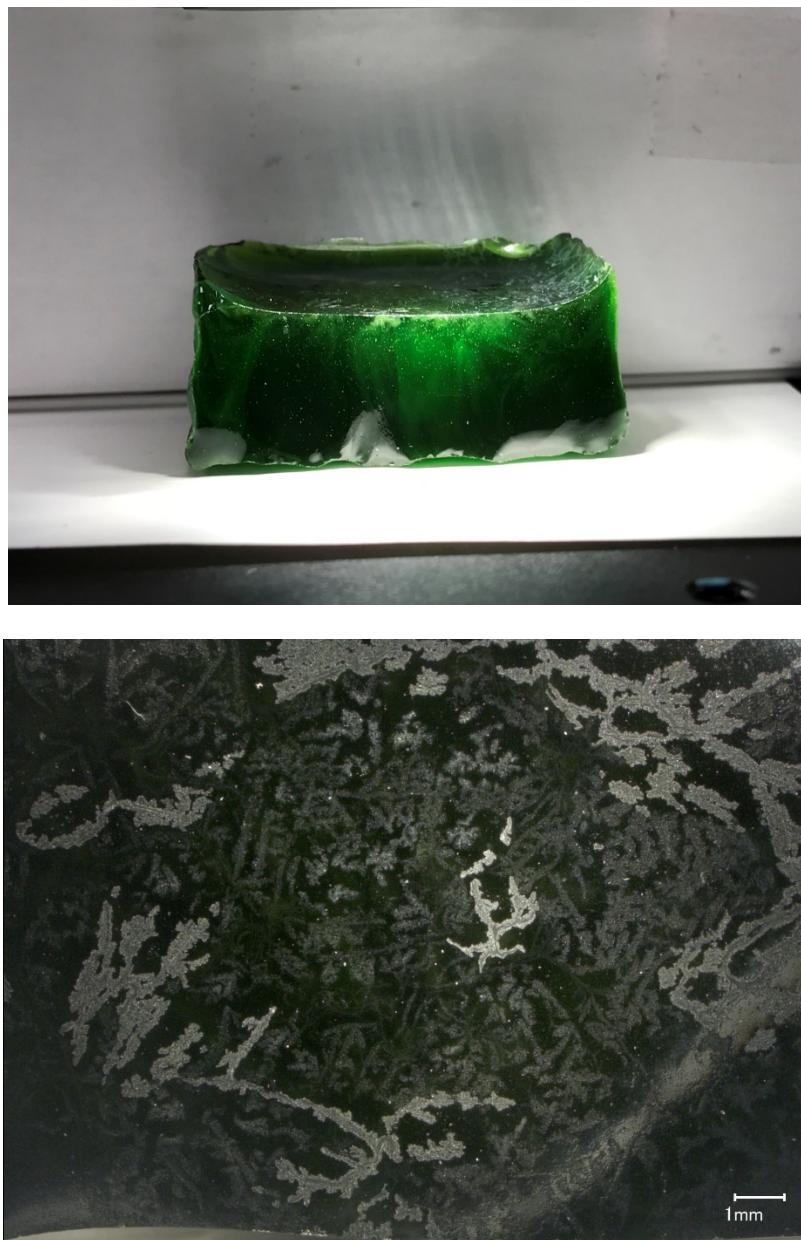


Figure G.15. Glass LP2-IL-15 after CCC Beginning at 1150°C both Glass (left) and Magnified 20X (right)

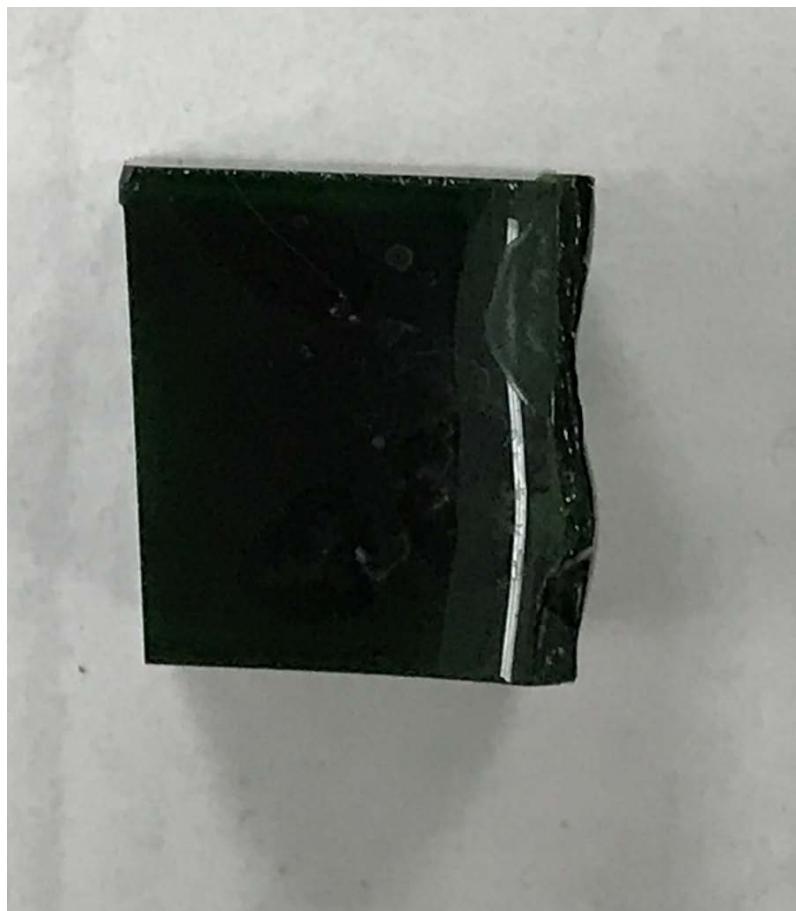


Figure G.16. Glass LP2-IL-16 after CCC Beginning at 1150°C

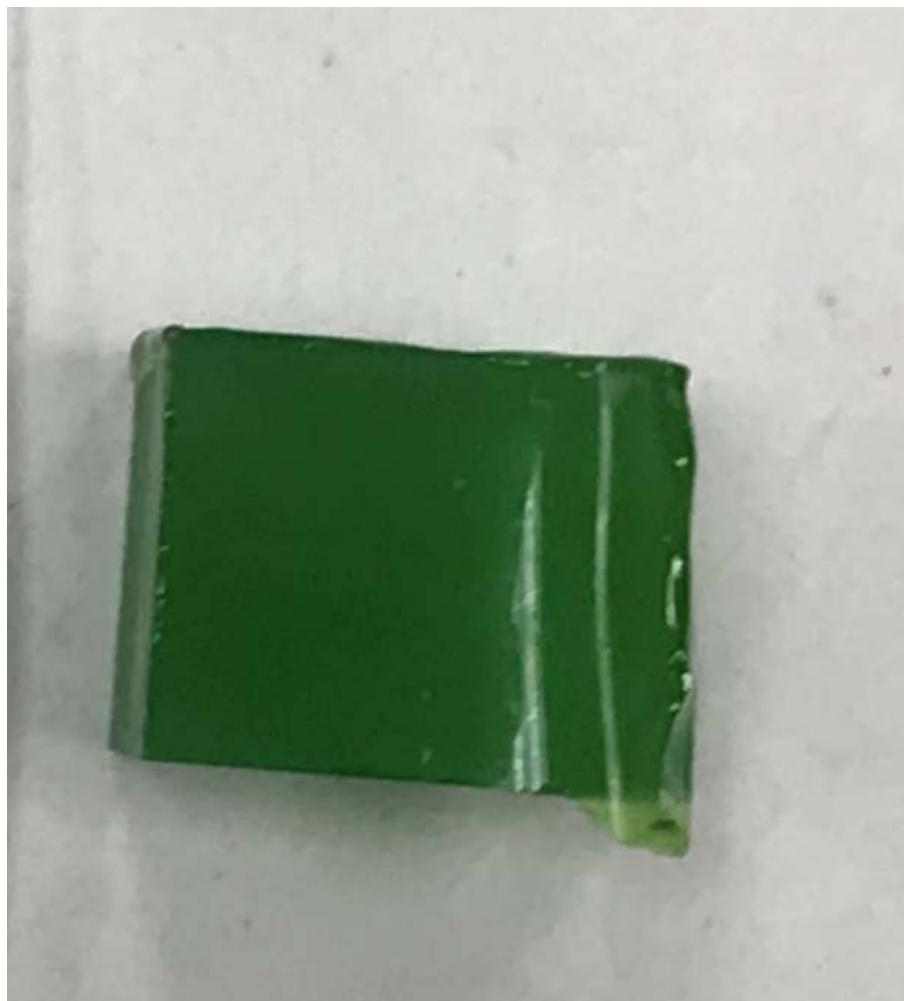


Figure G.17. Glass LP2-IL-17 after CCC Beginning at 1150°C

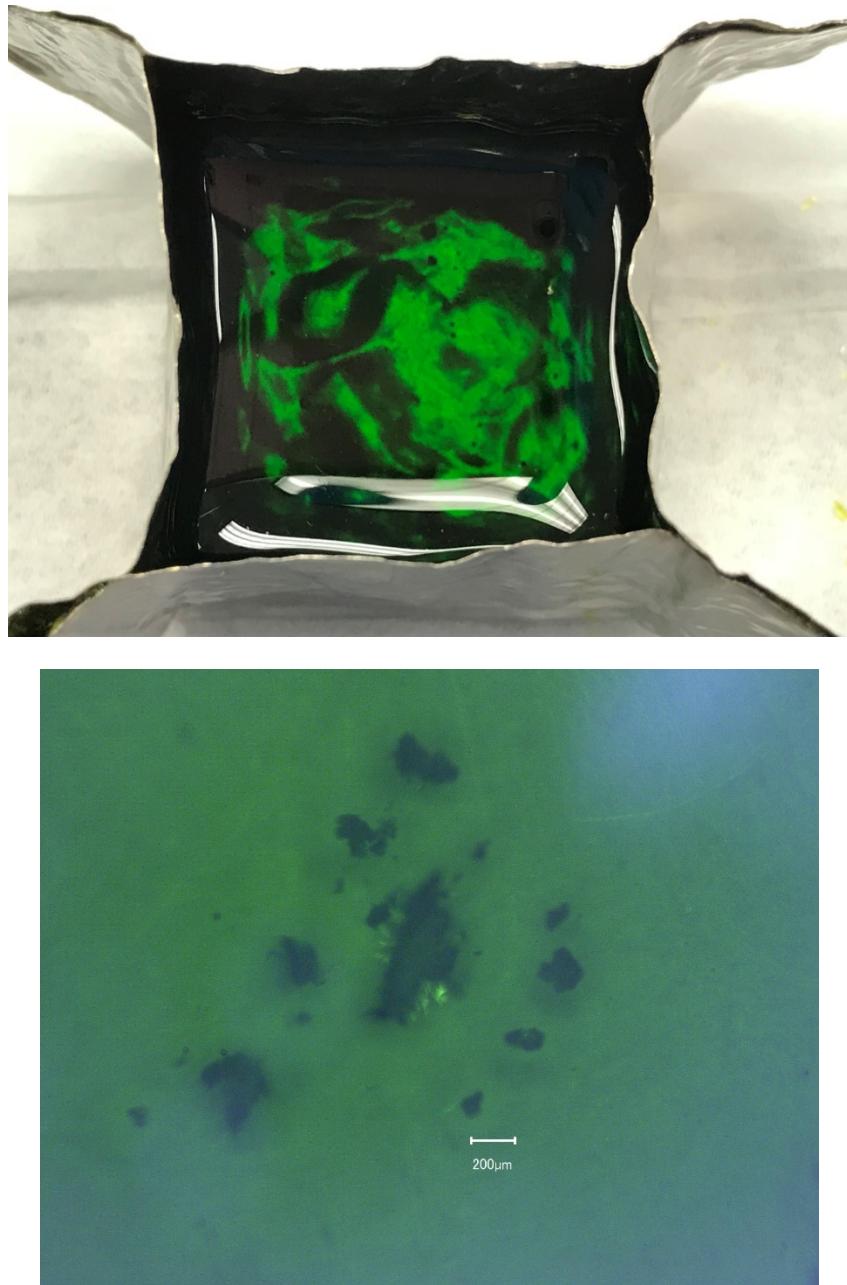


Figure G.18. Glass LP2-OL-01-3 after CCC Beginning at 1150°C both in Crucible (left) and Magnified 100X (right)

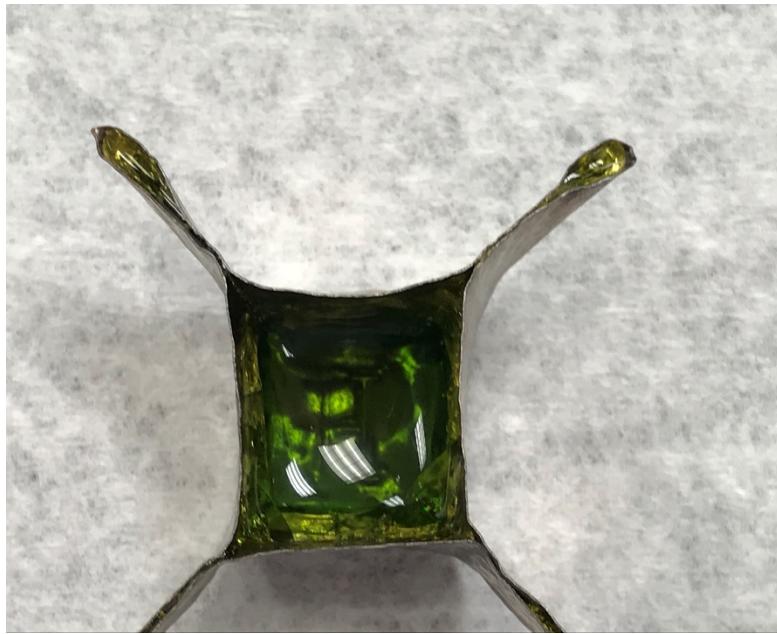


Figure G.19. Glass LP2-OL-02-1 after CCC Beginning at 1150°C both in Crucible (left) and Glass (right)

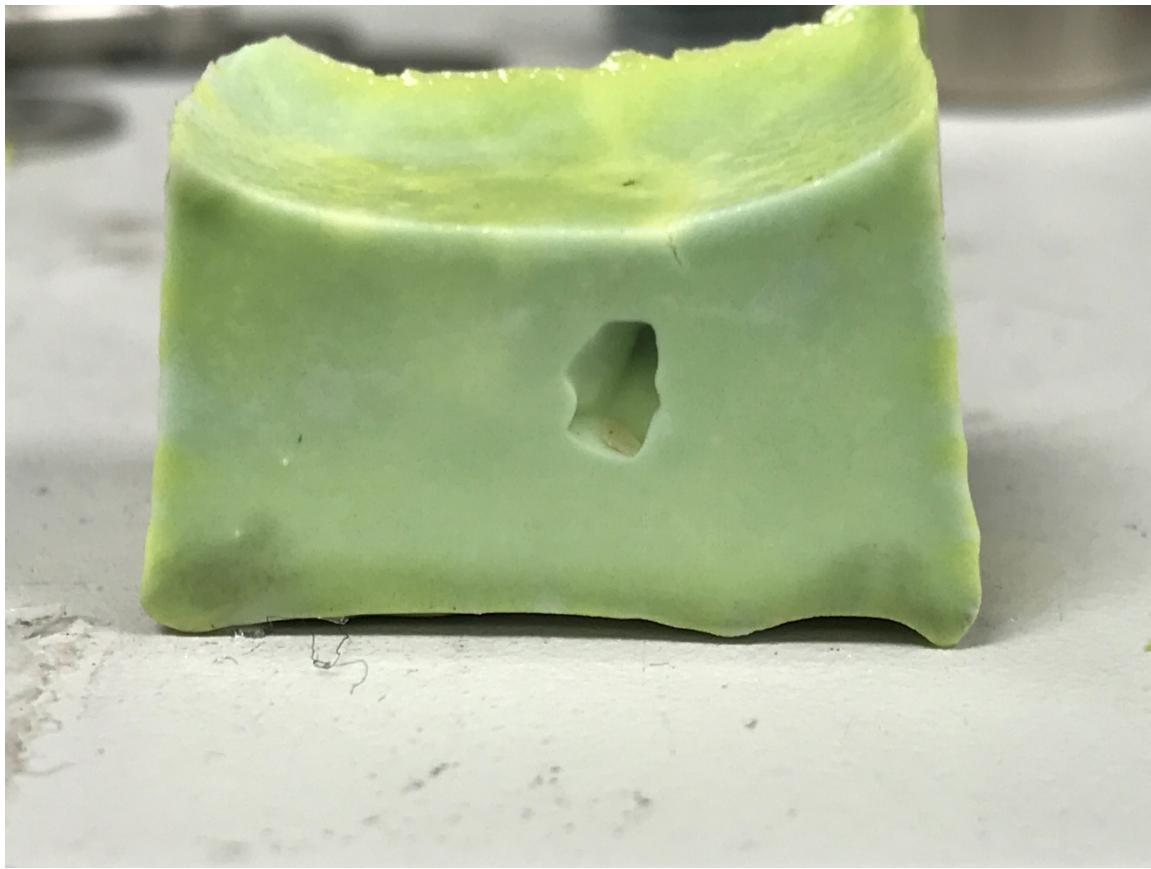


Figure G.20. Glass LP2-OL-03MOD2 after CCC Beginning at 1150°C



Figure G.21. Glass LP2-OL-04-1 after CCC Beginning at 1150°C



Figure G.22. Glass LP2-OL-05 after CCC Beginning at 1150°C both in Crucible (left) and Glass (right)

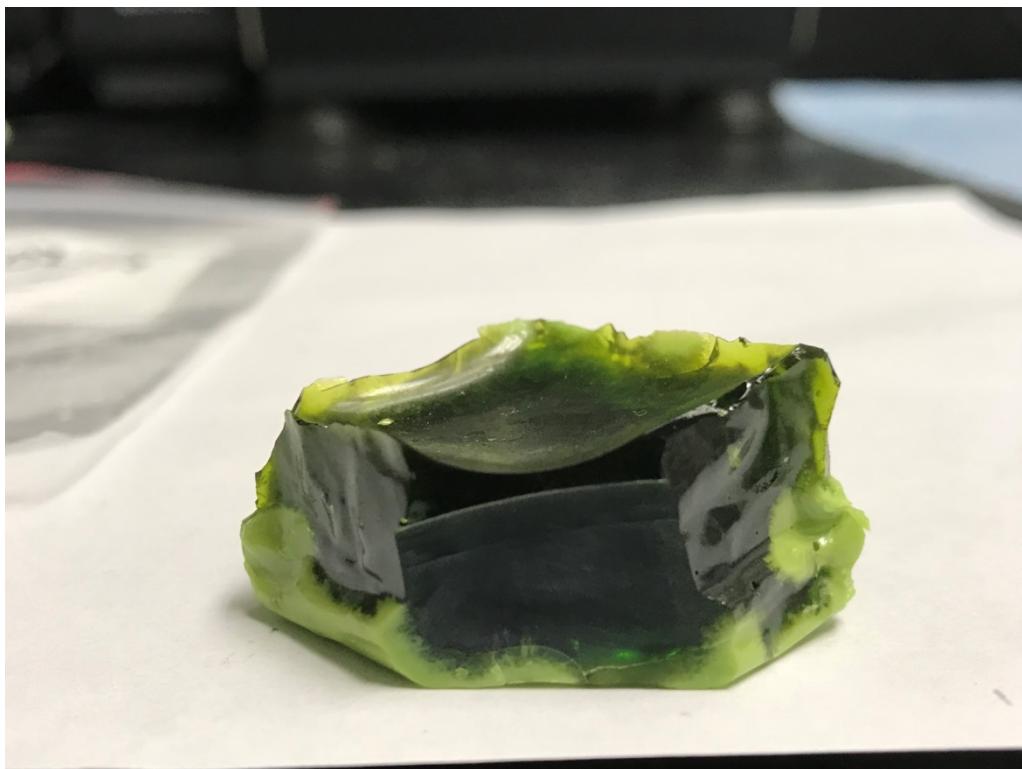


Figure G.23. Glass LP2-OL-07-1 after CCC Beginning at 1150°C



Figure G.24. Glass LP2-OL-08MOD after CCC Beginning at 1150°C

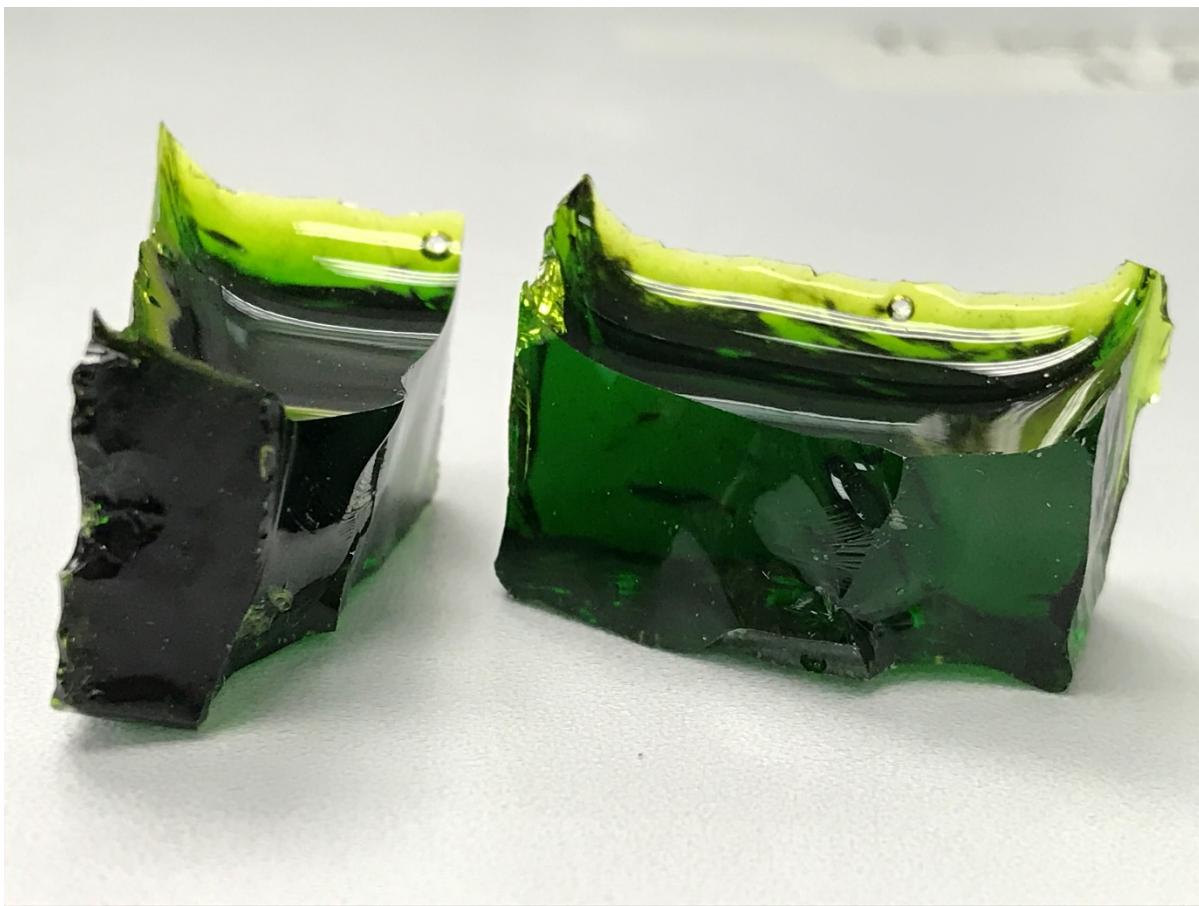


Figure G.25. Glass LP2-OL-09-1 after CCC Beginning at 1150°C

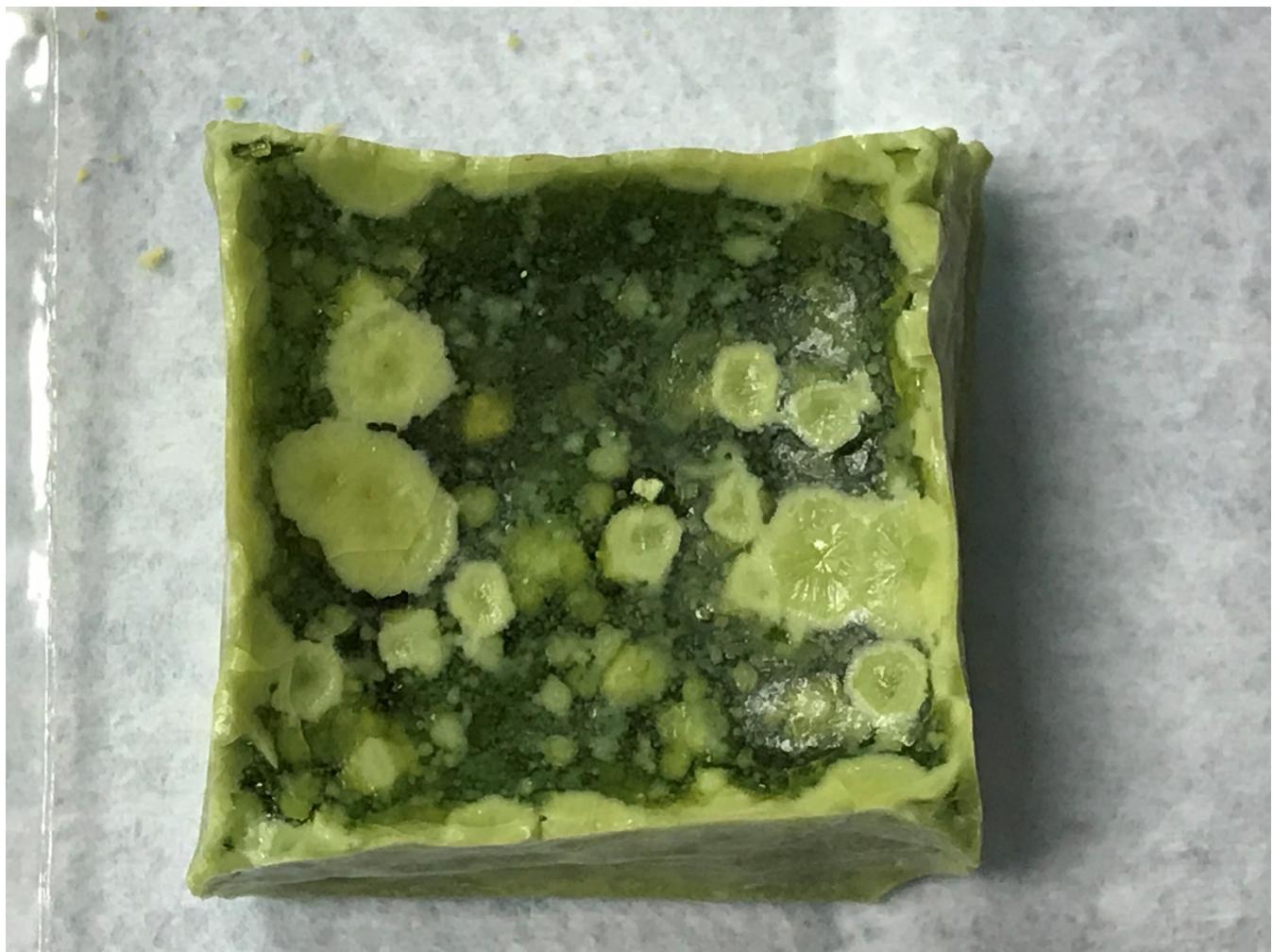


Figure G.26. Glass LP2-OL-10MOD after CCC Beginning at 1150°C

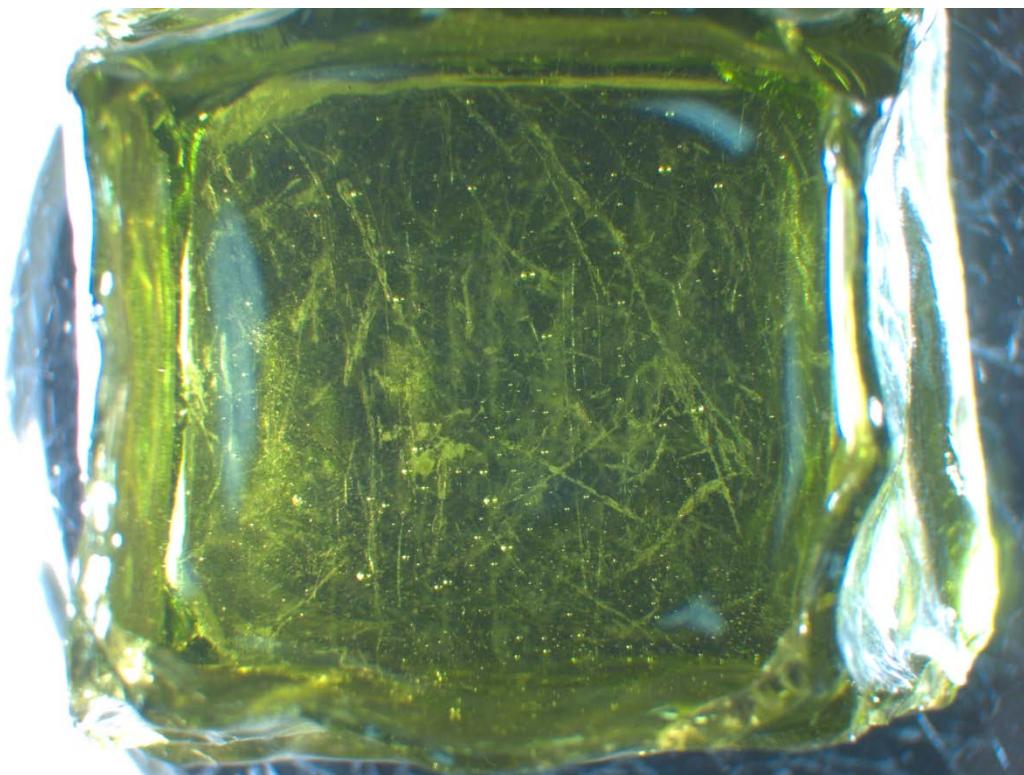


Figure G.27. Glass LP2-OL-11 after CCC Beginning at 1150°C

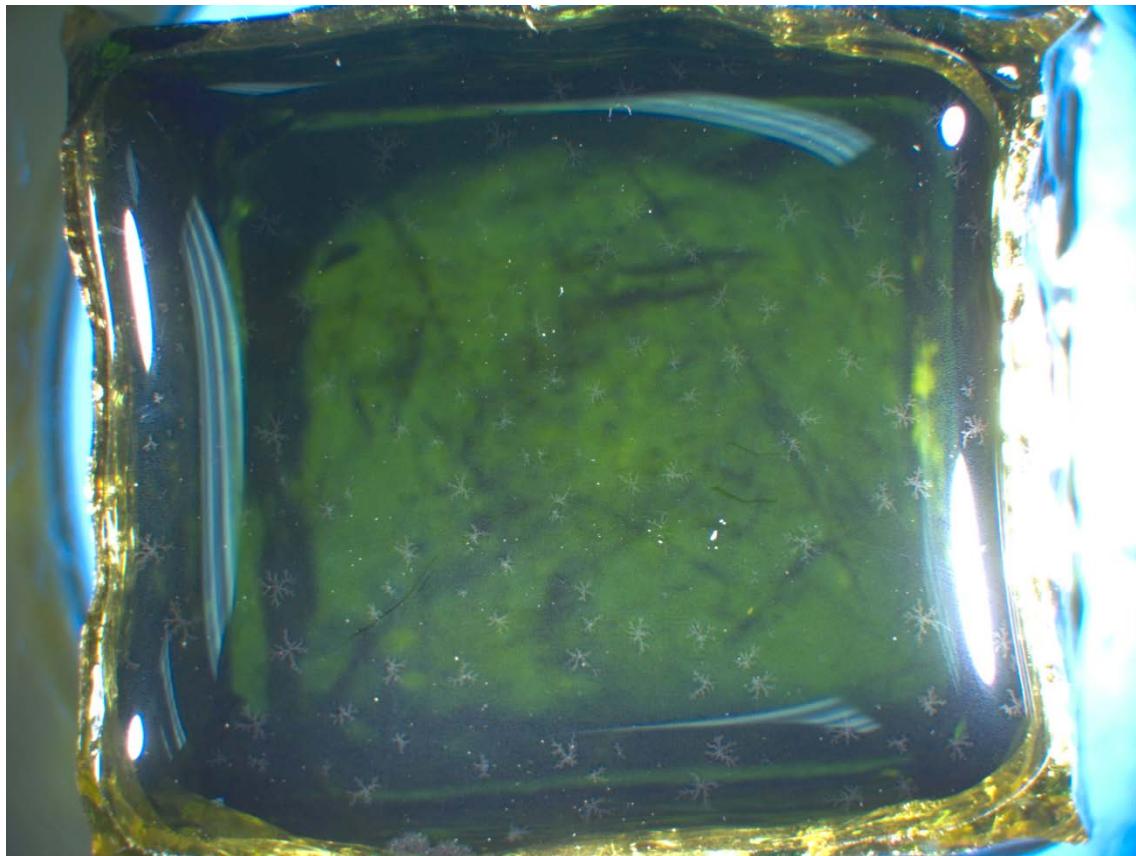


Figure G.28. Glass LP2-OL-12 after CCC Beginning at 1150°C

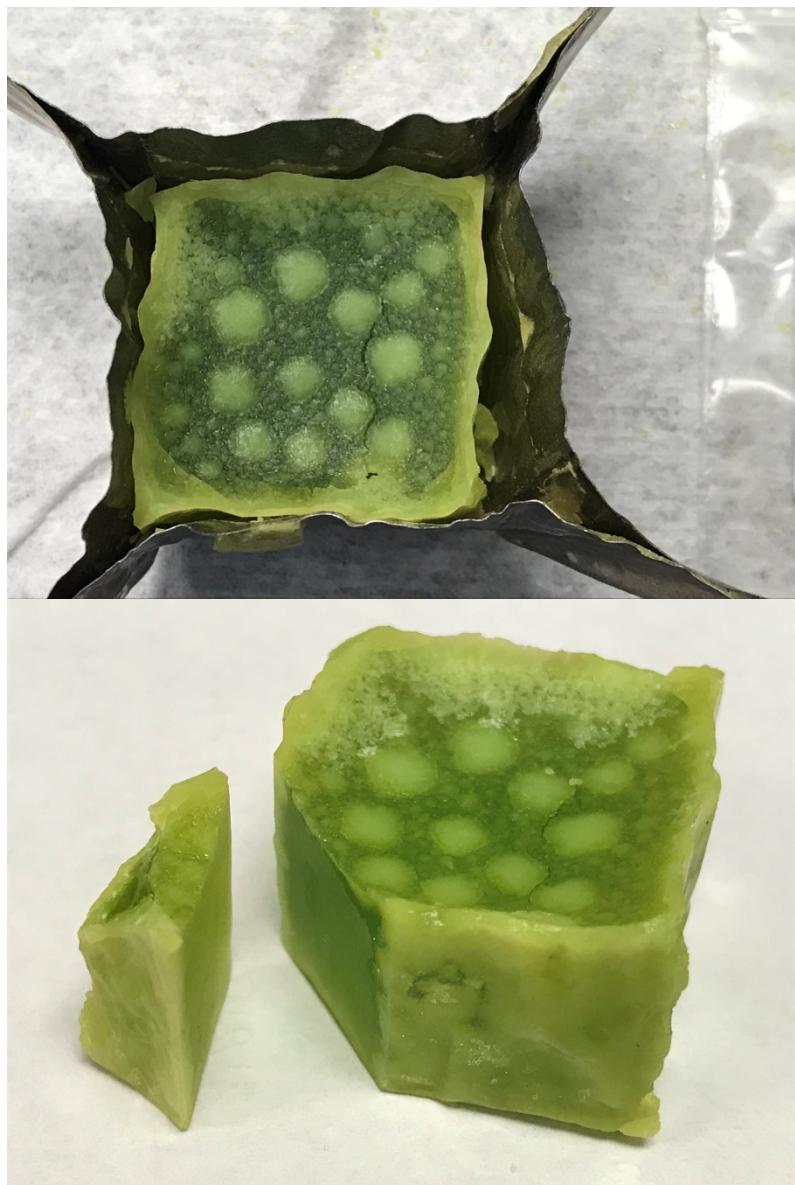


Figure G.29. Glass LP2-OL-13 after CCC Beginning at 1150°C both in Crucible (left) and Glass (right)



Figure G.30. Glass LP2-OL-14 after CCC Beginning at 1150°C

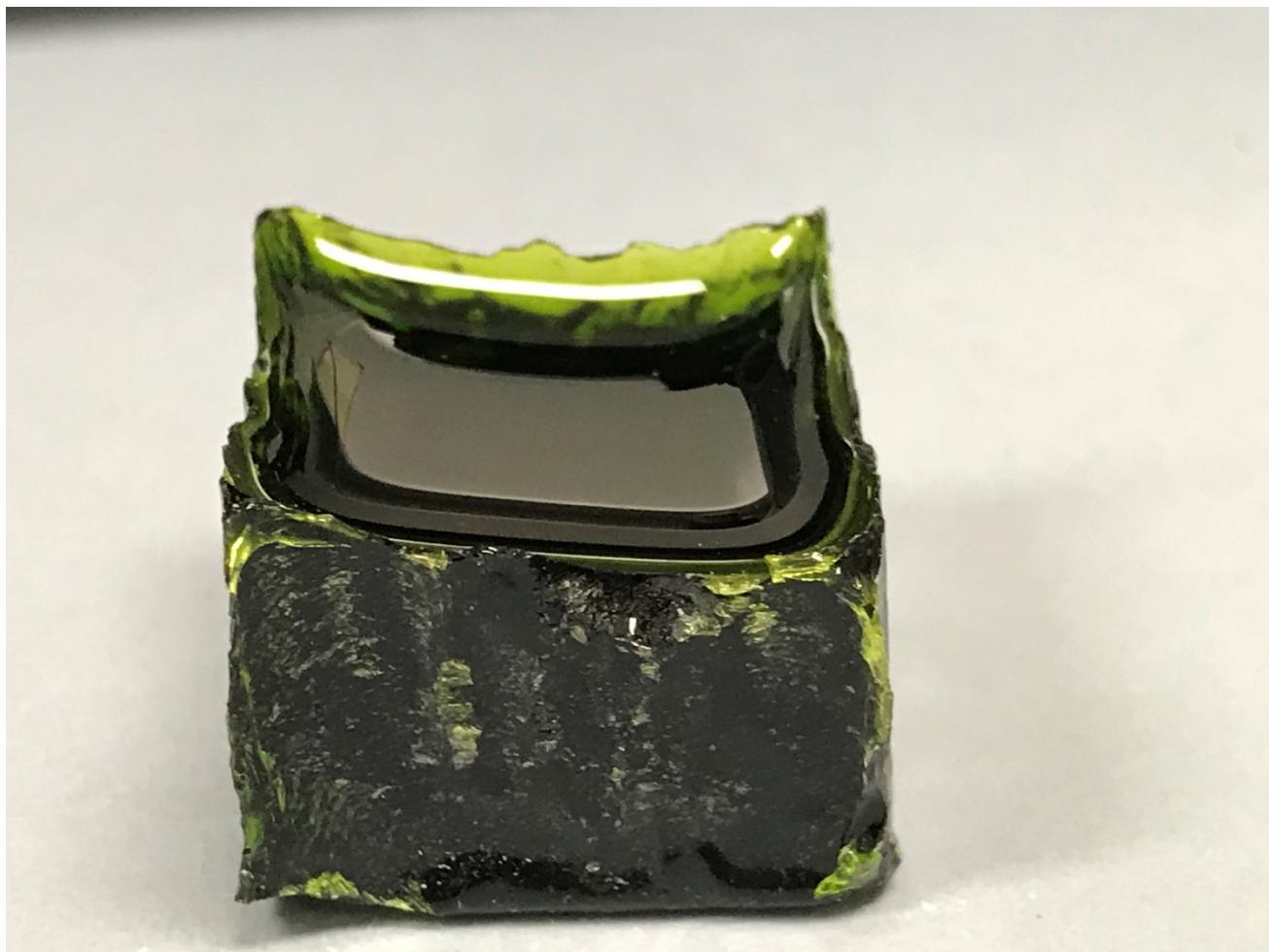


Figure G.31. Glass LP2-OL-15 after CCC Beginning at 1150°C

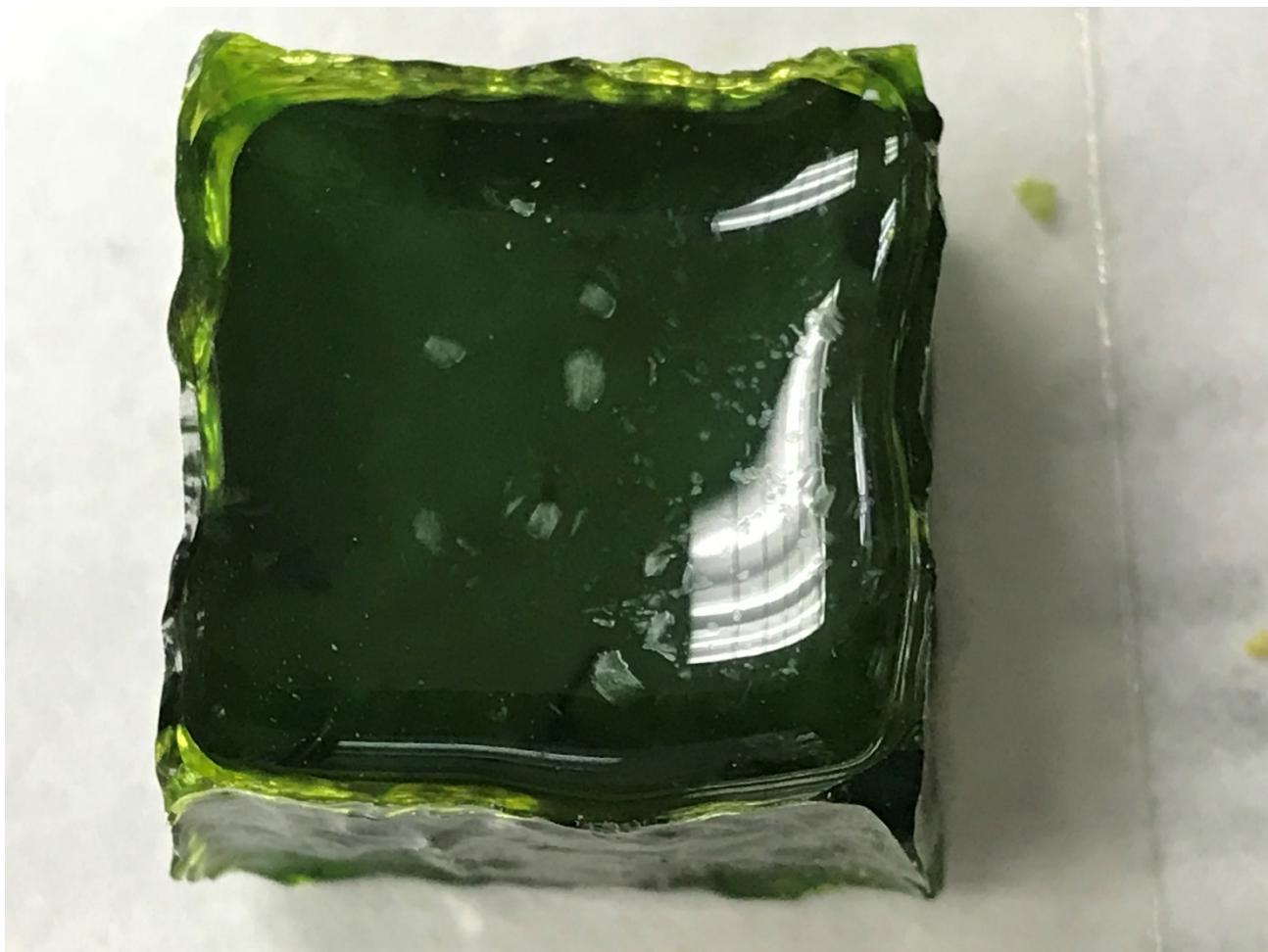


Figure G.32. Glass LP2-OL-16MOD after CCC Beginning at 1150°C



Figure G.33. Glass LP2-OL-17 after CCC Beginning at 1150°C



Figure G.34. Glass LP2-OL-18 after CCC Beginning at 1150°C



Figure G.35. Glass LP2-OL-19 after CCC Beginning at 1150°C

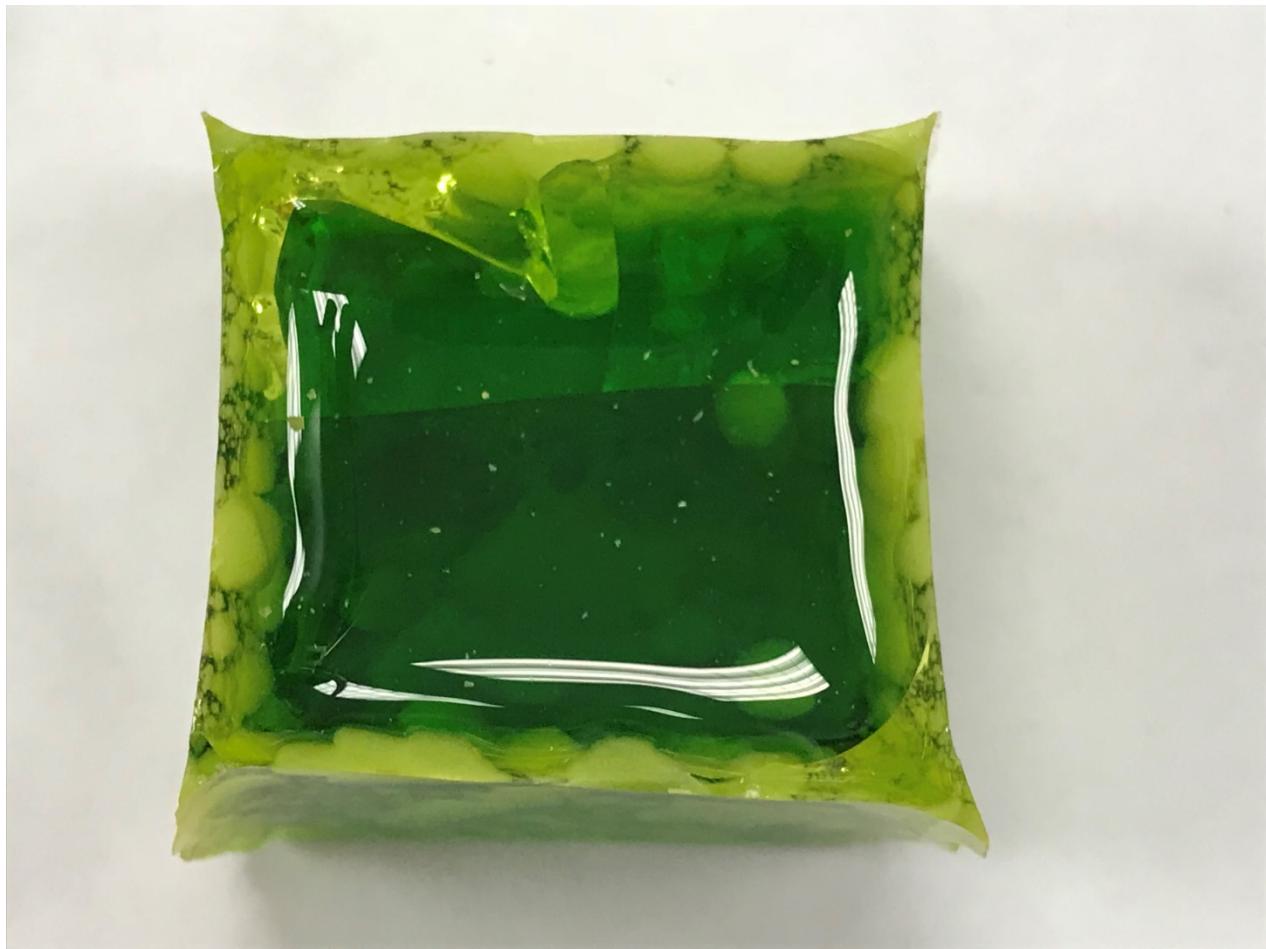


Figure G.36. Glass LP2-OL-20 after CCC Beginning at 1150°C

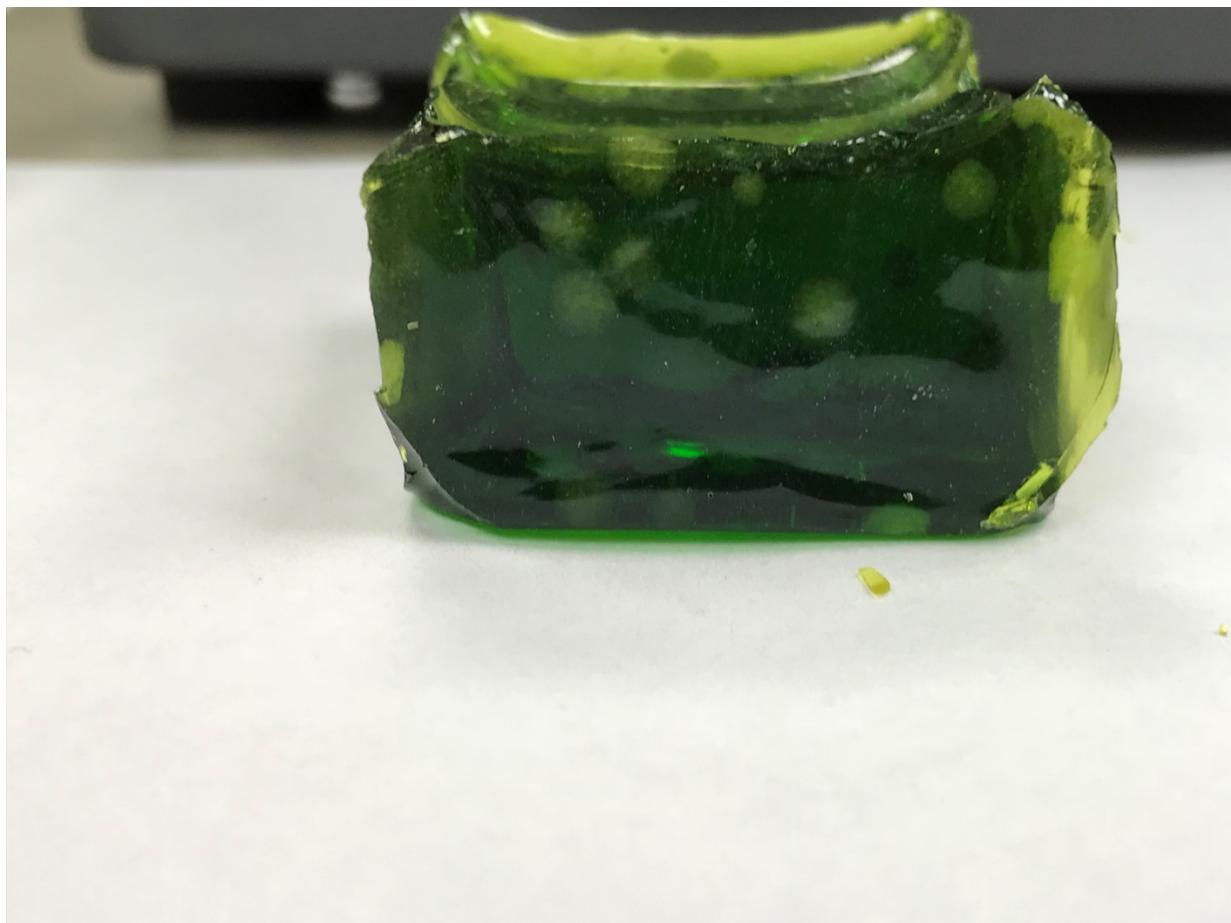


Figure G.37. Glass LP2-OL-21 after CCC Beginning at 1150°C

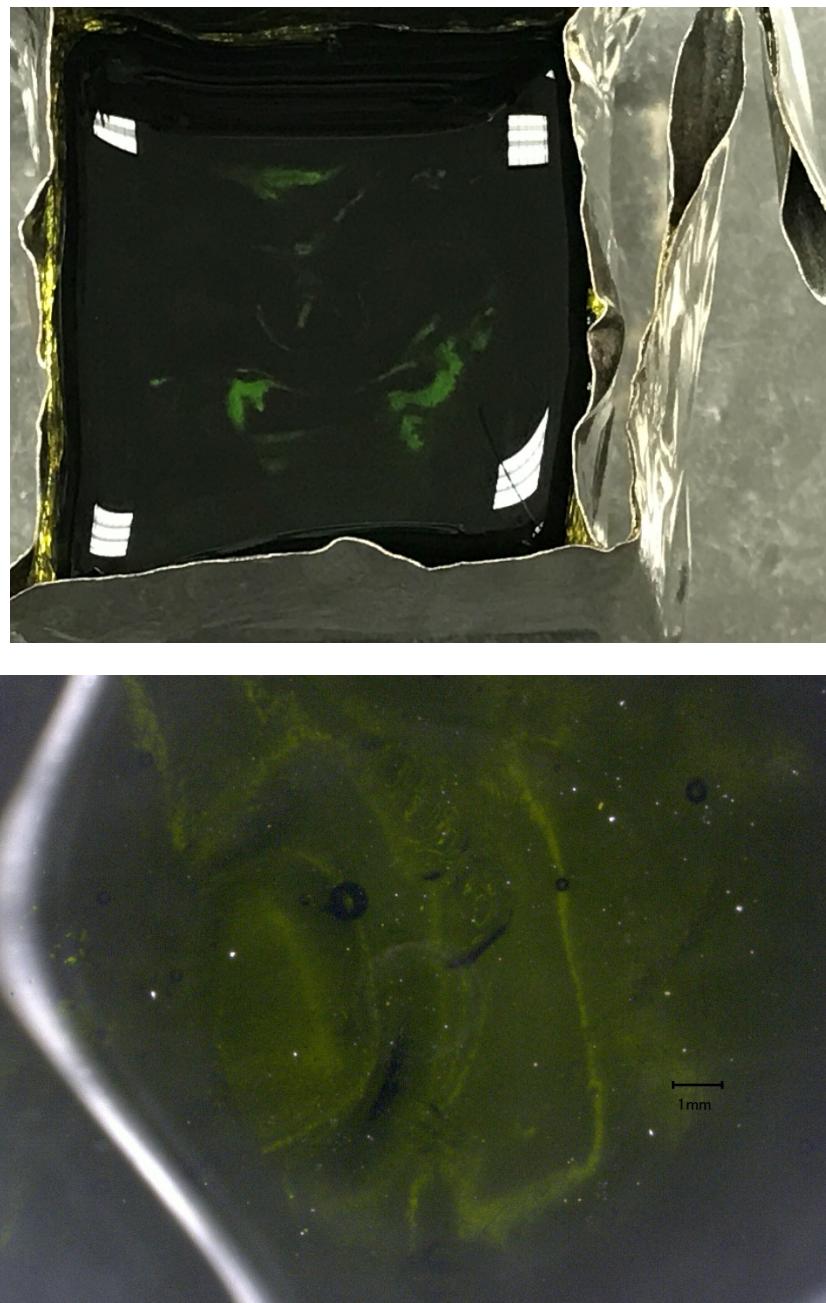


Figure G.38. Glass LP2-OL-22 after CCC Beginning at 1150°C both in Crucible (left) and Magnified 20X (right)



Figure G.39. Glass LP2-OL-23 after CCC Beginning at 1150°C

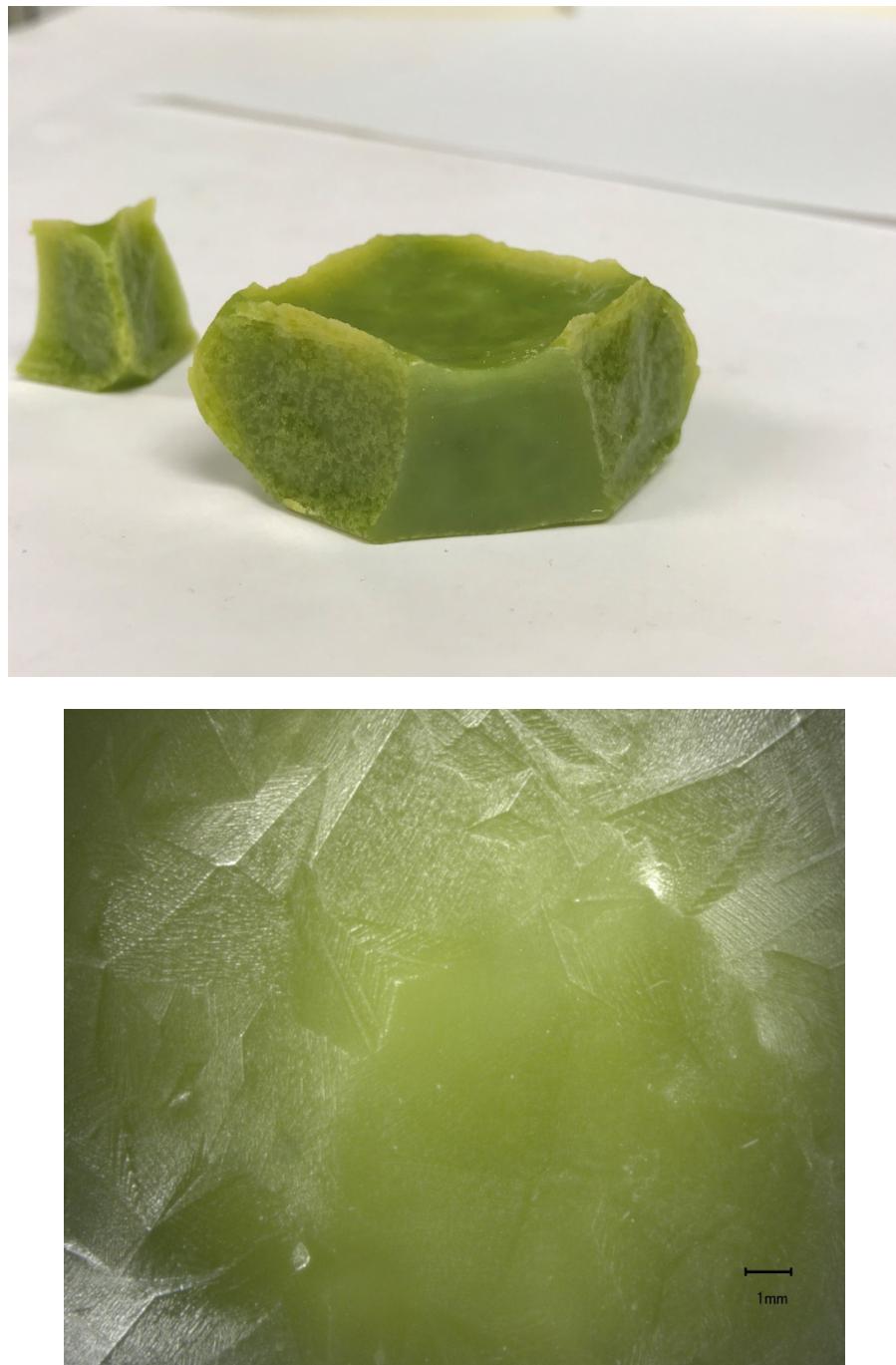


Figure G.40. Glass LP2-OL-24 after CCC Beginning at 1150°C both Glass (left) and Magnified 20X (right)

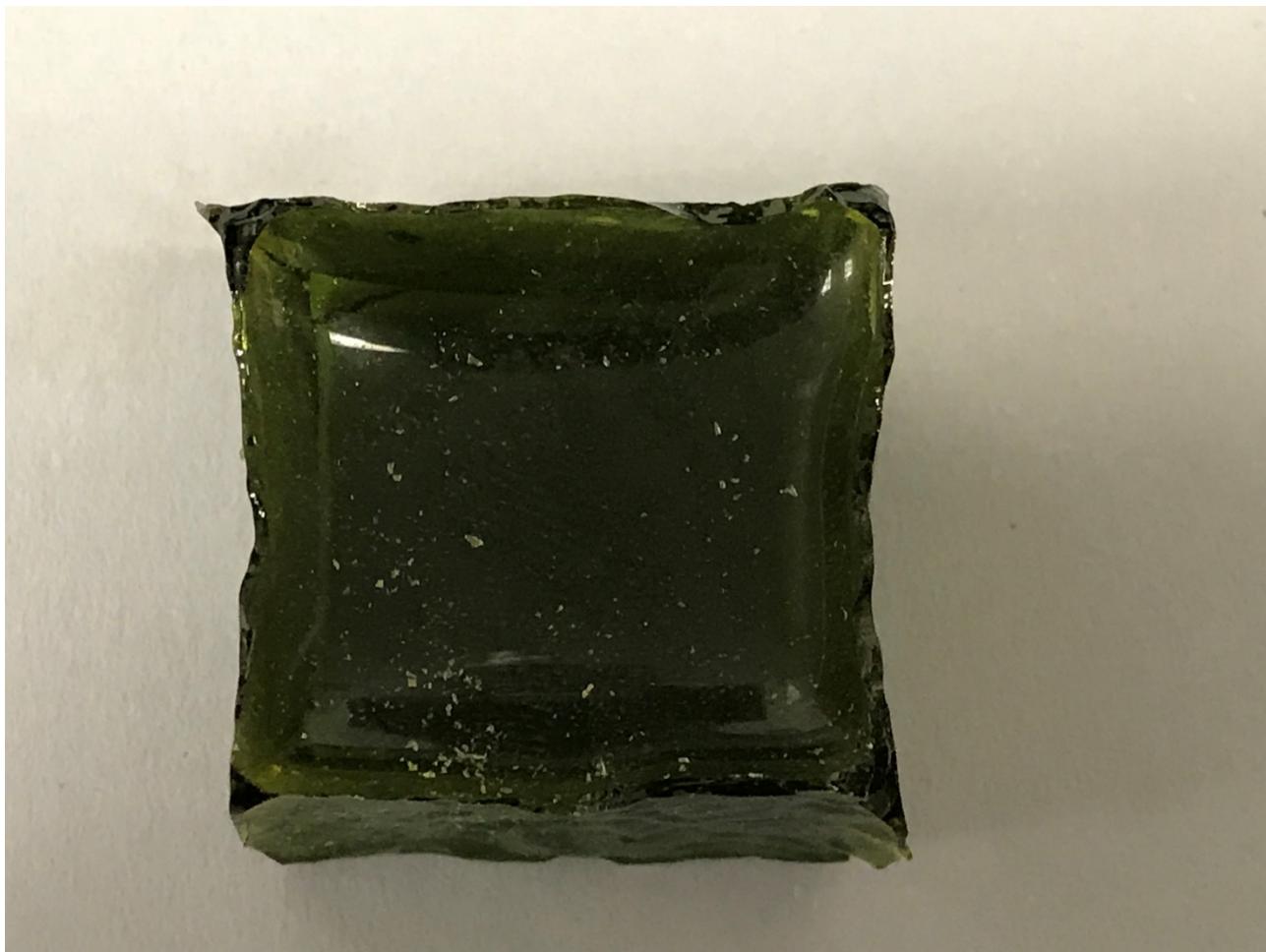
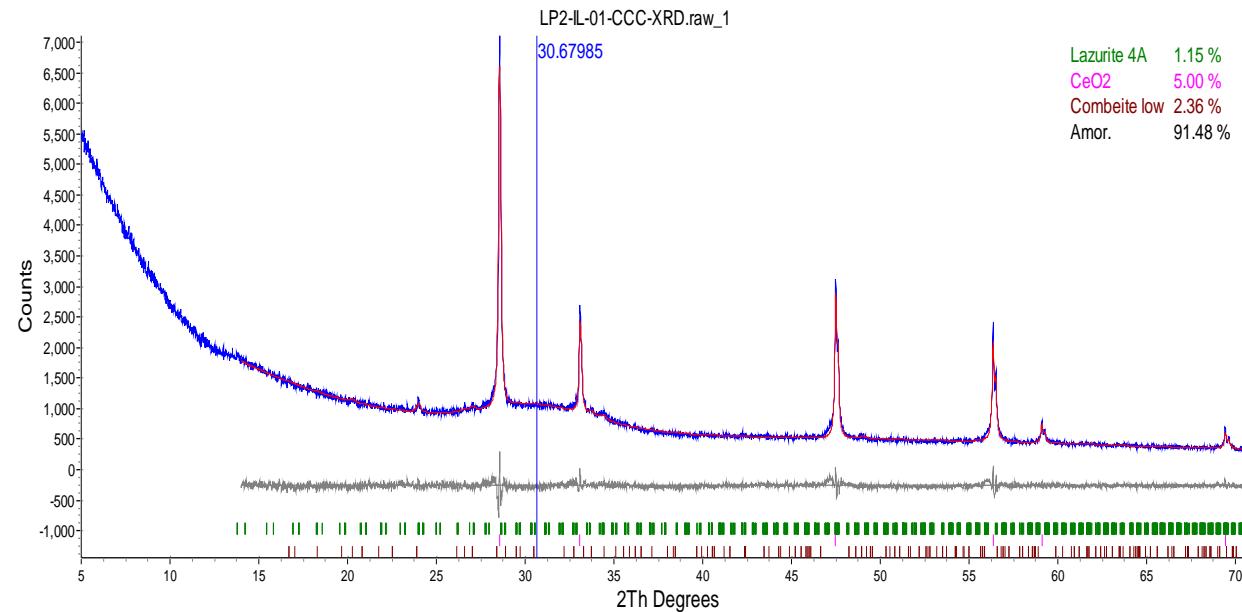


Figure G.41. Glass LP2-OL-25 after CCC Beginning at 1150°C

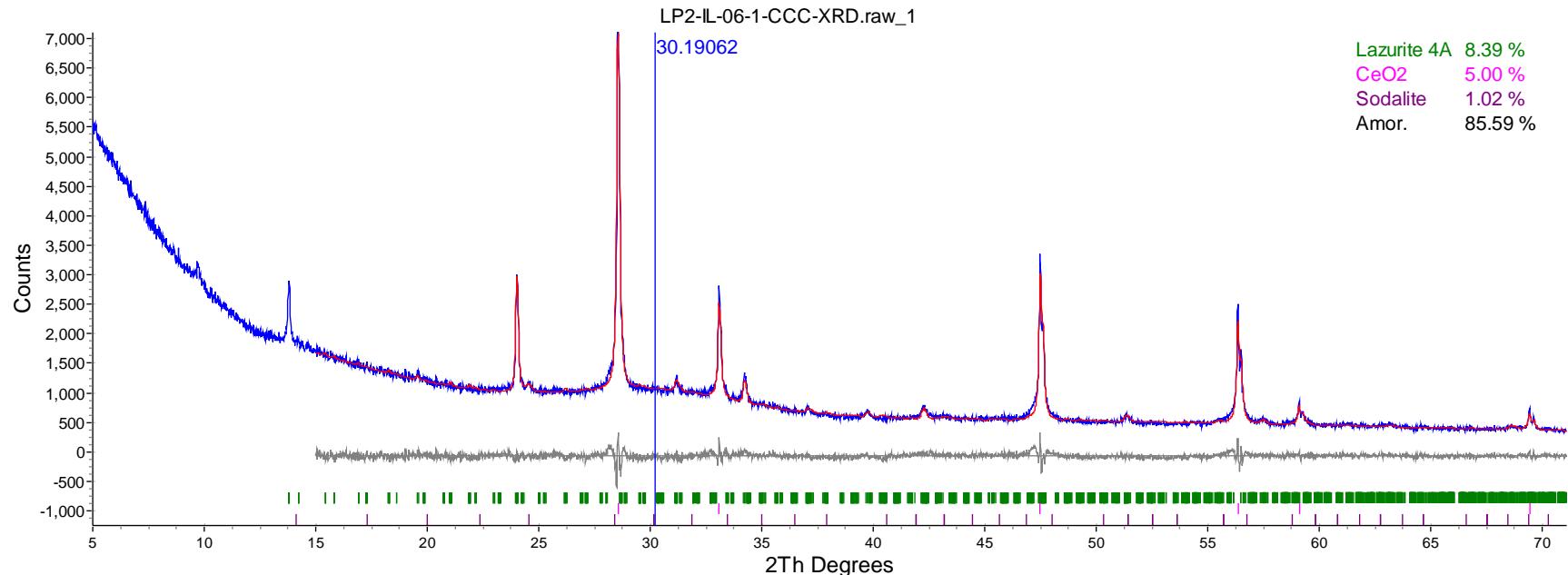
## Appendix H – XRD of Canister Centerline Cooling (CCC) Treated Glasses

This appendix shows the XRD plots of several Phase 2 enhanced LAW glasses after CCC heat-treatment. These glasses all responded very differently to the CCC heat-treatment from remaining amorphous to developing quite a few crystals of various kinds as shown by the following plots. Some glasses did not contain enough crystals to perform XRD and therefore are not included here. They were LP2-IL-02, LP2-IL-03, LP2-IL-04, LP2-IL-05, LP2-IL-07, LP2-IL-09, LP2-IL-11, LP2-IL-12, LP2-IL-13, LP2-IL-14, LP2-IL-16, LP2-OL-01-3, LP2-OL-09-1, LP2-OL-11, LP2-OL-12, LP2-OL-15, LP2-OL-21, LP2-OL-22, LP2-OL-23, and LP2-OL-25.



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.004	5.004	0
Lazurite 4A	0	1.155	1.215
Combeite low	0	2.36	2.484

Figure H.1. XRD Spectrum of CCC-Treated Glass LP2-IL-01



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.001	5.001	0
Lazurite 4A	0	8.388	8.83
Sodalite	0	1.019	1.07

Figure H.2. XRD Spectrum of CCC-Treated Glass LP2-IL-06

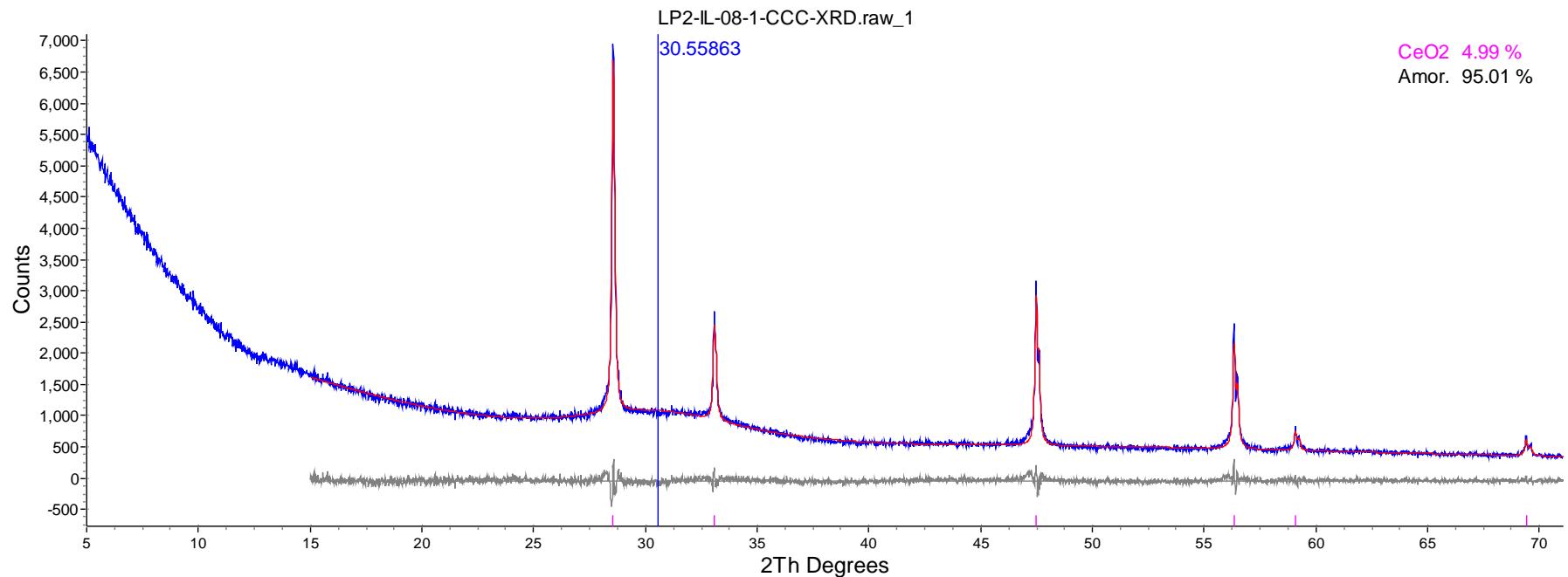


Figure H.3. XRD Spectrum of CCC-Treated Glass LP2-IL-08

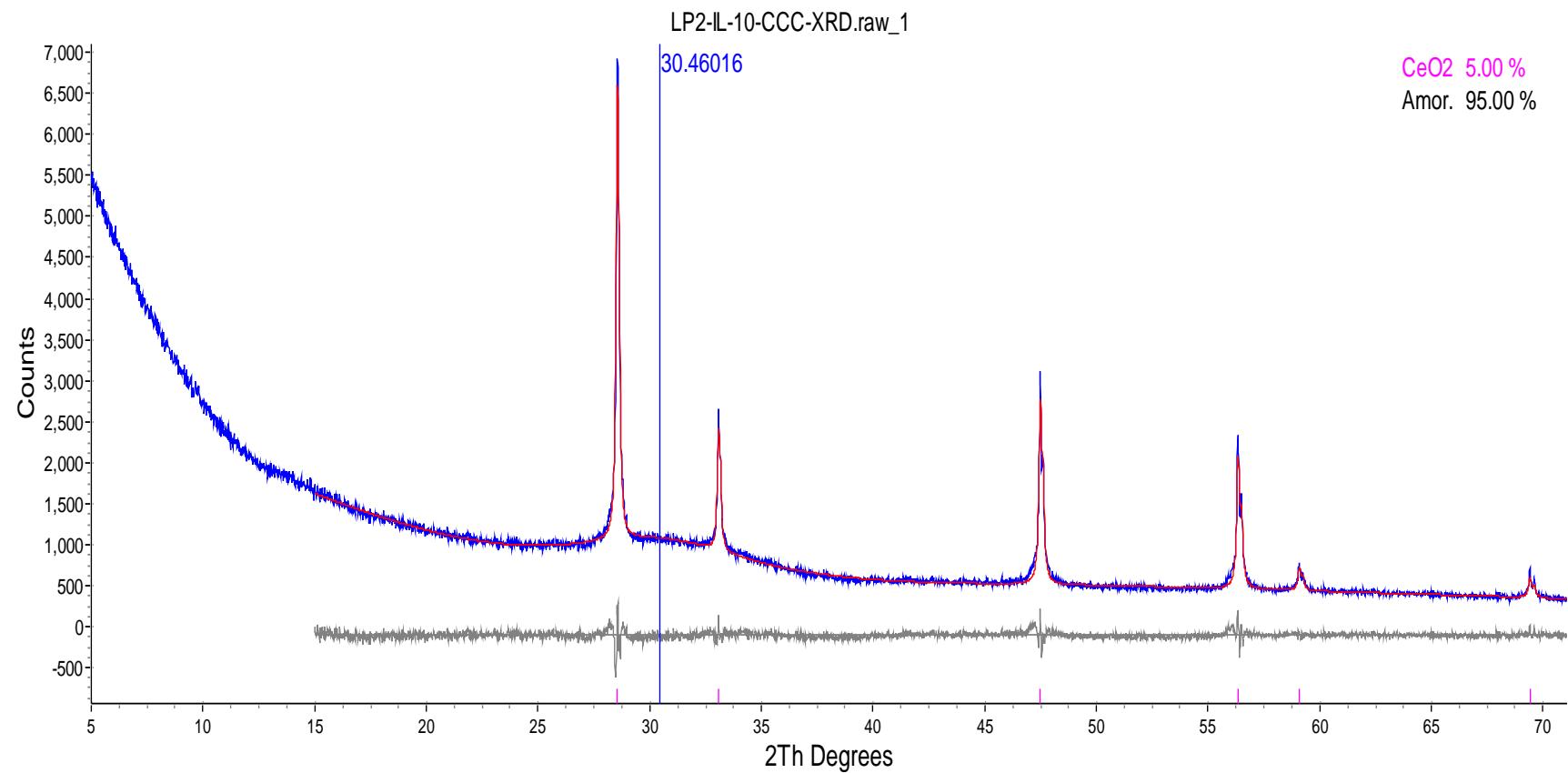


Figure H.4. XRD Spectrum of CCC-Treated Glass LP2-IL-10

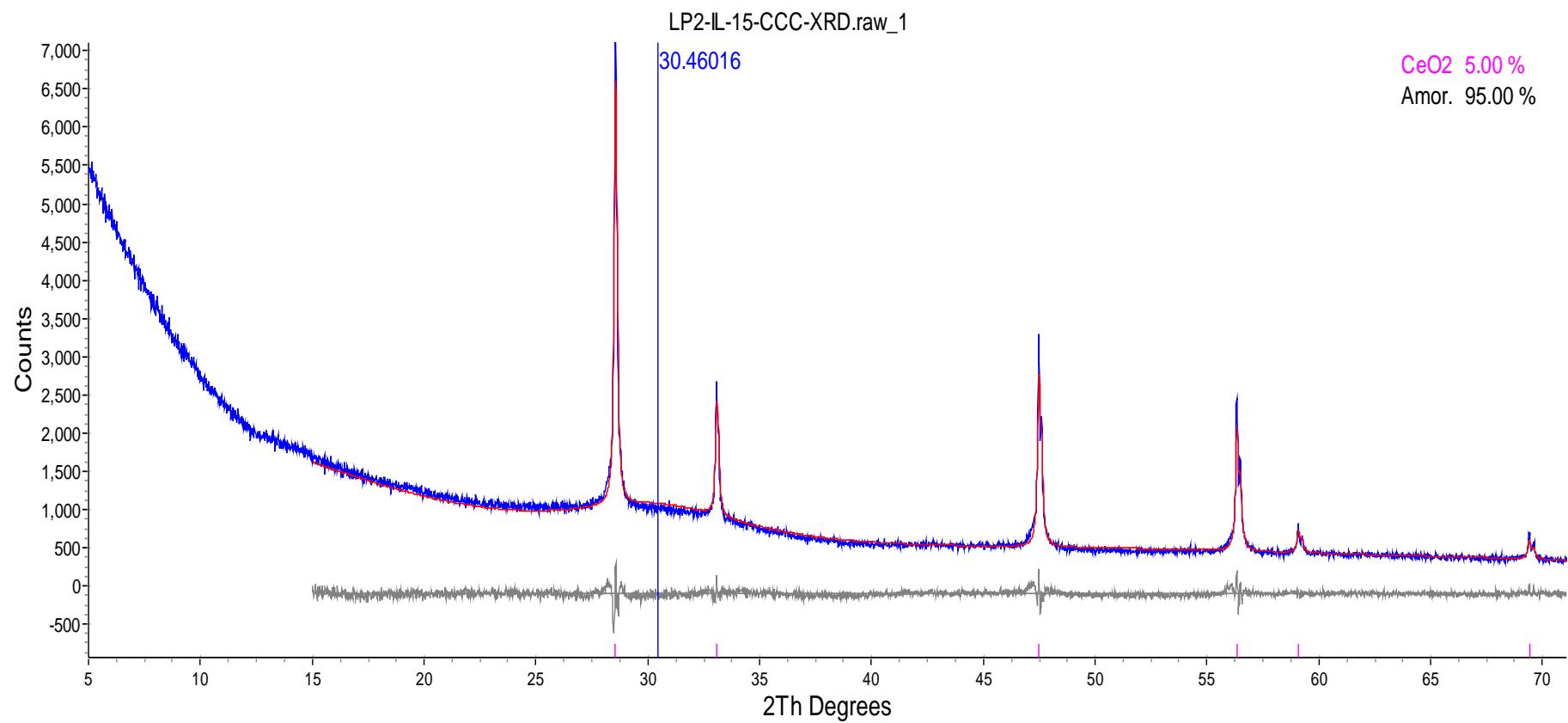
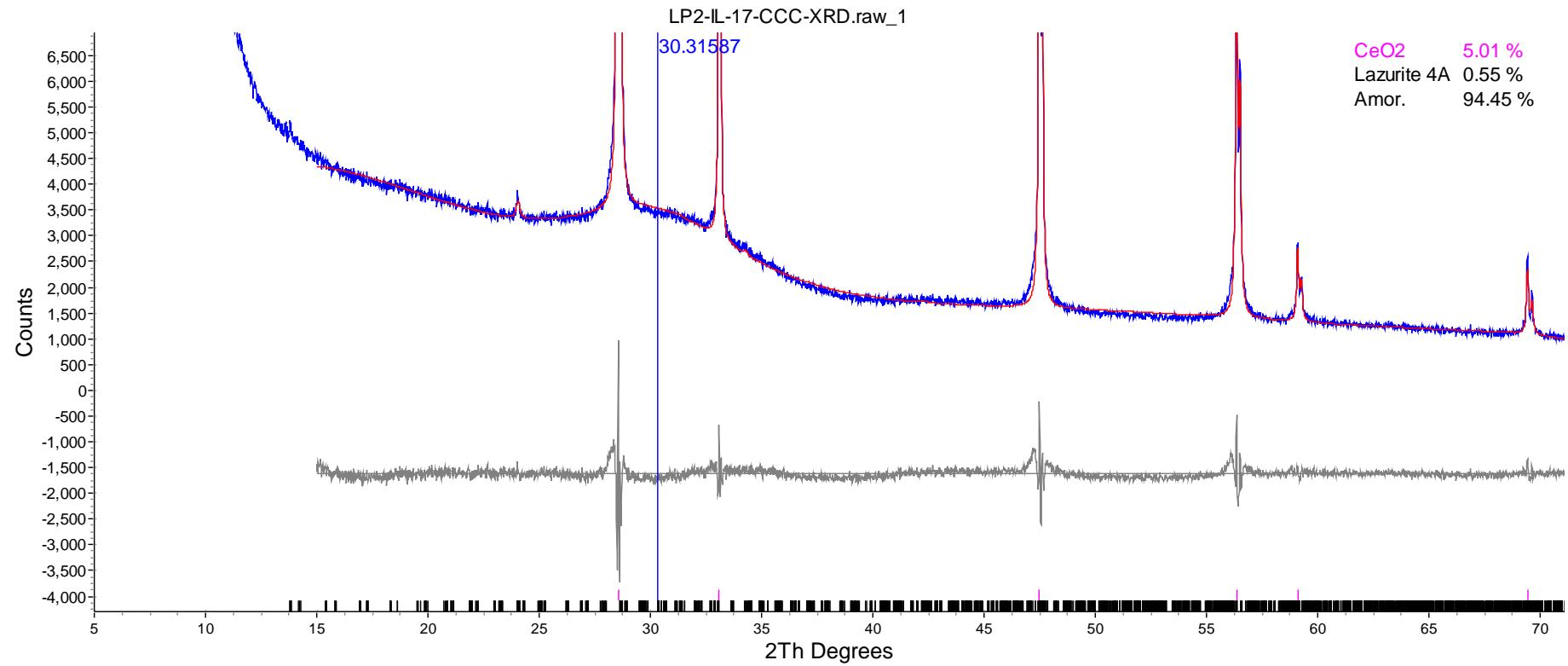


Figure H.5. XRD Spectrum of CCC-Treated Glass LP2-IL-15



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.007	5.007	0
Lazurite 4A	0	0.547	0.576

Figure H.6. XRD Spectrum of CCC-Treated Glass LP2-IL-17

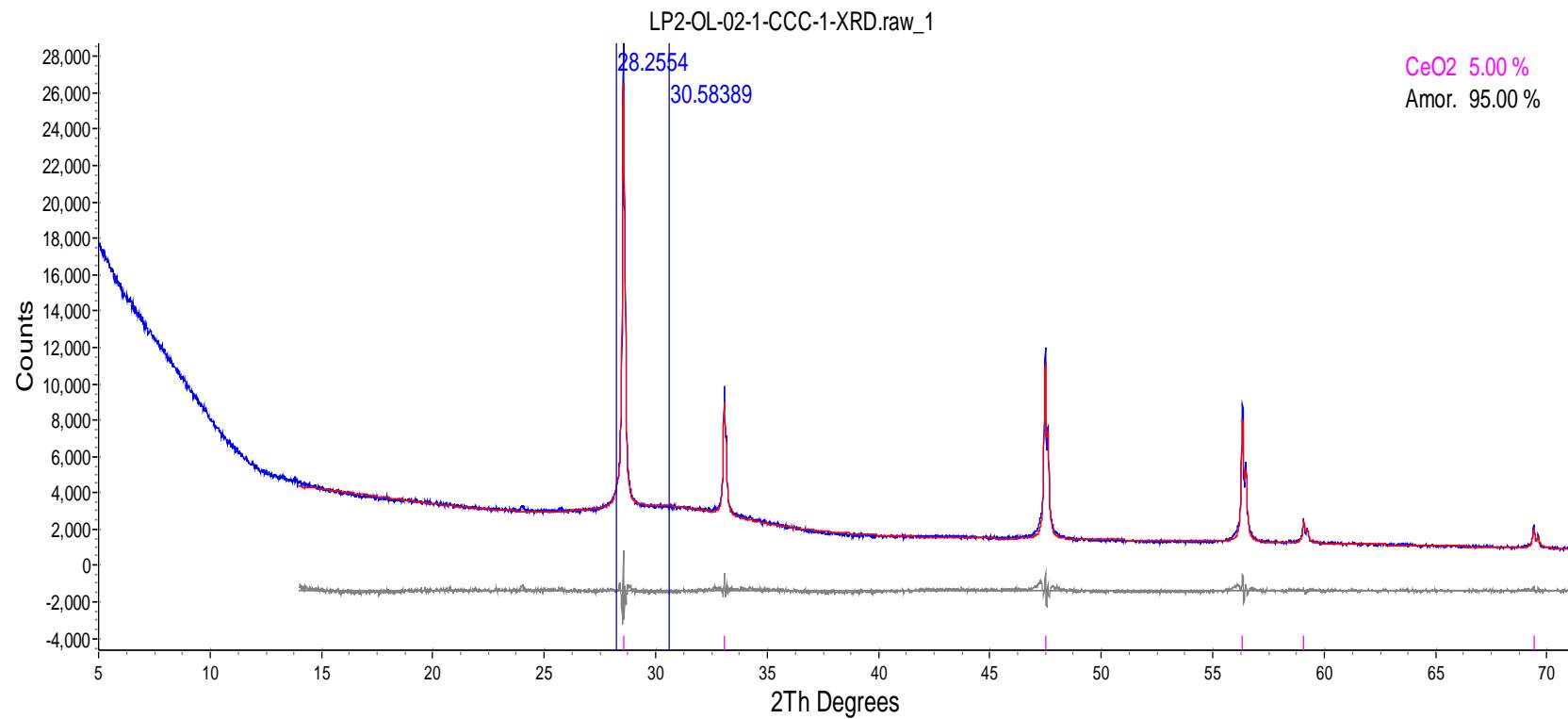
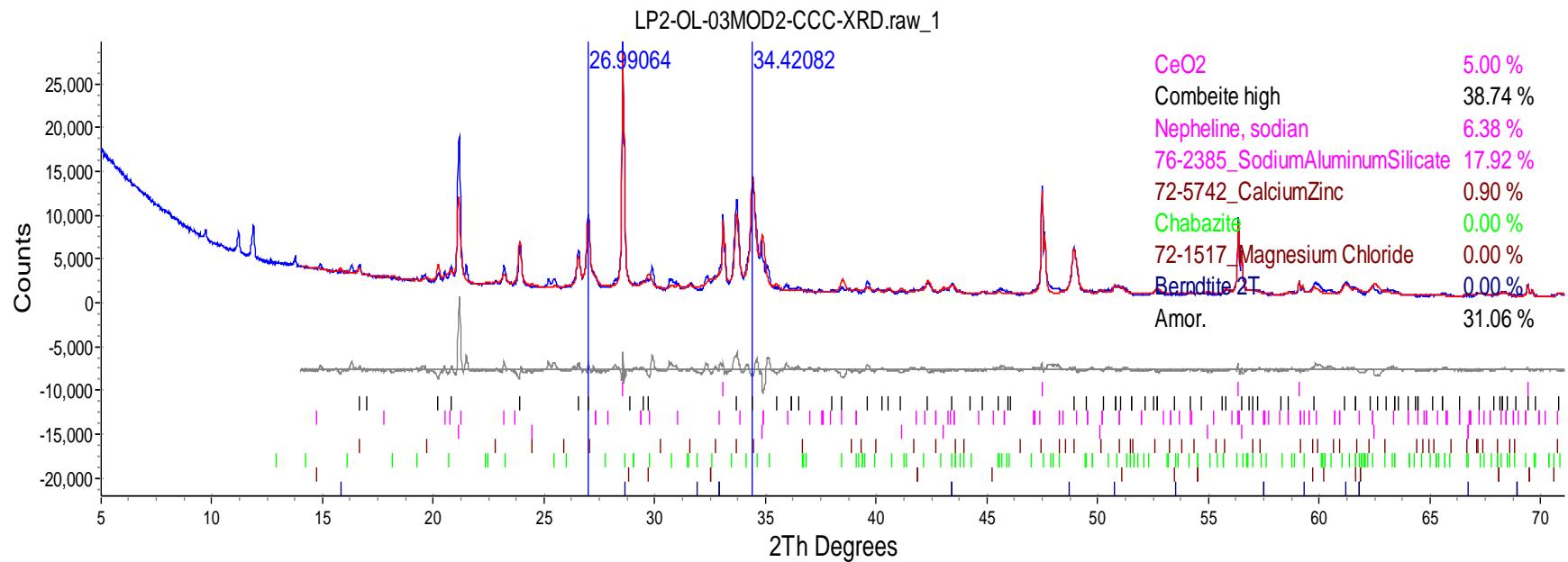
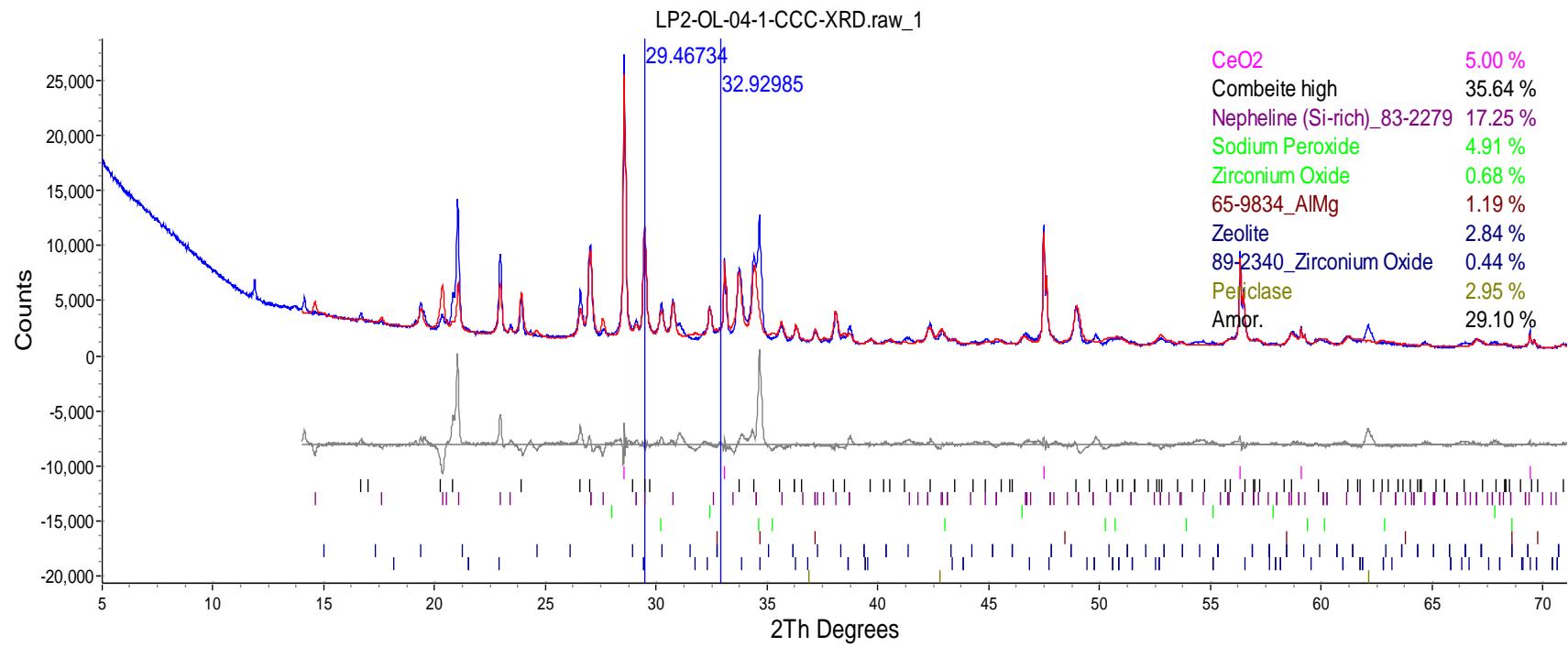


Figure H.7. XRD Spectrum of CCC-Treated Glass LP2-OL-02-1



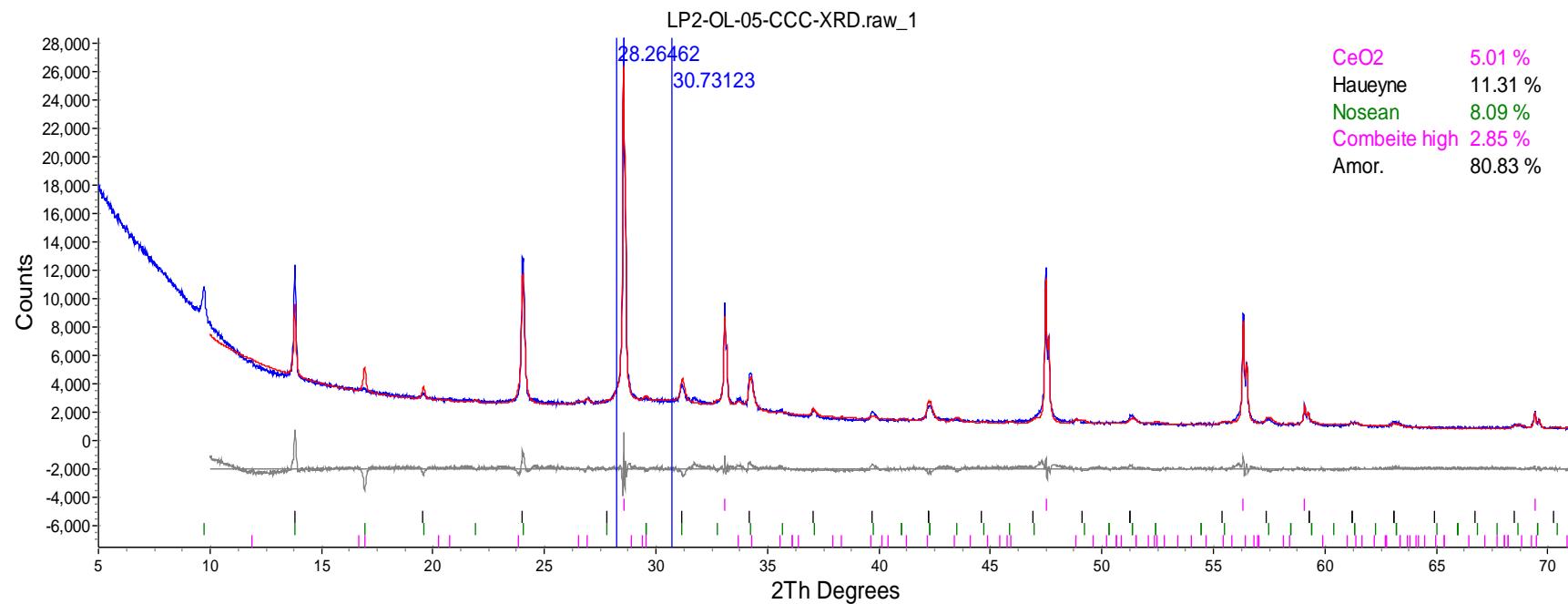
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.003	5.003	0
Combeite high	0	38.739	40.779
Nepheline, sodian	0	6.379	6.715
Sodium Aluminum Silicate	0	17.923	18.866
Calcium Zinc	0	0.896	0.943

Figure H.8. XRD Spectrum of CCC-Treated Glass LP2-OL-03 MOD2



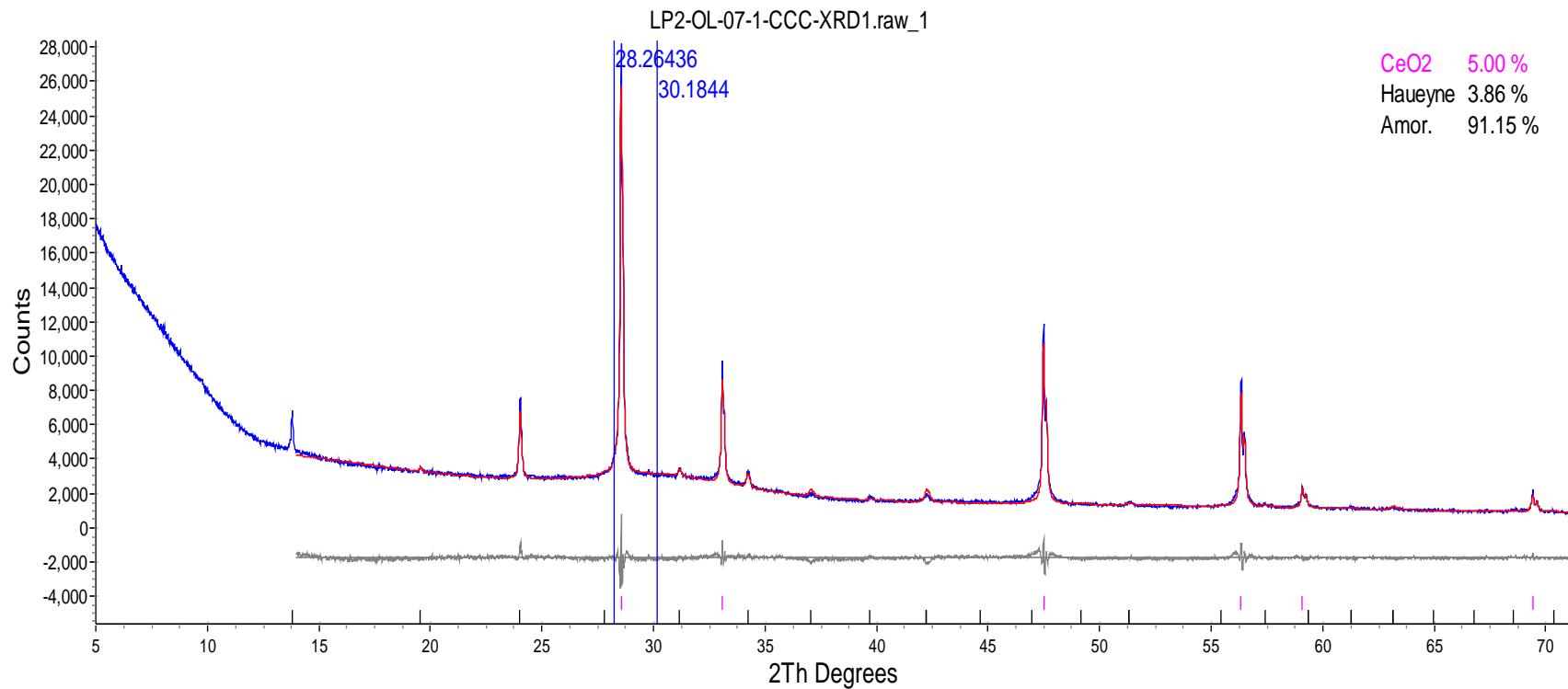
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.998	4.998	0
Combeite high	0	35.645	37.520
Nepheline (Si-rich)	0	17.253	18.161
Sodium Peroxide	0	4.914	5.173
Zirconium Oxide	0	0.680	0.716
65-9834_AlMg	0	1.186	1.248
Zeolite	0	2.835	2.984
89-2340_Zirconium Oxide	0	0.438	0.461
Periclase	0	2.955	3.110

Figure H.9. XRD Spectrum of CCC-Treated Glass LP2-OL-04-1



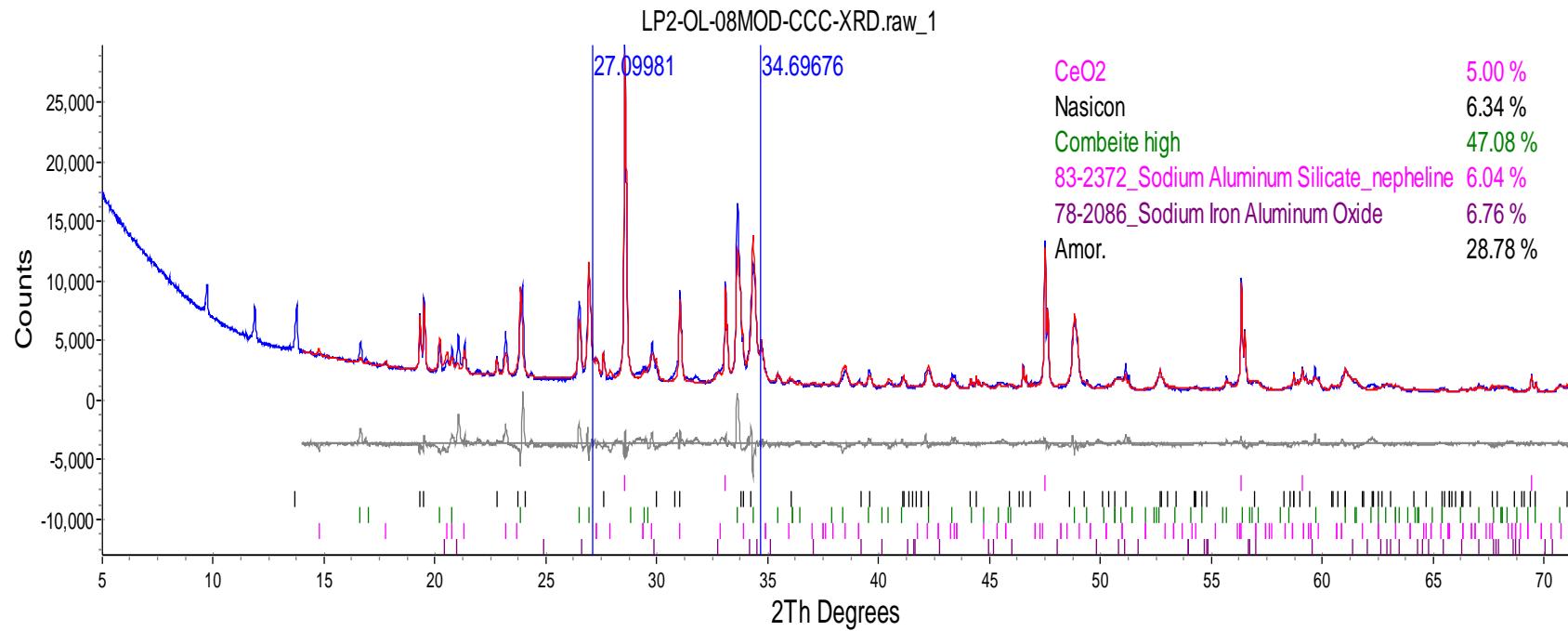
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.008	5.008	0
Haueyne	0	11.311	11.907
Nosean	0	8.088	8.514
Combeite high	0	2.849	2.999

Figure H.10. XRD Spectrum of CCC-Treated Glass LP2-OL-05



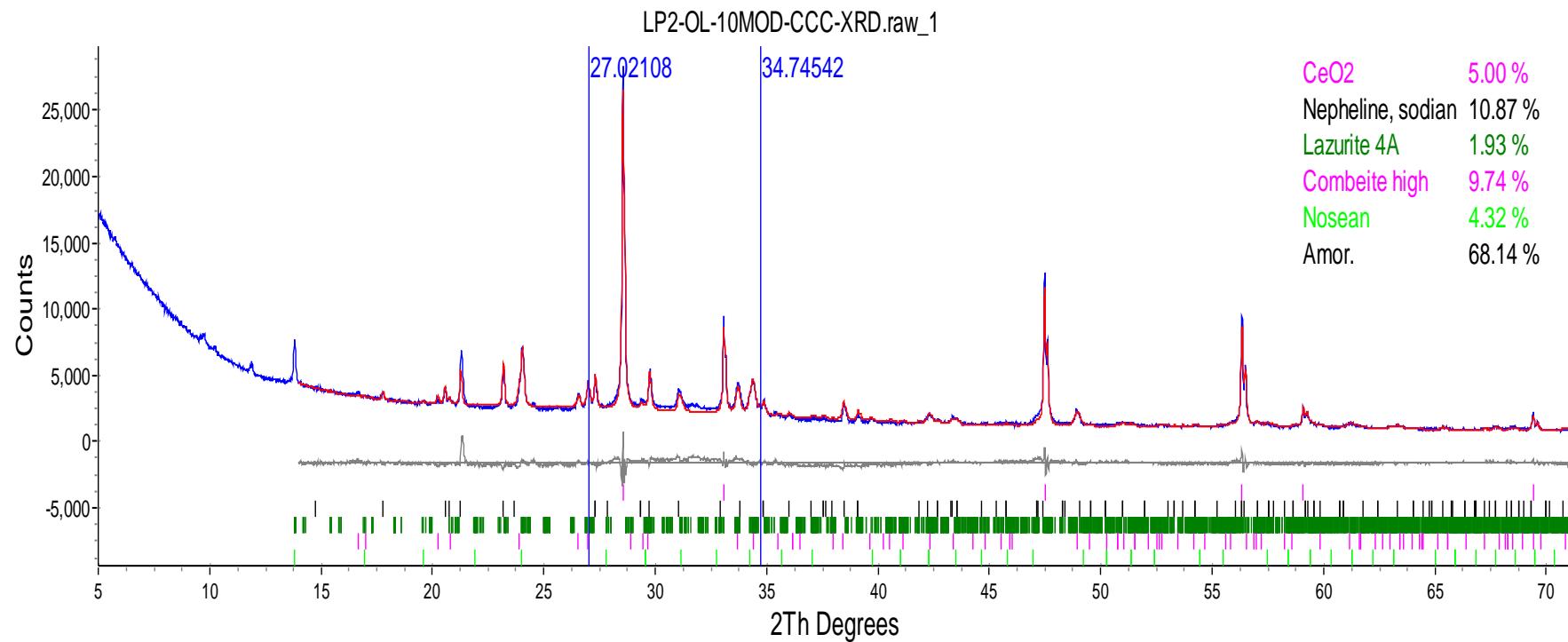
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.995	4.995	0
Haueyne	0	3.855	4.058

Figure H.11. XRD Spectrum of CCC-Treated Glass LP2-OL-07-1



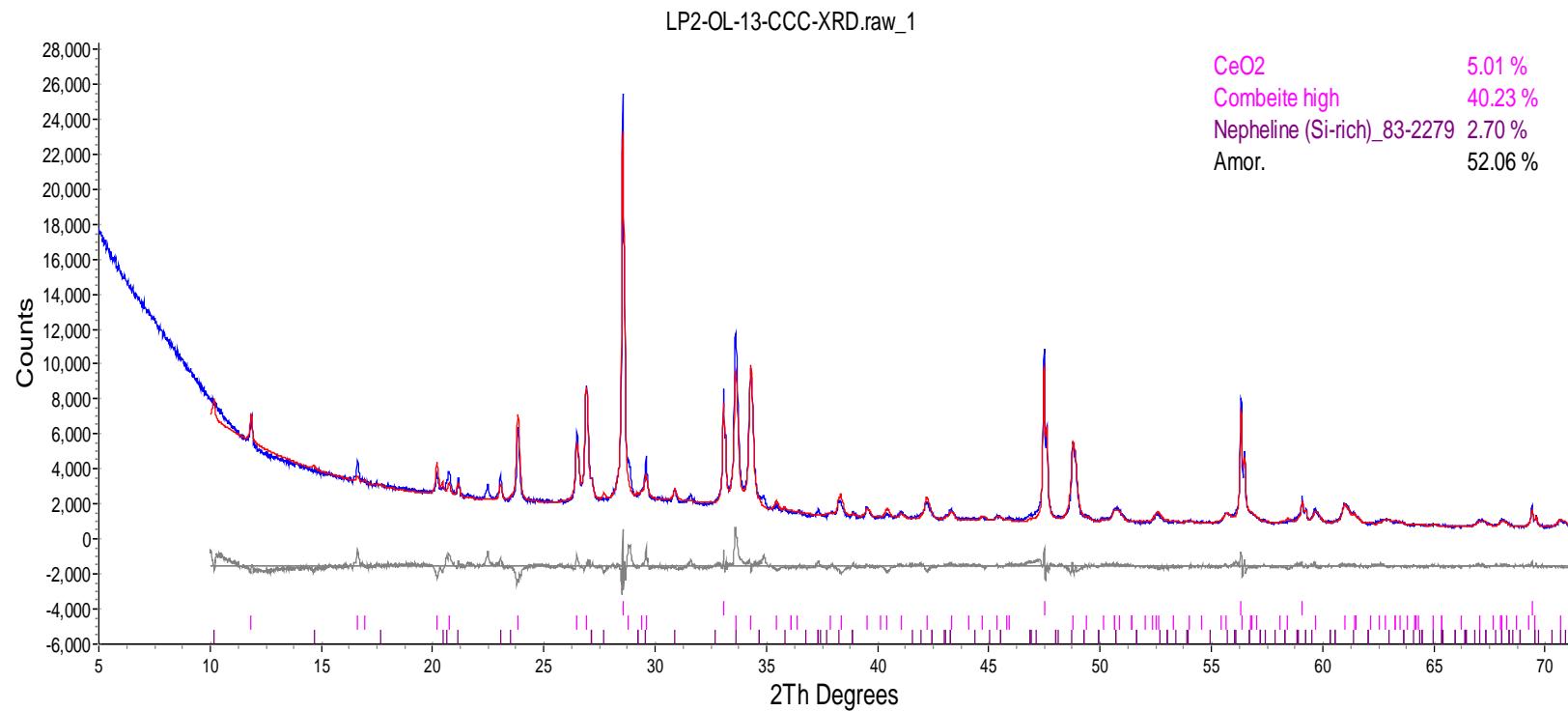
Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.001	5.001	0
Nasicon	0	6.343	6.677
Combeite, high	0	47.076	49.555
Sodium Aluminum Silicate-Nepheline	0	6.037	6.355
Sodium Iron Aluminum Oxide	0	6.763	7.119

Figure H.12. XRD Spectrum of CCC-Treated Glass LP2-OL-08 MOD



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.995	4.995	0
Nepheline, sodian	0	10.873	11.445
Combeite, high	0	9.739	10.251
Lazurite 4A	0	1.934	2.035
Nosean	0	4.320	4.547

Figure H.13. XRD Spectrum of CCC-Treated Glass LP2-OL-10 MOD



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.007	5.007	0
Combeite high	0	40.235	42.356
Nepheline (Si-rich)	0	2.696	2.838

Figure H.14. XRD Spectrum of CCC-Treated Glass LP2-OL-13

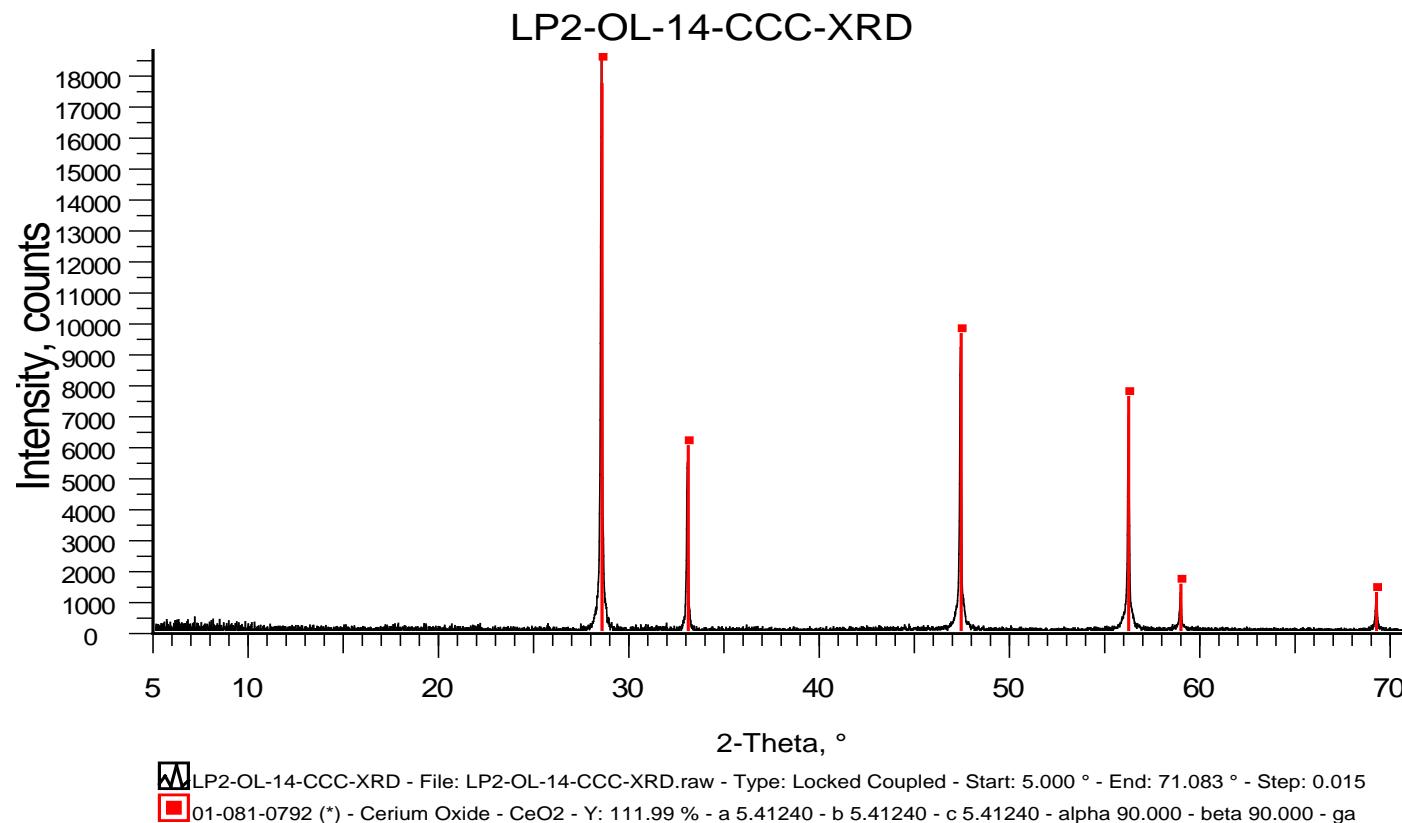


Figure H.15. XRD Spectrum of CCC-Treated Glass LP2-OL-14

### LP2-OL-16MOD-CCC-XRD

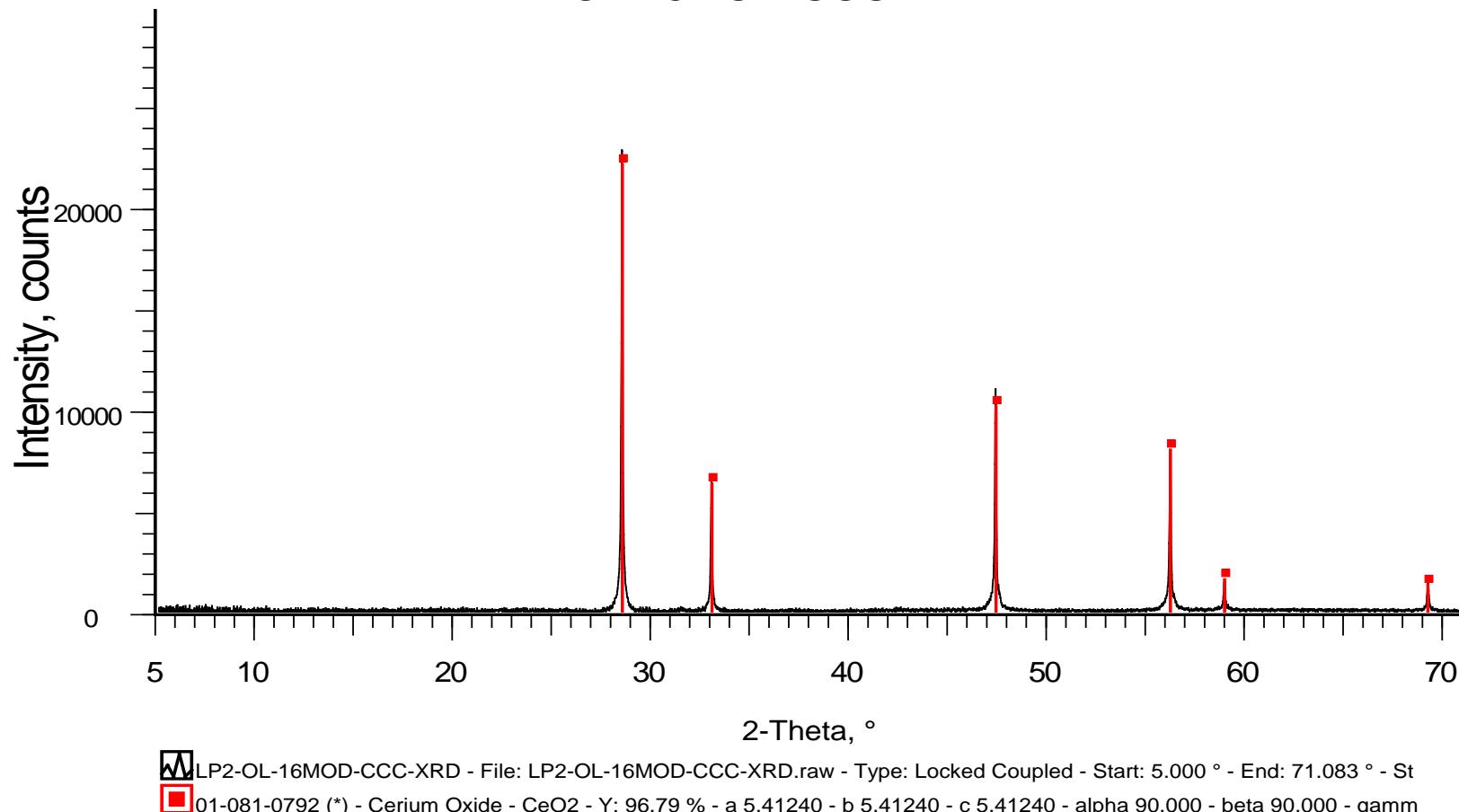


Figure H.16. XRD Spectrum of CCC-Treated Glass LP2-OL-16 MOD

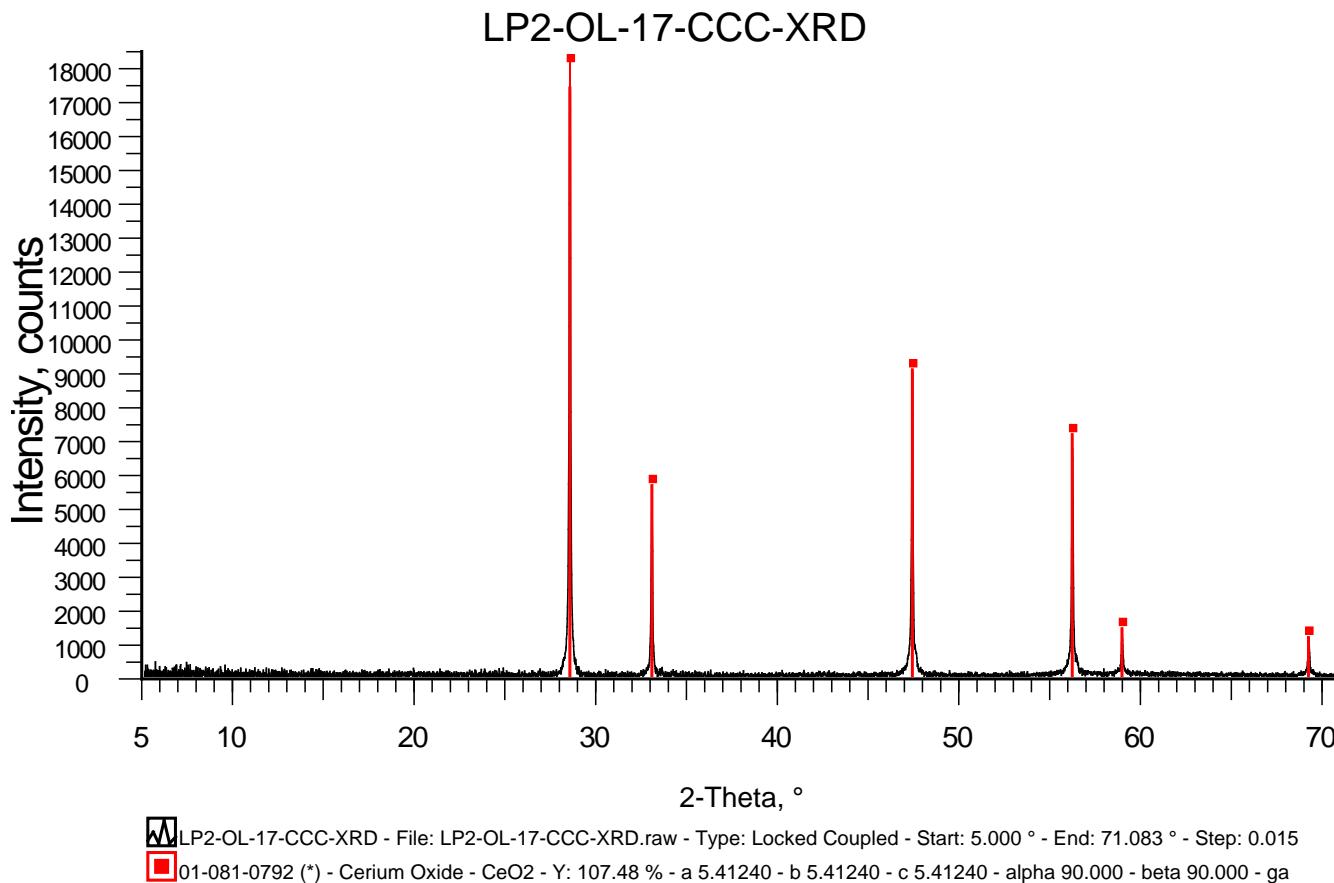
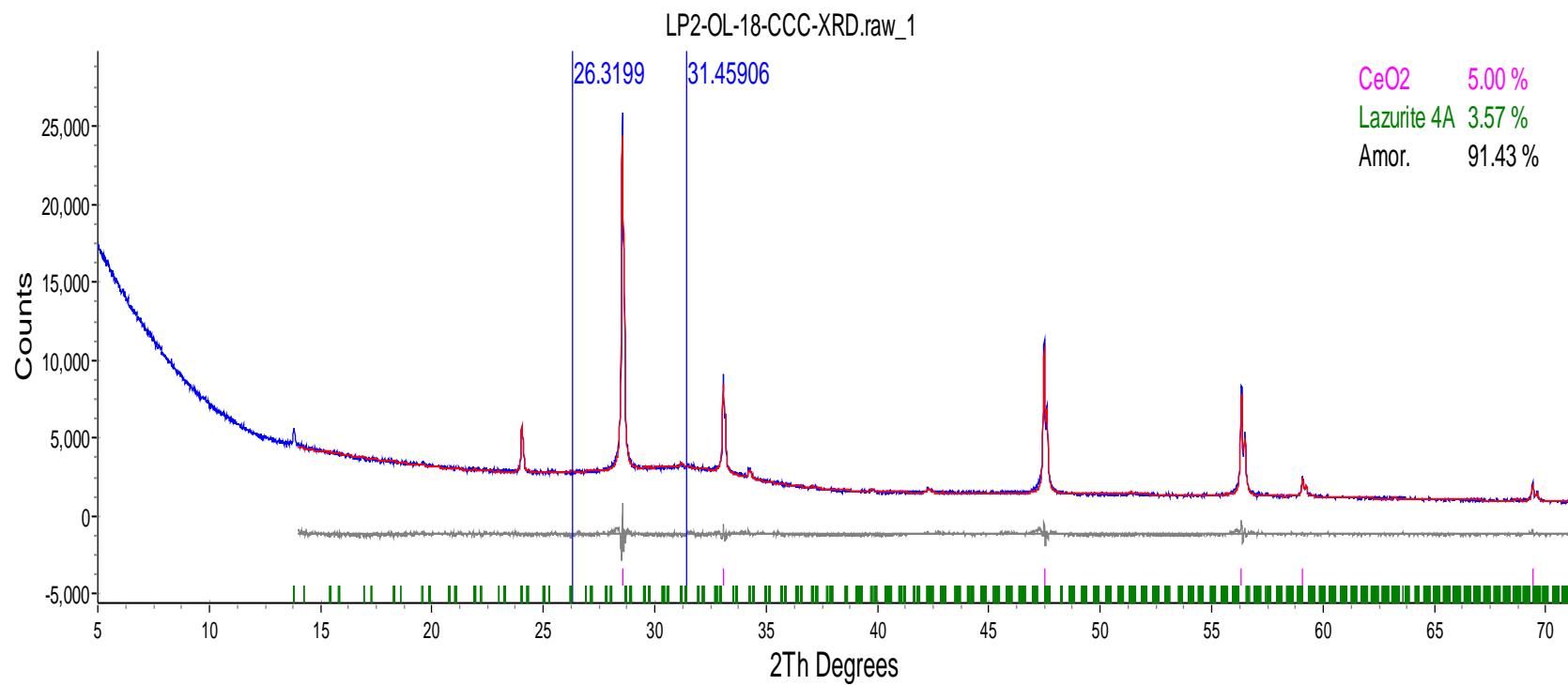


Figure H.17. XRD Spectrum of CCC-Treated Glass LP2-OL-17



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.997	4.997	0
Lazurite 4A	0	3.572	3.760

Figure H.18. XRD Spectrum of CCC-Treated Glass LP2-OL-18

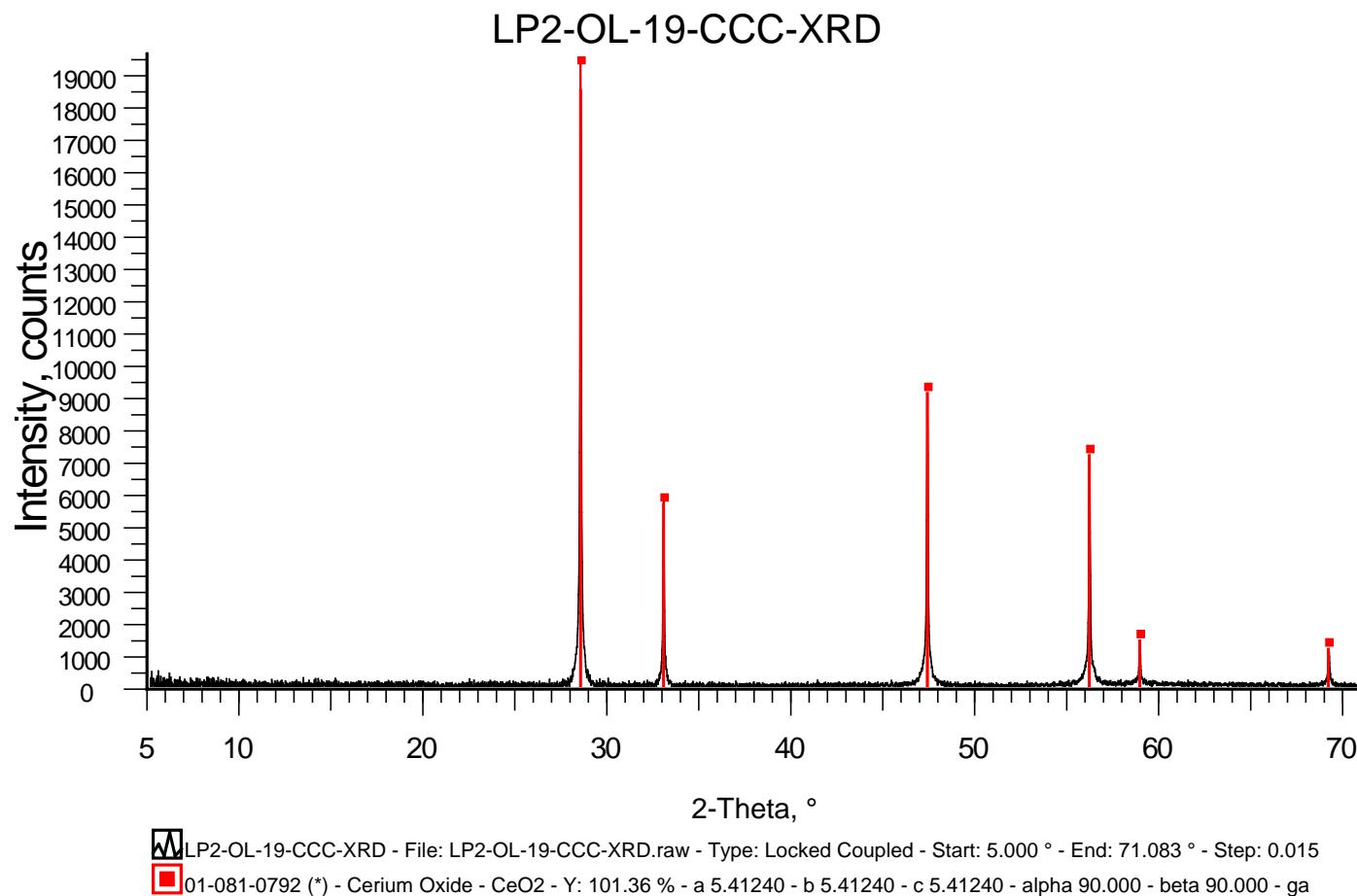
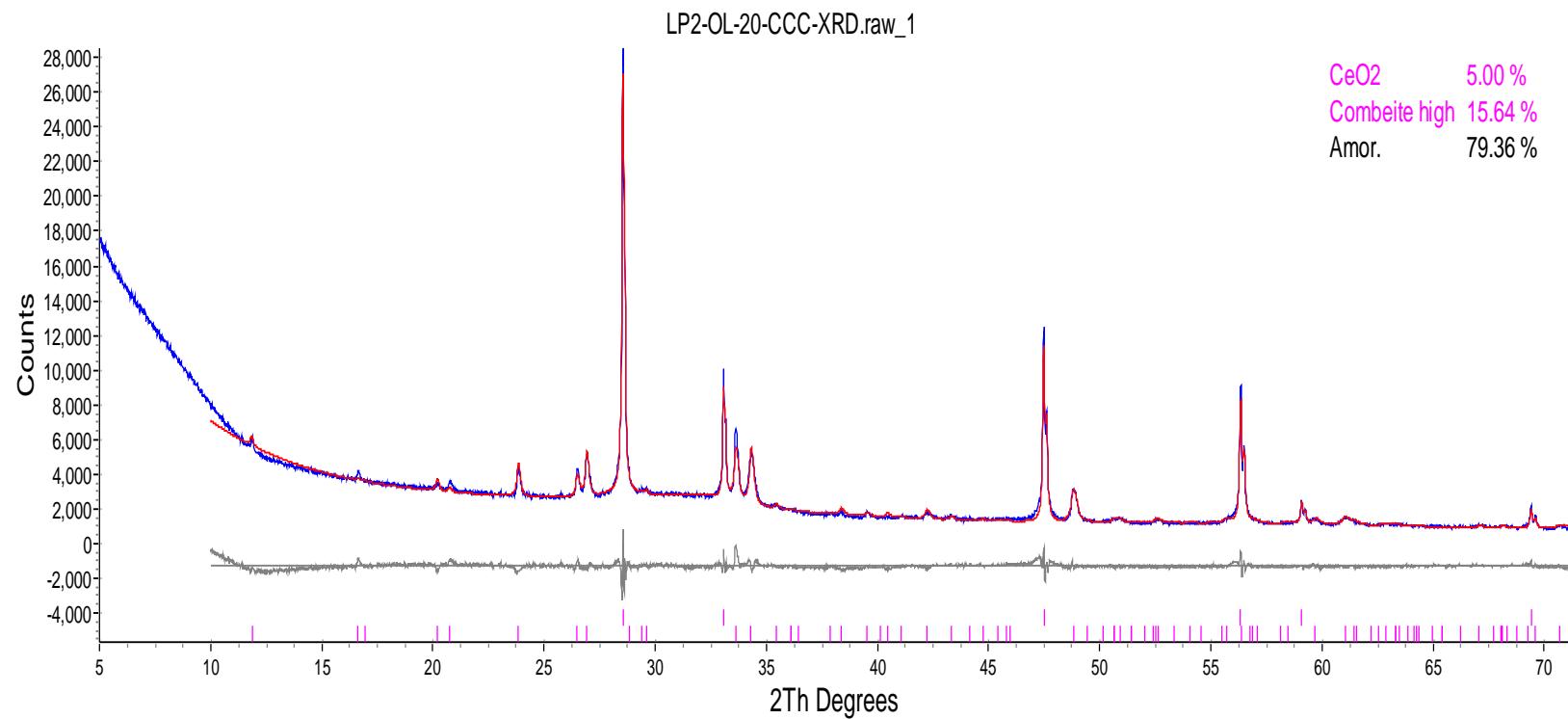
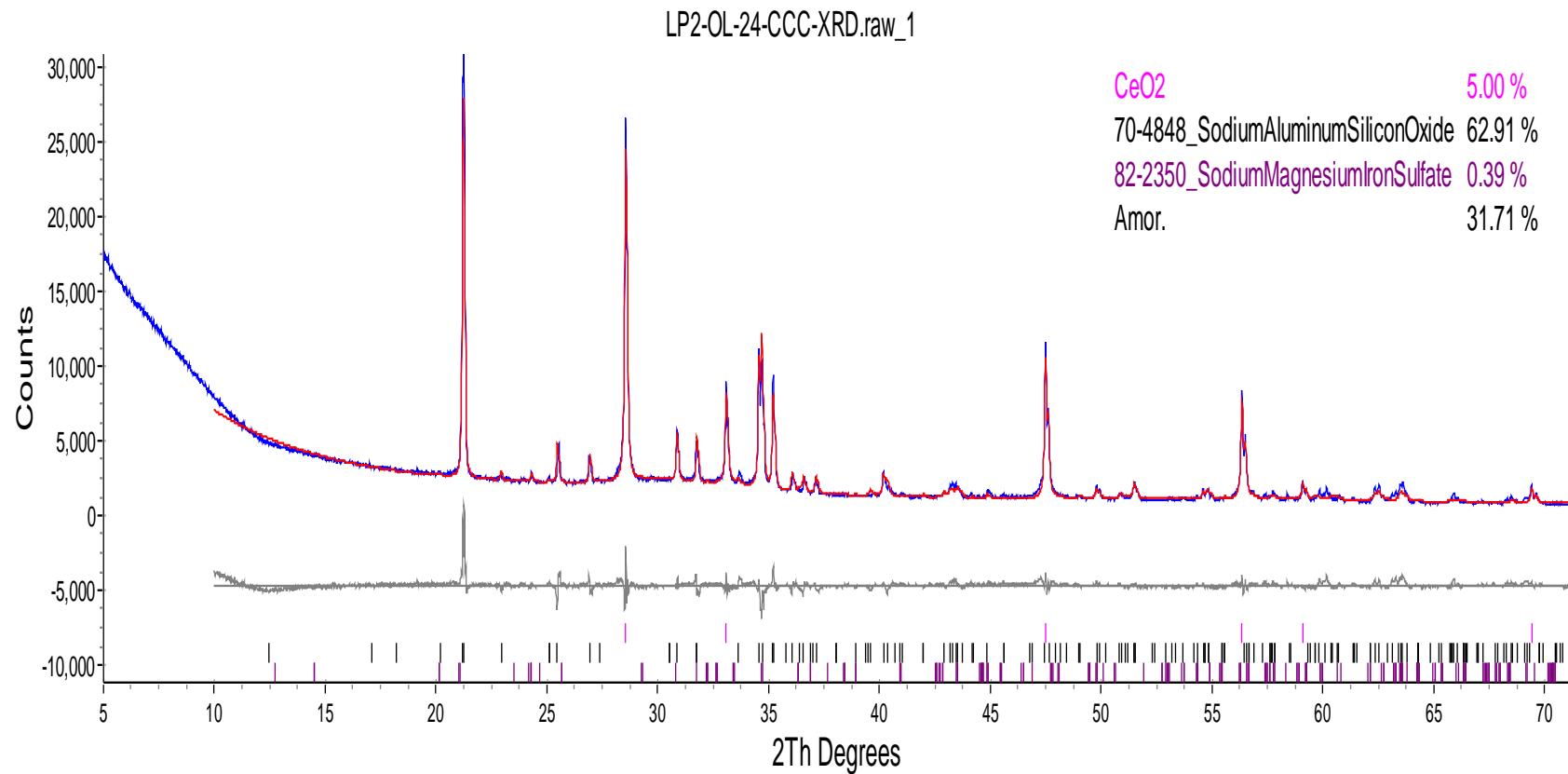


Figure H.19. XRD Spectrum of CCC-Treated Glass LP2-OL-19



Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	5.001	5.001	0
Combeite high	0	15.641	16.464

Figure H.20. XRD Spectrum of CCC-Treated Glass LP2-OL-20

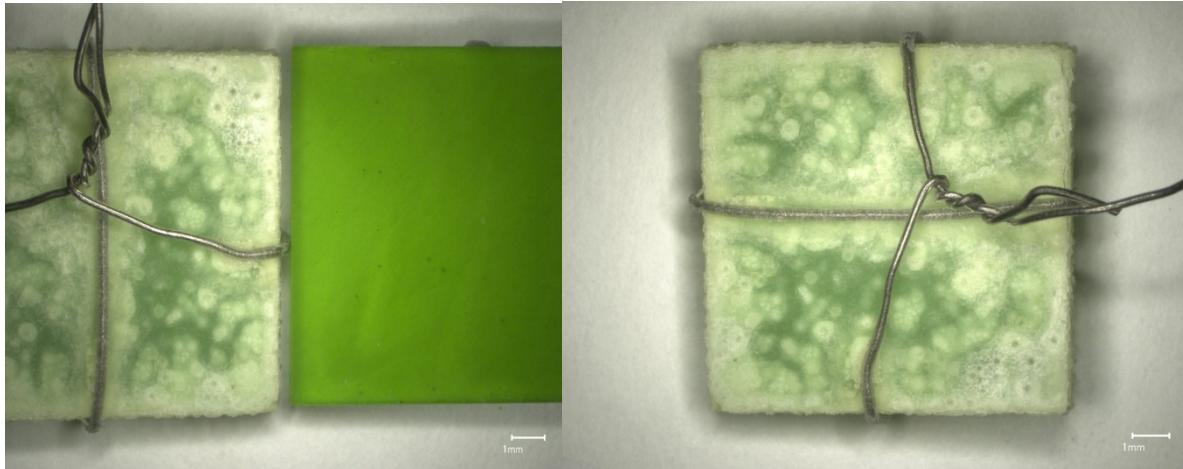


Phase Name	Wt% of Spiked	Wt% in Spiked Sample	Wt% in Original Sample
CeO <sub>2</sub>	4.997	4.997	0
SodiumAluminumSiliconOxide	0	62.908	62.908
SodiumMagnesiumIronSulfate	0	0.386	0.406

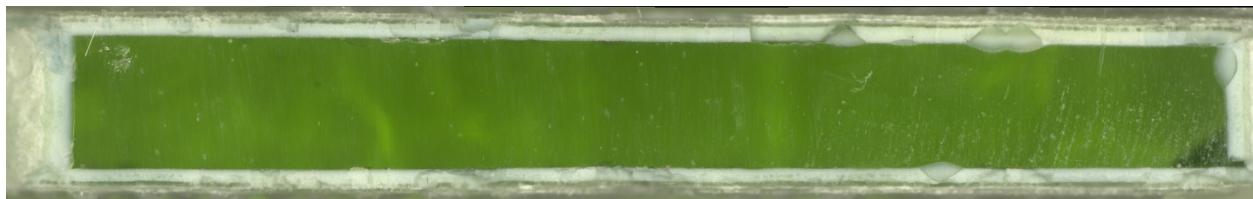
Figure H.21. XRD Spectrum of CCC-Treated Glass LP2-OL-24

## Appendix I – Vapor Hydration Test (VHT) Results

This appendix shows photos of the VHT samples of Phase 2 enhanced LAW glasses both before and after testing. The glasses tested performed either extremely well or extremely poor, with only four glasses near the corrosion rate limit. These photos show the variation in corrosion with the samples.

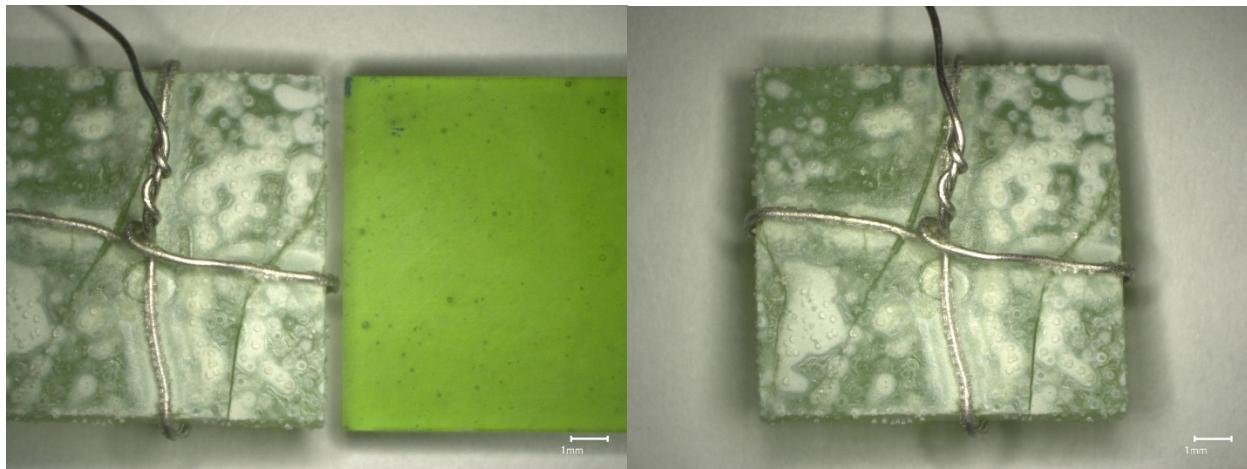


a) Glass square after (left) and before (right) VHT; b) Glass square after VHT



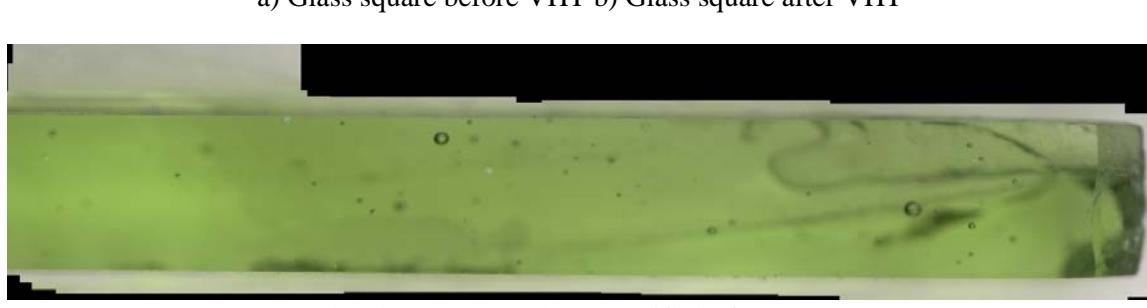
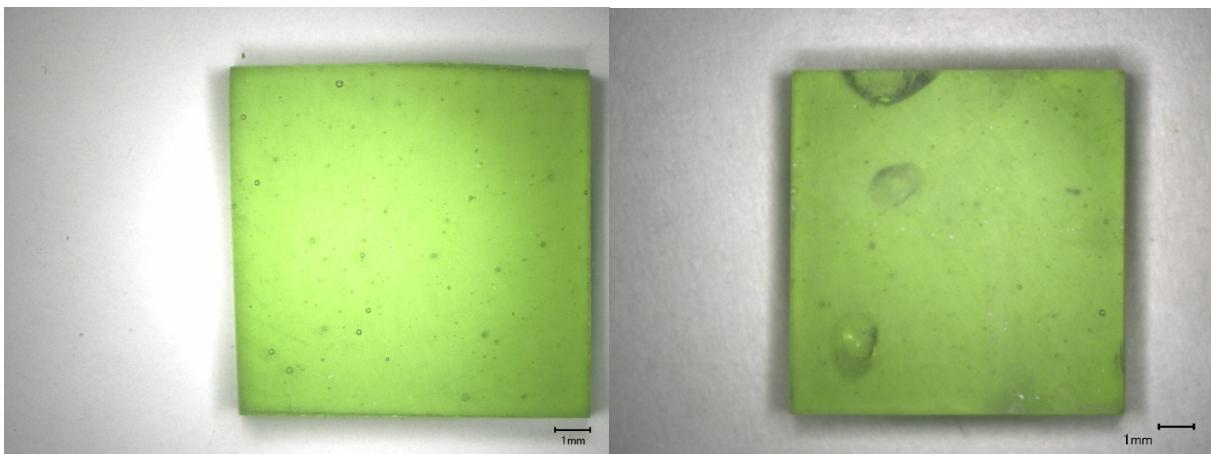
c) Glass cross section magnified after VHT

Figure I.1. Quenched Glass LP2-IL-01 after VHT for 7 Days



c) Glass cross section magnified after VHT

Figure I.2. Quenched Glass LP2-IL-02 after VHT for 7 Days



b) Glass cross section magnified after VHT

Figure I.3. Quenched Glass LP2-IL-02 after VHT for 24 Days

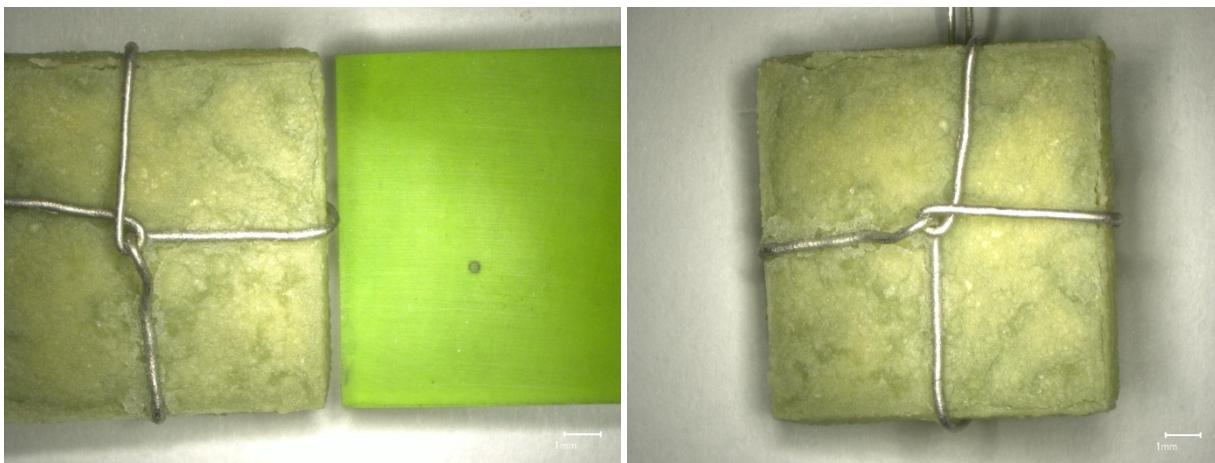


Figure I.4. Quenched Glass LP2-IL-03 after VHT for 7 Days

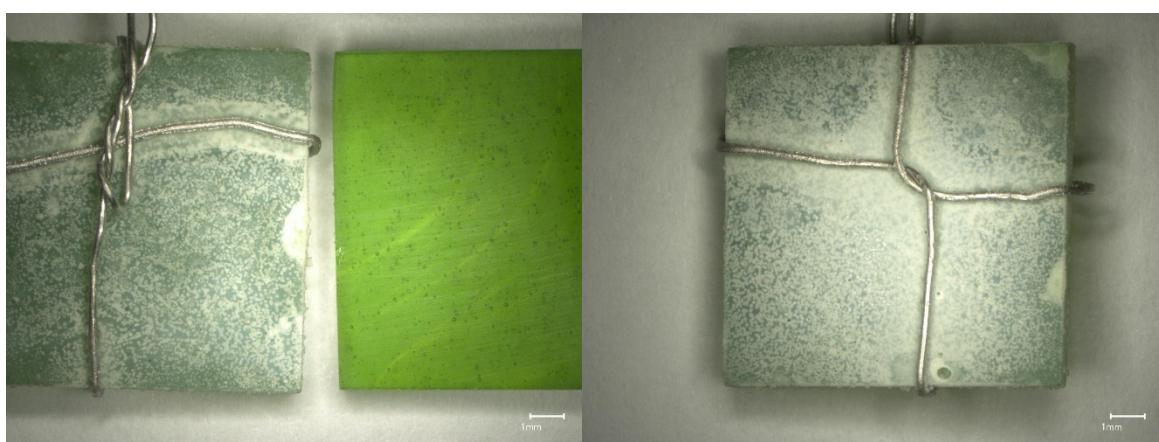
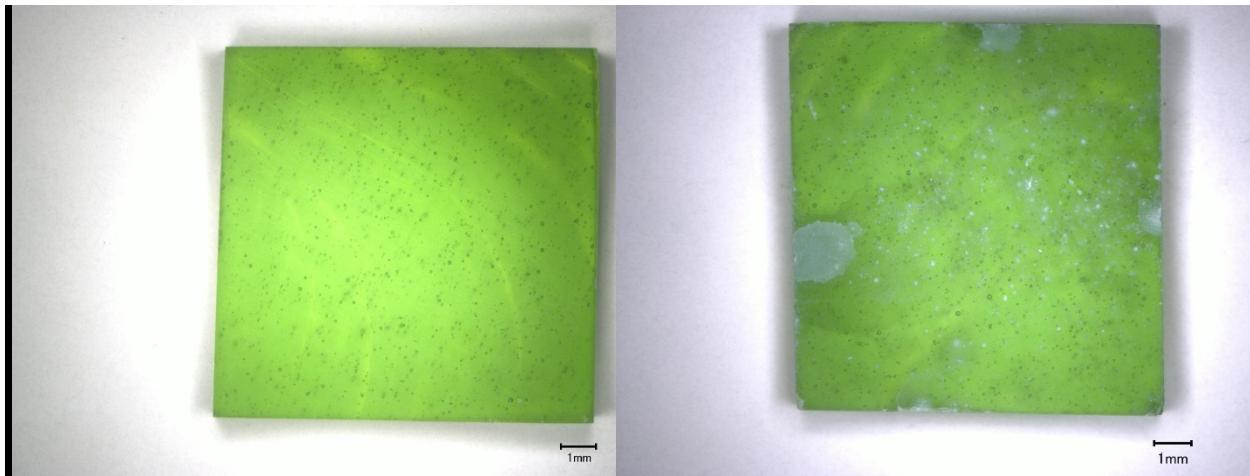
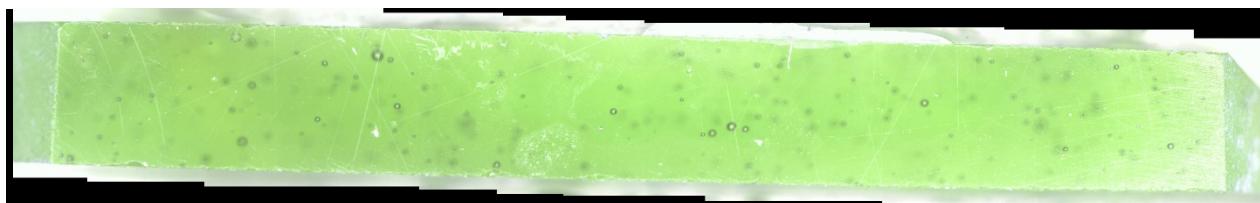


Figure I.5. Quenched Glass LP2-IL-04 after VHT for 7 Days

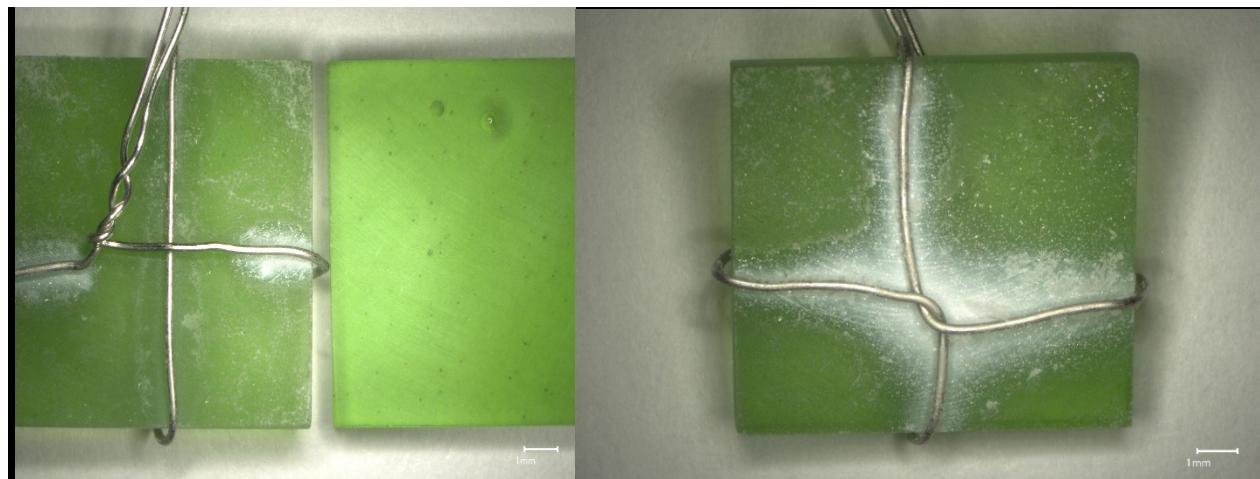


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.6. Quenched Glass LP2-IL-04 after VHT for 24 Days



a) Glass square after (left) and before (right) VHT; b) Glass square after VHT



c) Glass cross section magnified after VHT

Figure I.7. Quenched Glass LP2-IL-05 after VHT for 7 Days

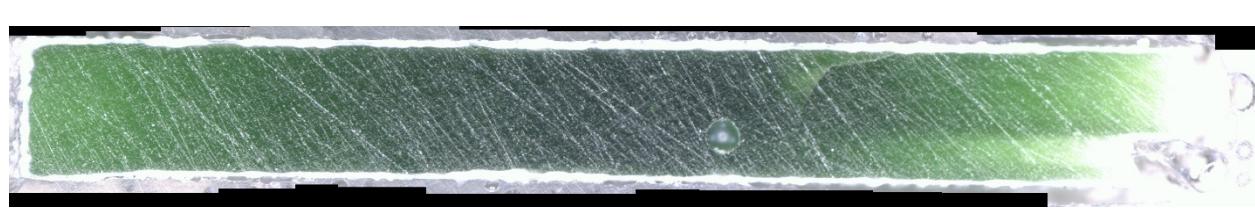
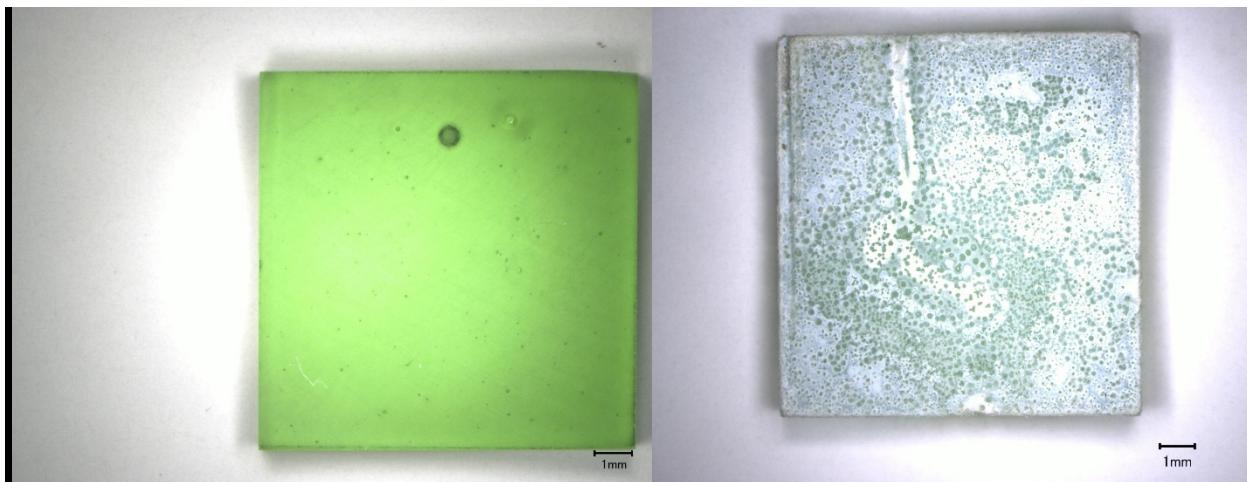


Figure I.8. Quenched Glass LP2-IL-05 after VHT for 24 Days

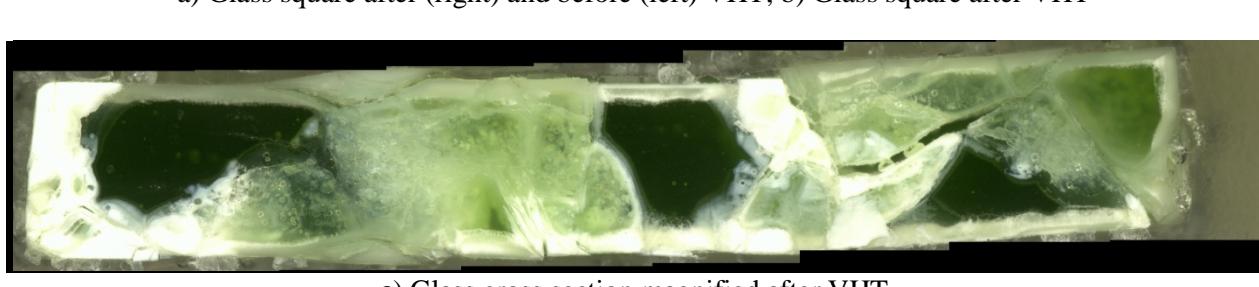
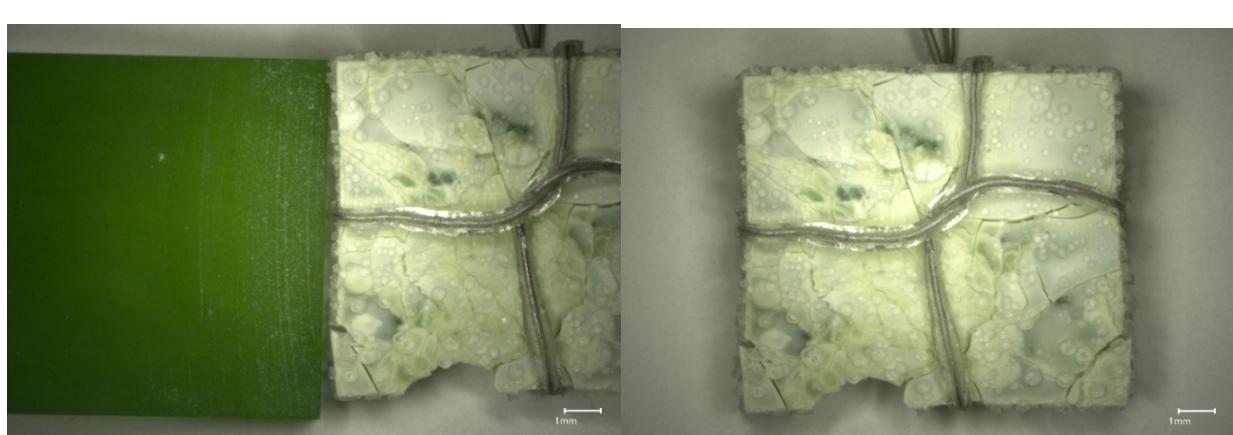
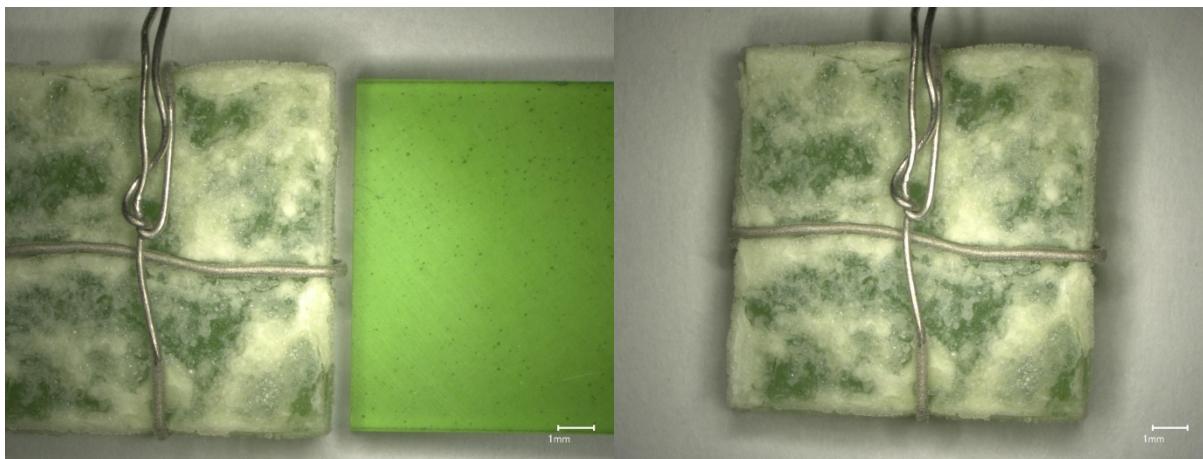
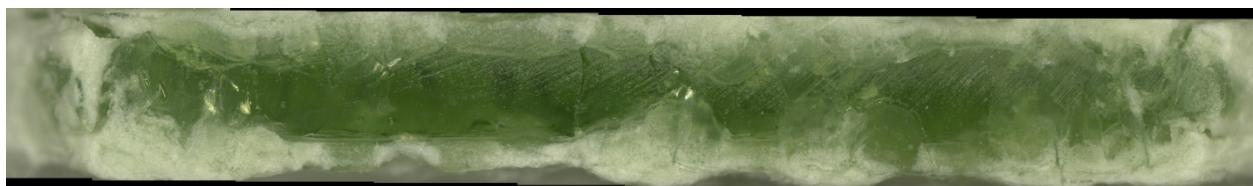


Figure I.9. Quenched Glass LP2-IL-06 after VHT for 7 Days

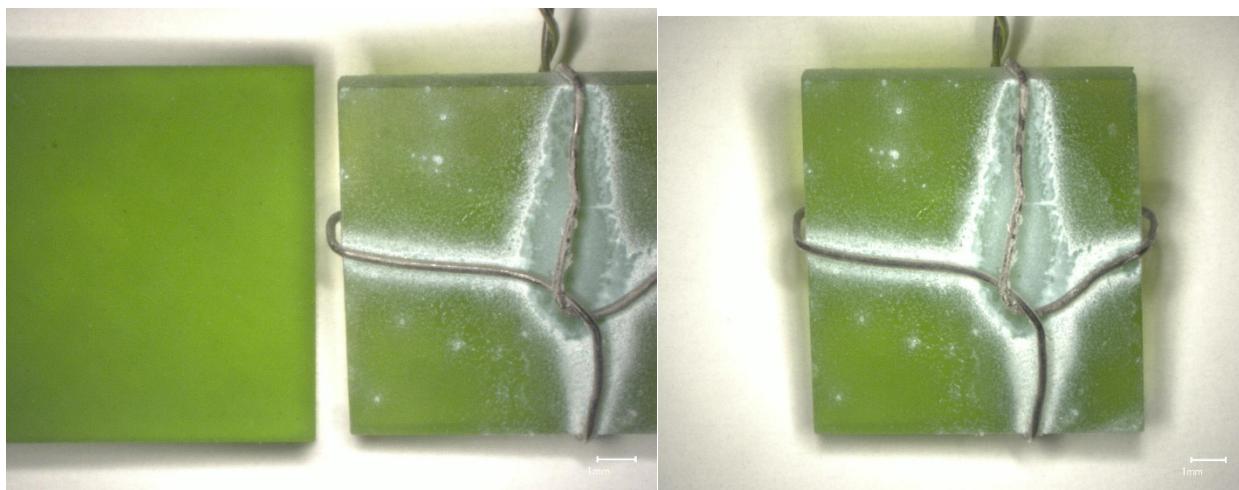


a) Glass square after (left) and before (right) VHT; b) Glass square after VHT

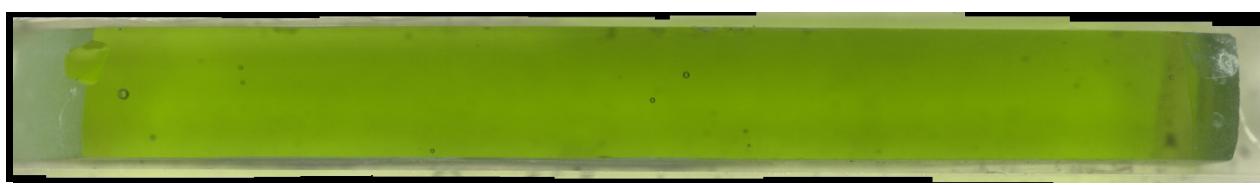


c) Glass cross section magnified after VHT

Figure I.10. Quenched Glass LP2-IL-07 after VHT for 7 Days



a) Glass square after (right) and before (left) VHT; b) Glass square after VHT



c) Glass cross section magnified after VHT

Figure I.11. Quenched Glass LP2-IL-08 after VHT after 7 Days

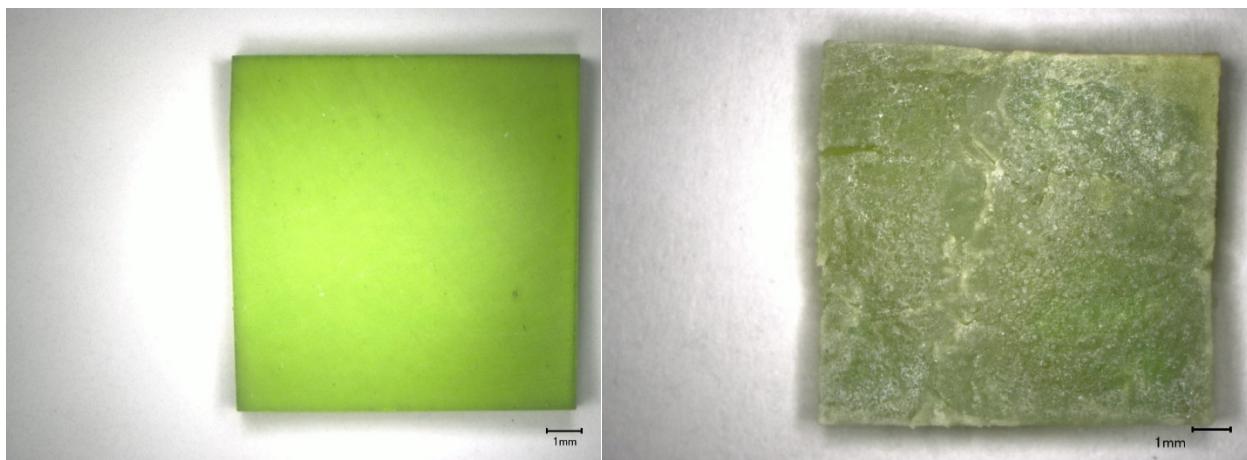


Figure I.12. Quenched Glass LP2-IL-08 after VHT after 24 Days

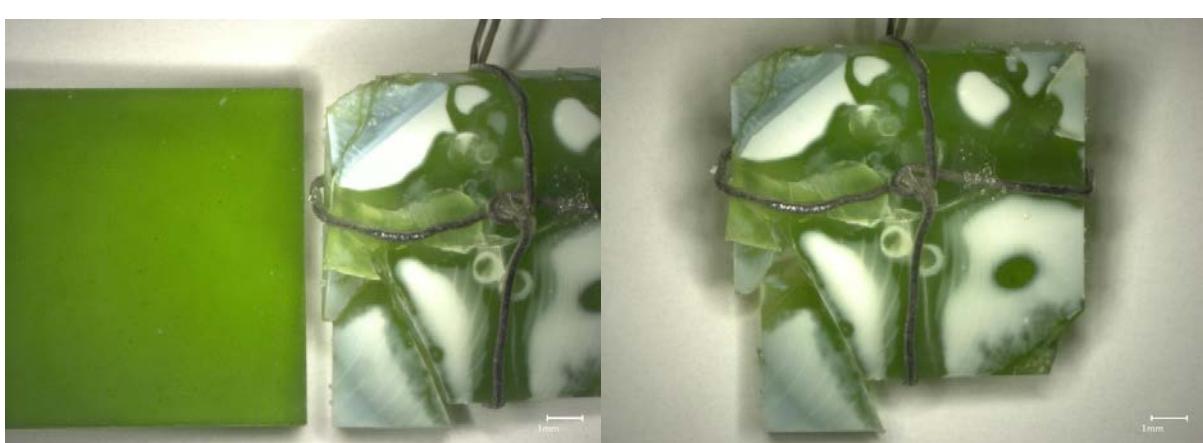
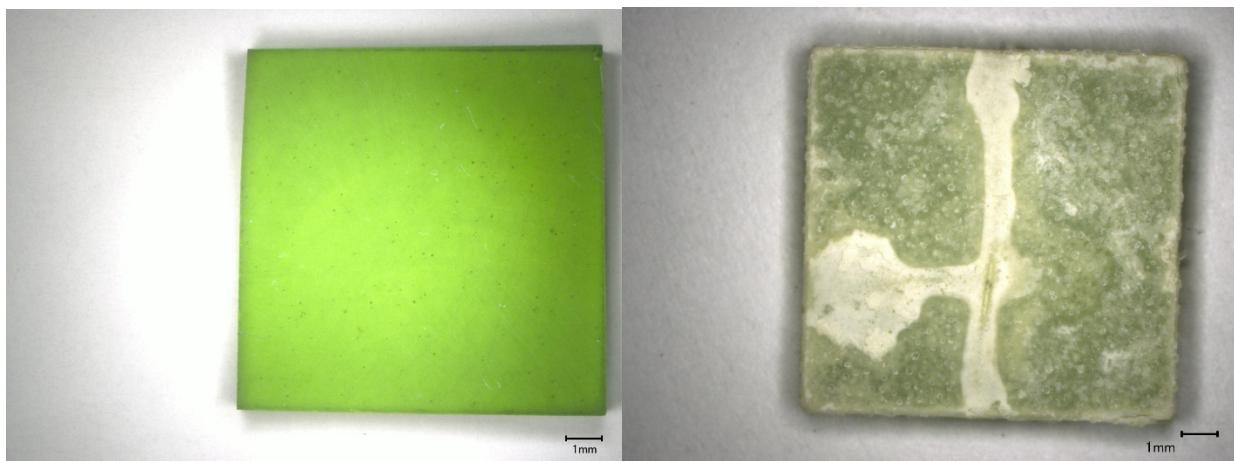
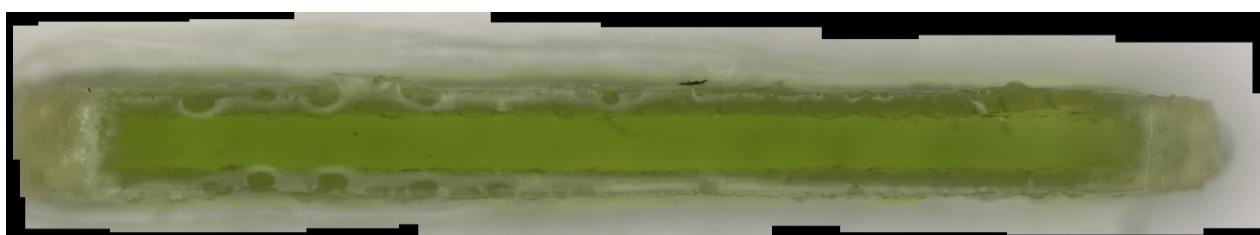


Figure I.13. Quenched Glass LP2-IL-09 after VHT after 7 Days

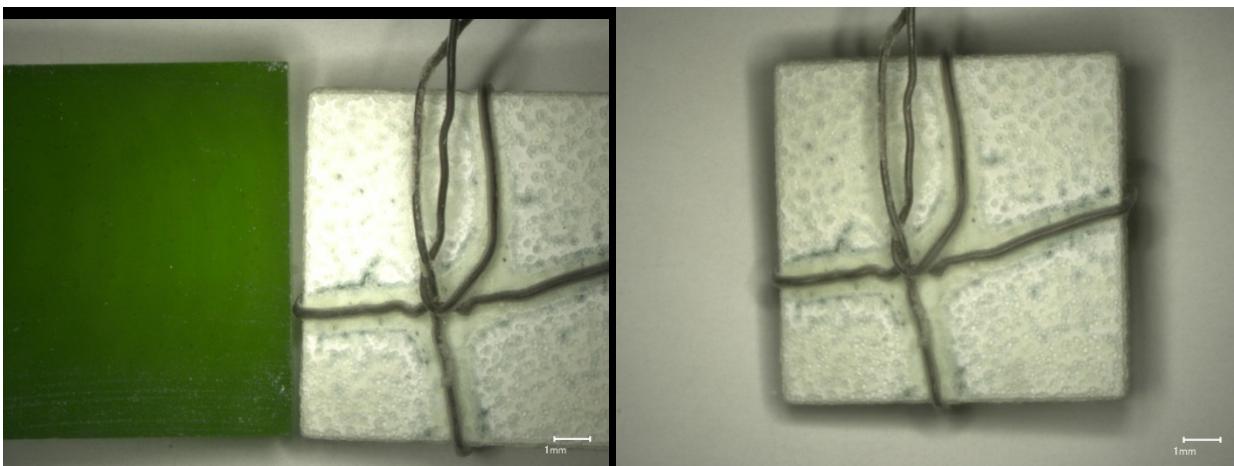


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.14. Quenched Glass LP2-IL-09 after VHT after 24 Days

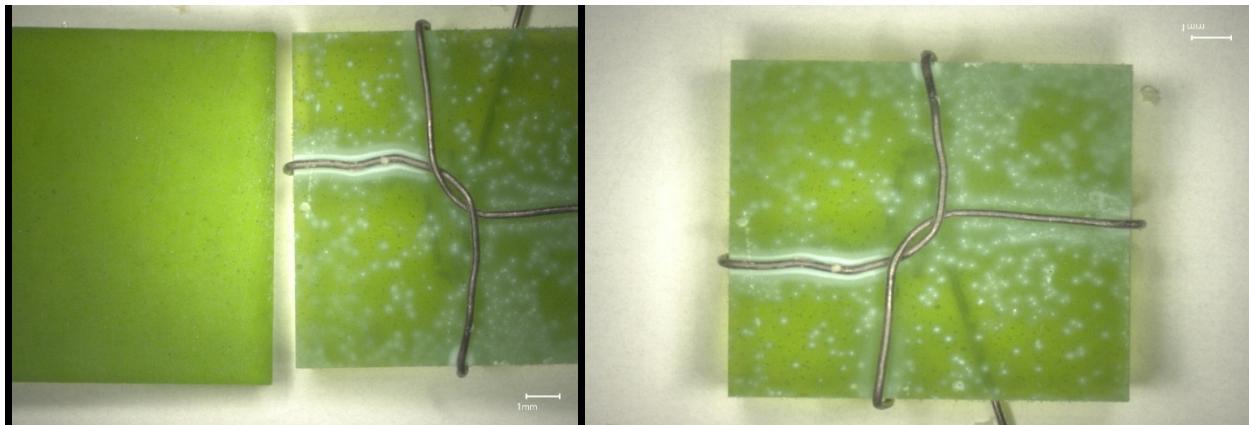


a) Glass square after (right) and before (left) VHT; b) Glass square after VHT

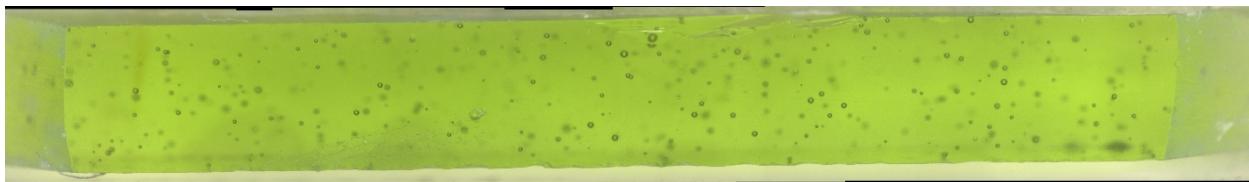


c) Glass cross section magnified after VHT

Figure I.15. Quenched Glass LP2-IL-10 after VHT for 7 Days

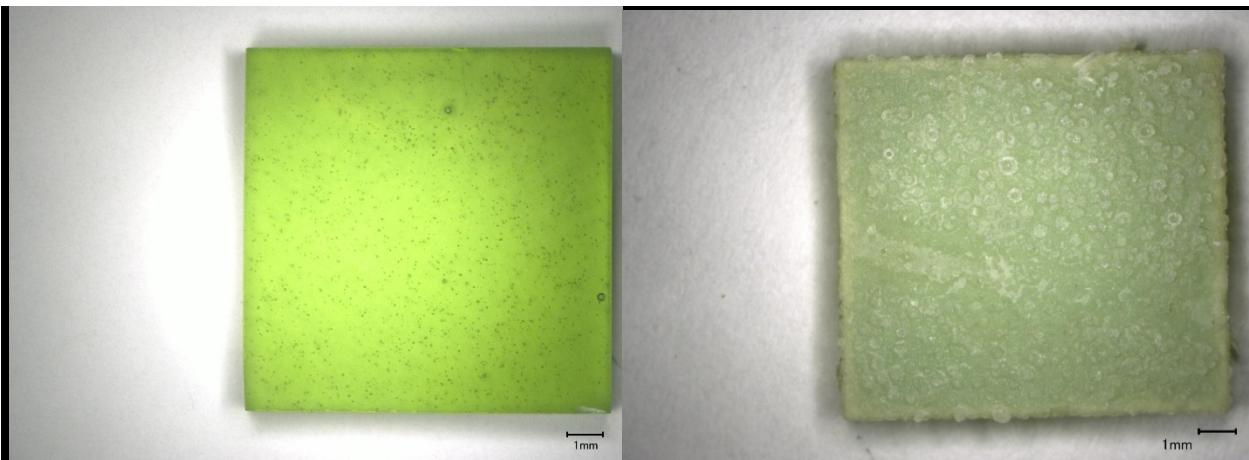


a) Glass square after (right) and before (left) VHT; b) Glass square after VHT

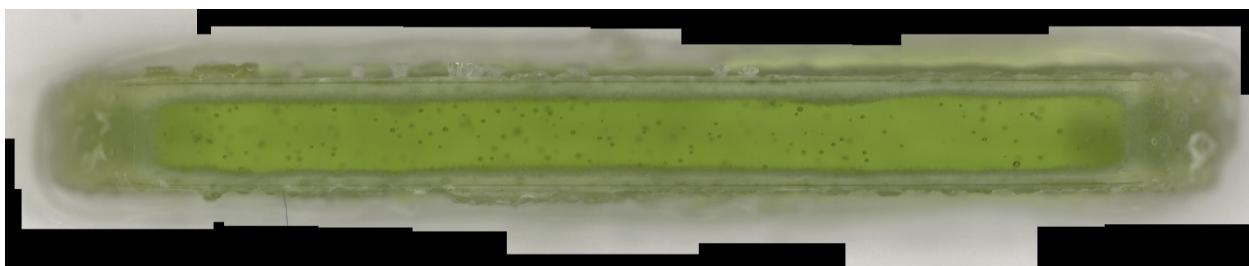


c) Glass cross section magnified after VHT

Figure I.16. Quenched Glass LP2-IL-11 after VHT for 7 Days



a) Glass square after (right) and before (left) VHT; b) Glass square after VHT



c) Glass cross section magnified after VHT

Figure I.17. Quenched Glass LP2-IL-11 after VHT for 24 Days

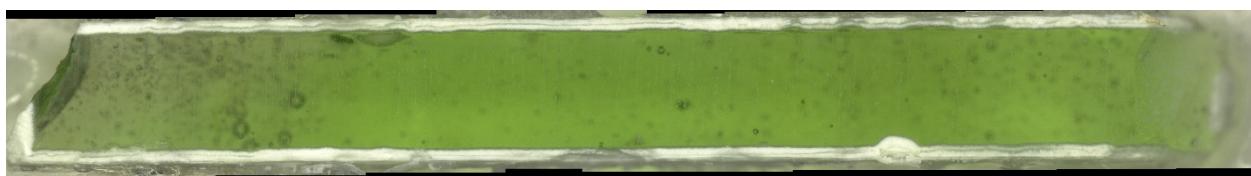
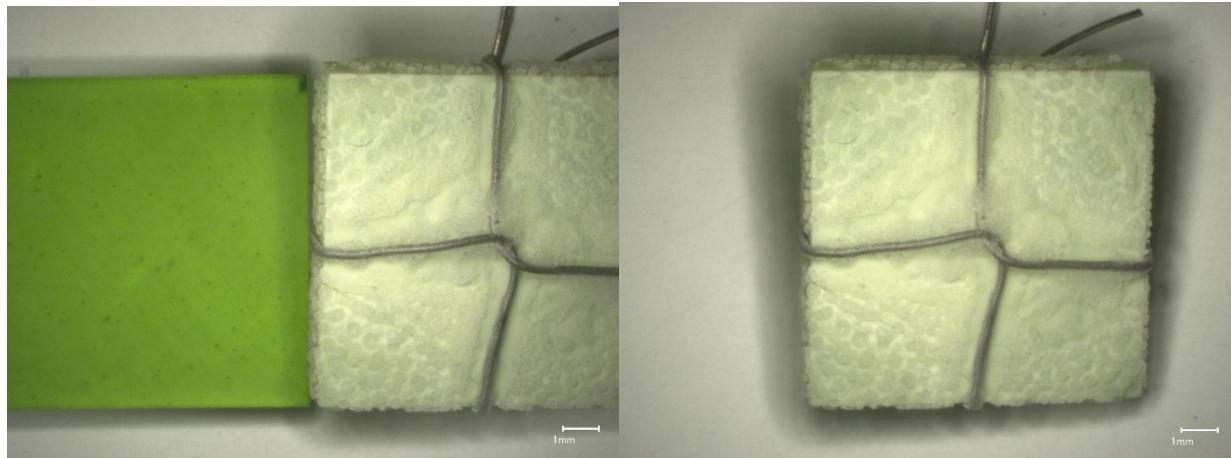


Figure I.18. Quenched Glass LP2-IL-12 after VHT for 7 Days

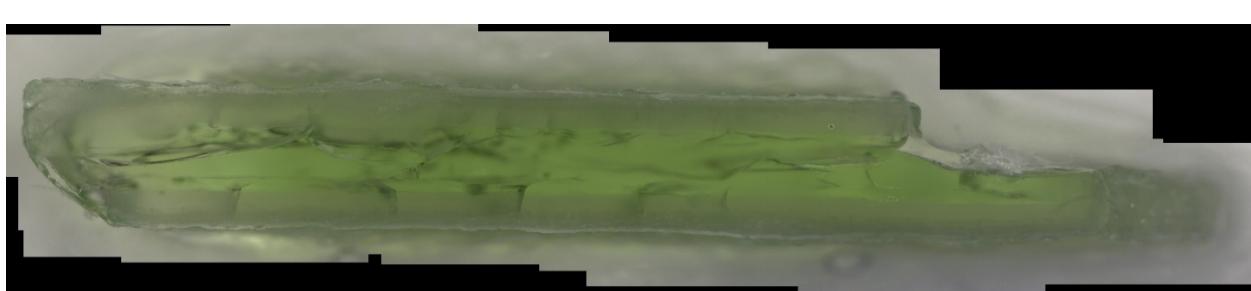
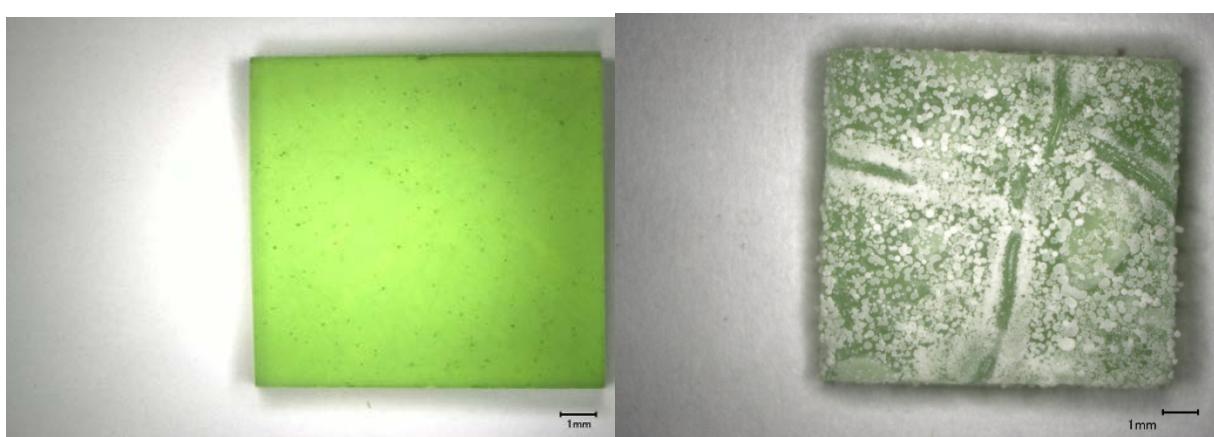
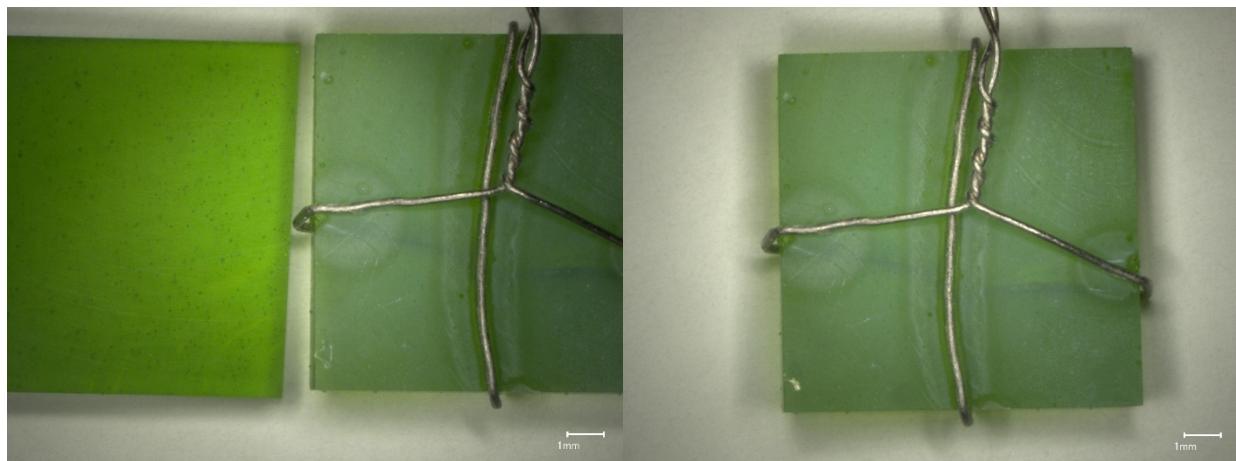
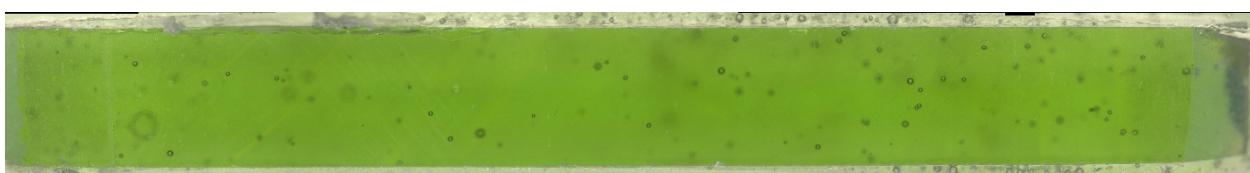


Figure I.19. Quenched Glass LP2-IL-12 after VHT for 24 Days

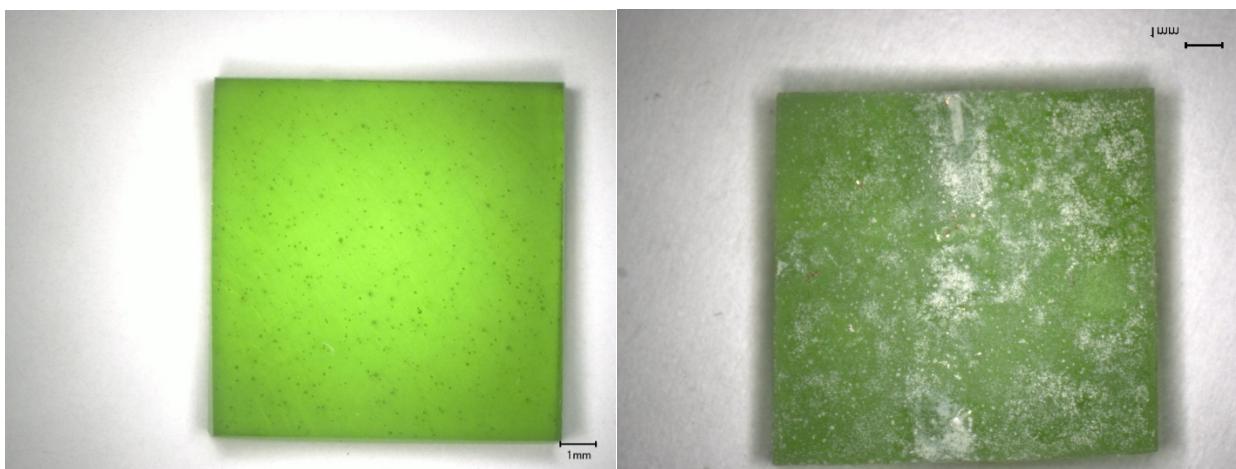


a) Glass square after (right) and before (left) VHT; b) Glass square after VHT

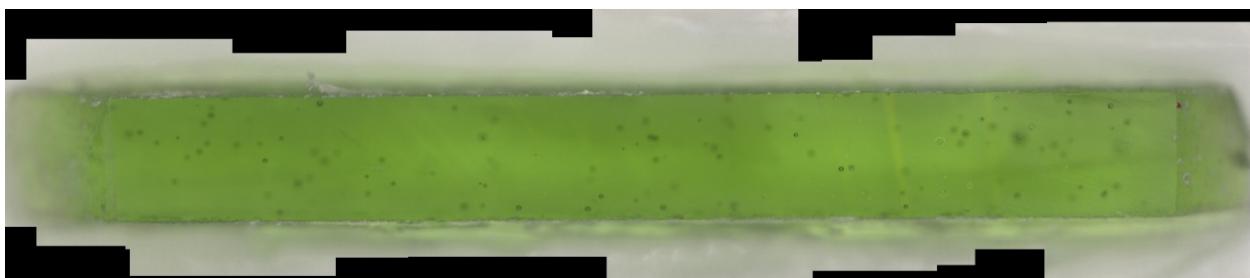


c) Glass cross section magnified after VHT

Figure I.20. Quenched Glass LP2-IL-13 after VHT for 7 Days



a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.21. Quenched Glass LP2-IL-13 after VHT for 24 Days

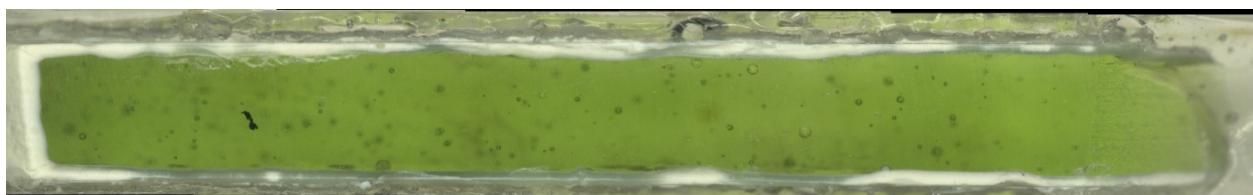
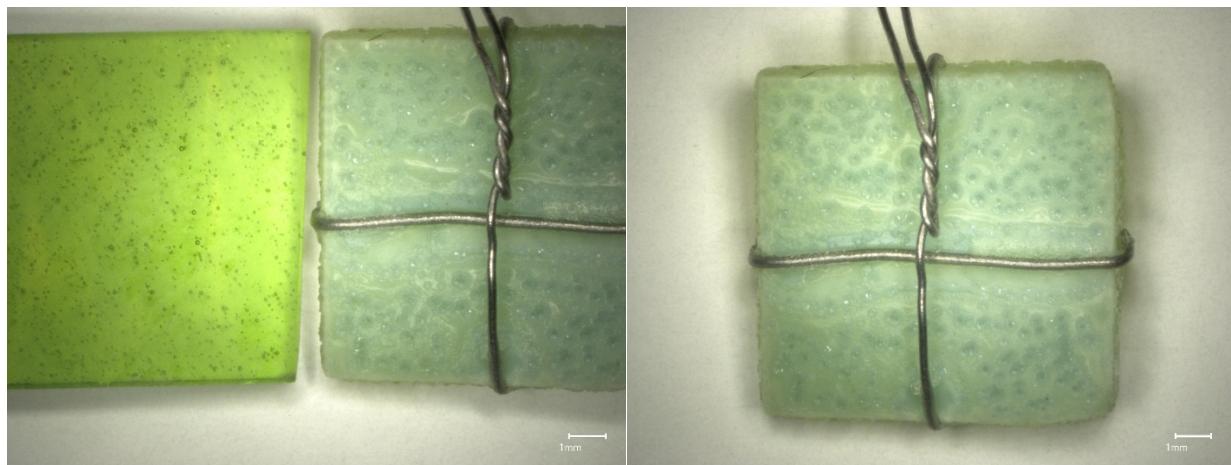


Figure I.22. Quenched Glass LP2-IL-14 after VHT for 7 Days

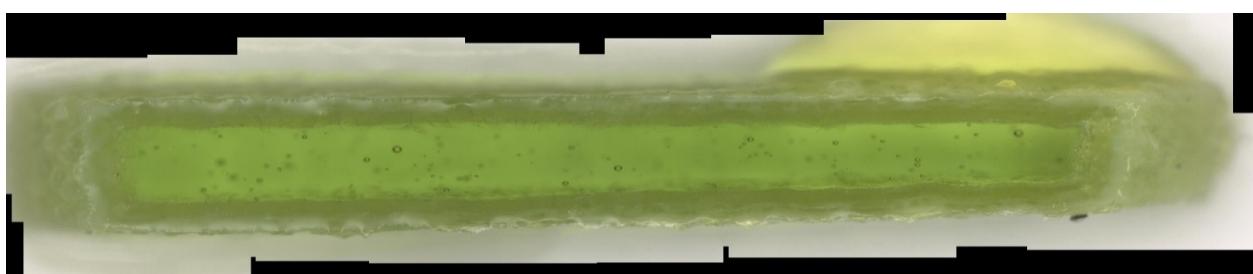
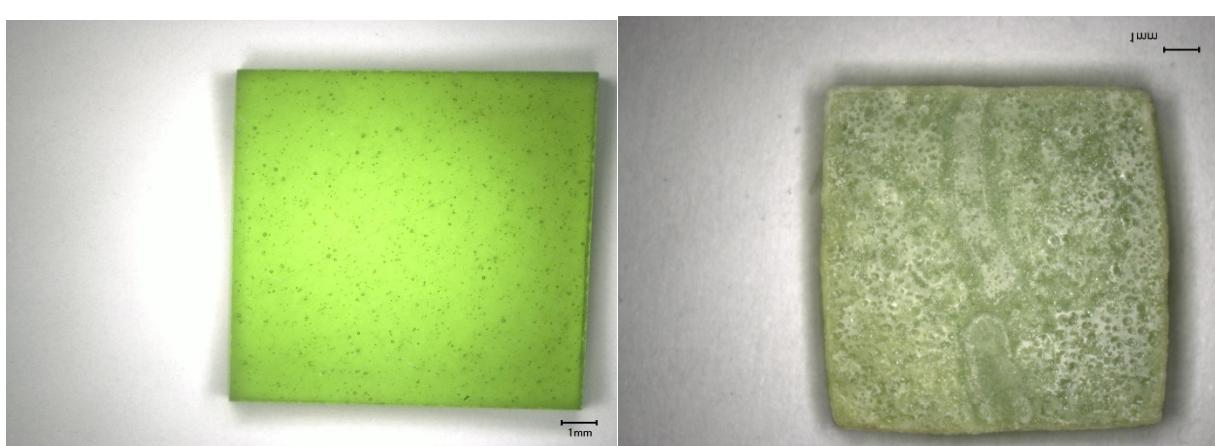


Figure I.23. Quenched Glass LP2-IL-14 after VHT for 24 Days

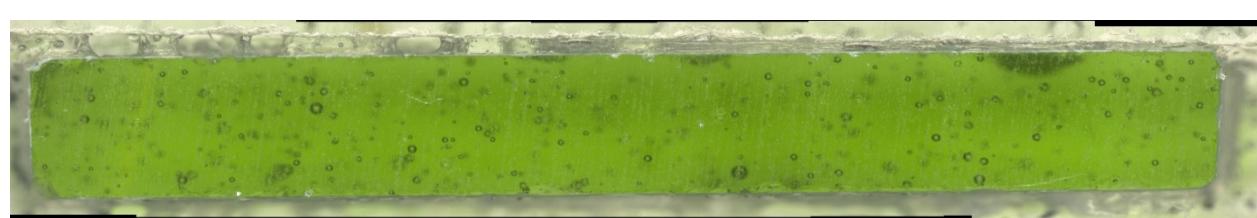
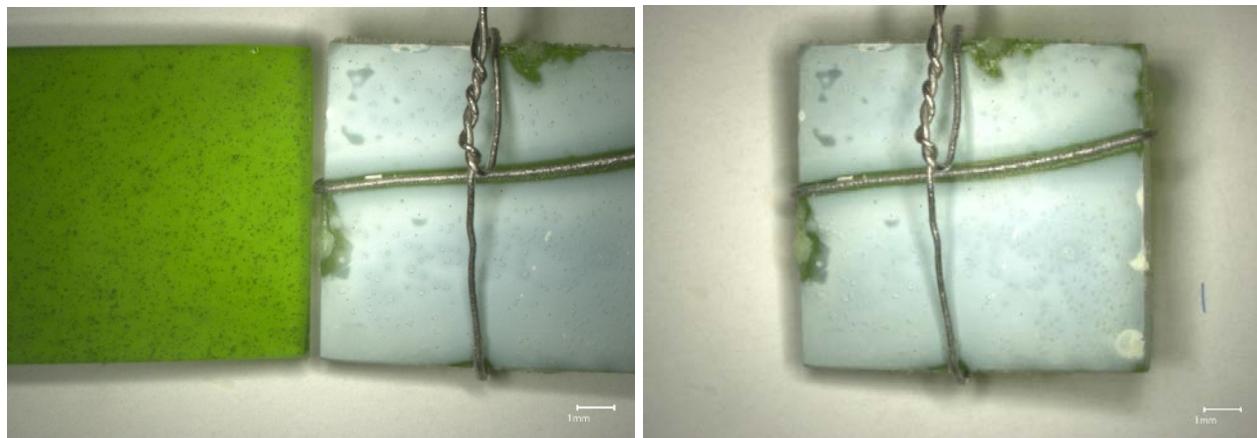


Figure I.24. Quenched Glass LP2-IL-15 after VHT for 7 Days

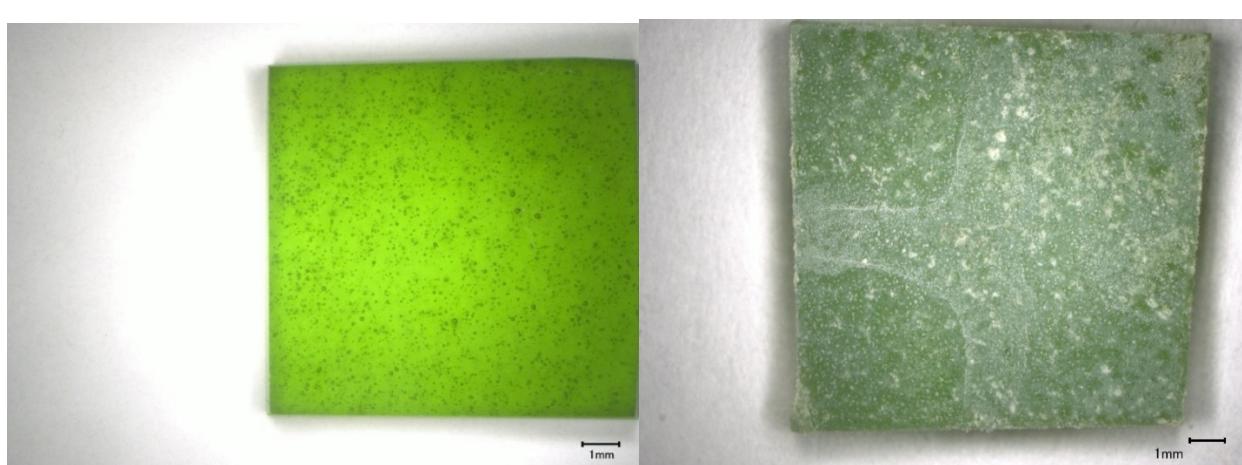
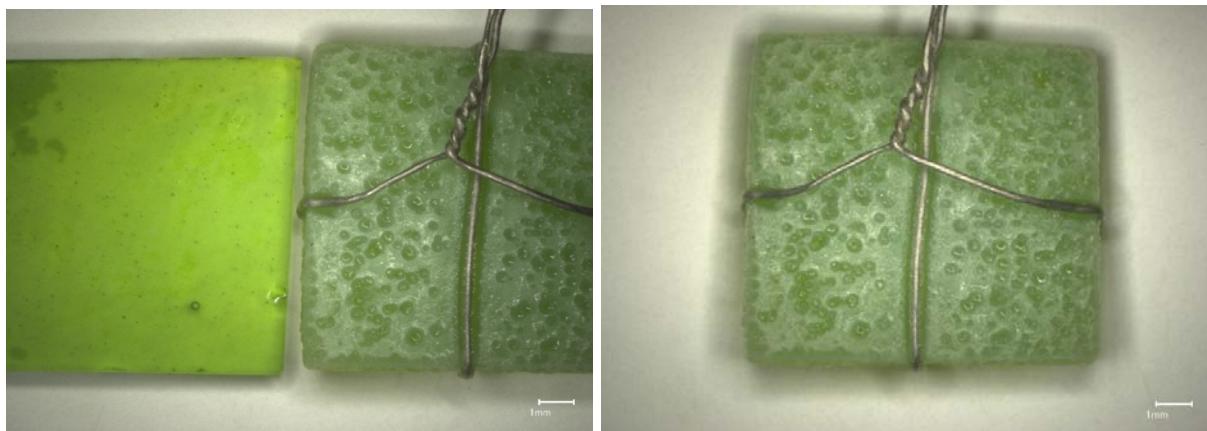
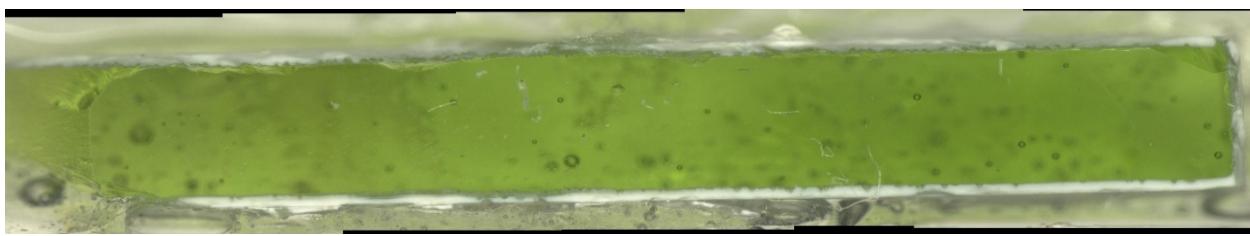


Figure I.25. Quenched Glass LP2-IL-15 after VHT for 24 Days

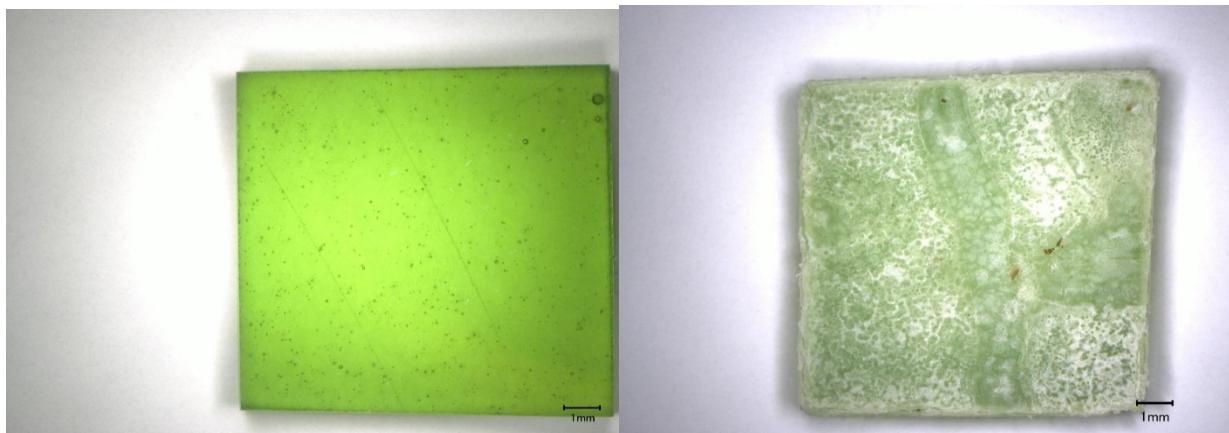


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.26. Quenched Glass LP2-IL-16 after VHT for 7 Days

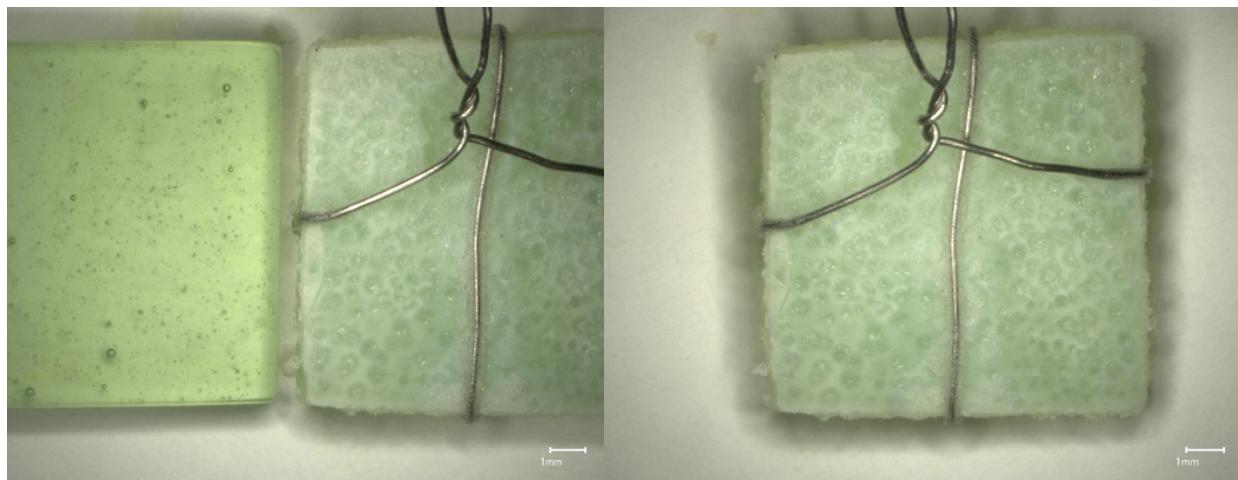


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT

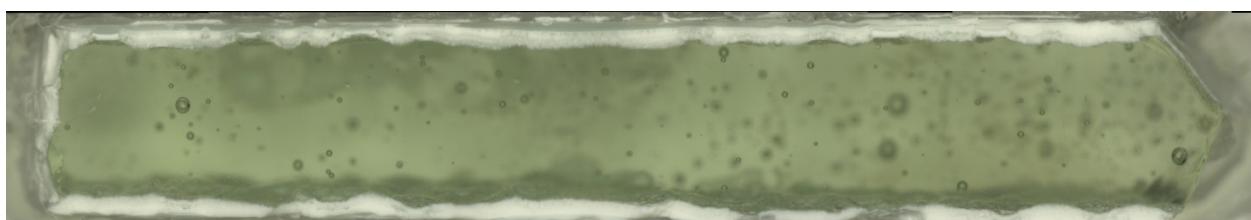


c) Glass cross section magnified after VHT

Figure I.27. Quenched Glass LP2-IL-16 after VHT for 24 Days

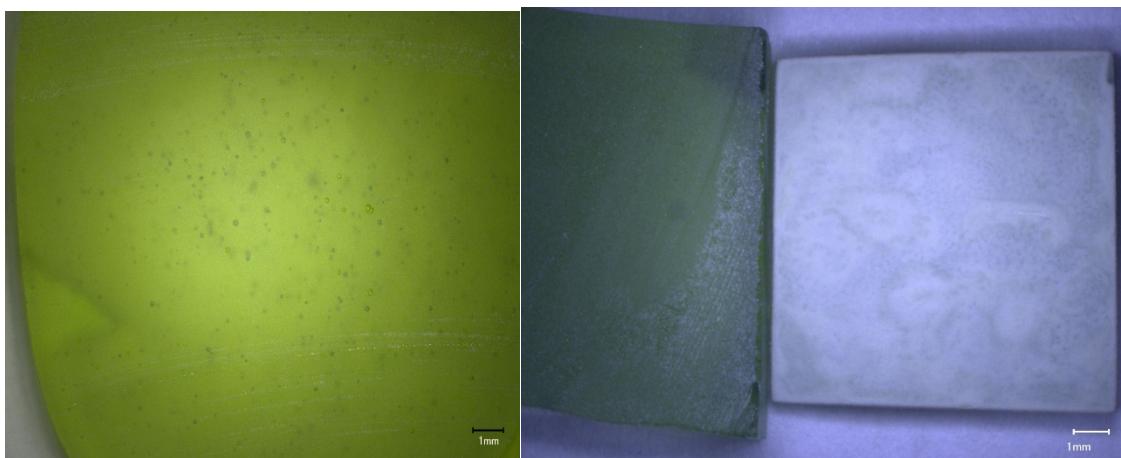


a) Glass square after (right) and before (left) VHT; b) Glass square after VHT

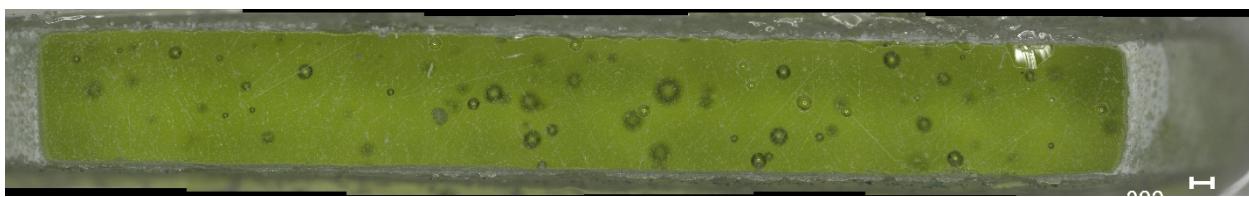


c) Glass cross section magnified after VHT

Figure I.28. Quenched Glass LP2-IL-17 after VHT for 7 Days

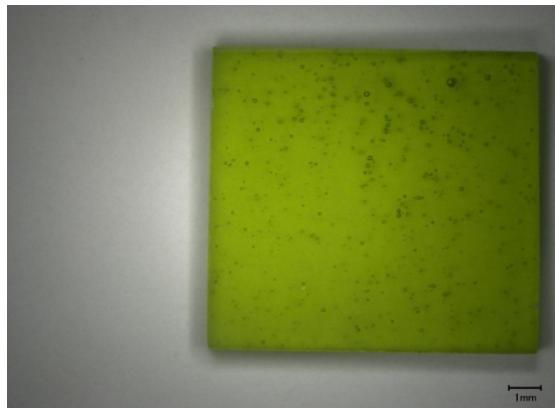


a) Glass square magnified 20X before VHT; b) Glass square after (right) and before (left) VHT

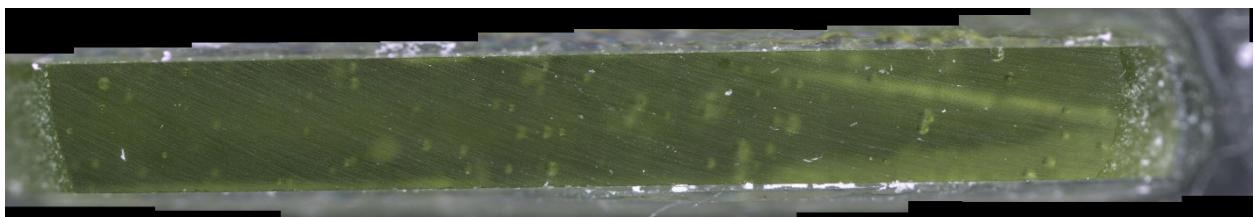


c) Glass cross section magnified after VHT

Figure I.29. Quenched Glass LP2-OL-01-3 after VHT for 11 Days

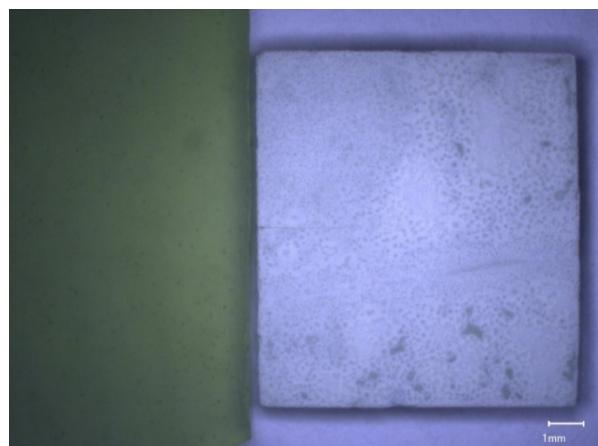


a) Glass square magnified 20X before VHT

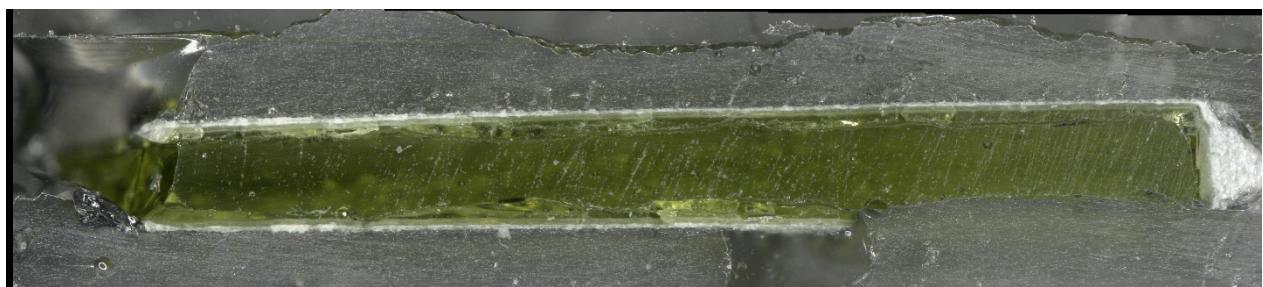


b) Glass cross section magnified after VHT

Figure I.30. Quenched Glass LP2-OL-01-3 after VHT for 24 Days

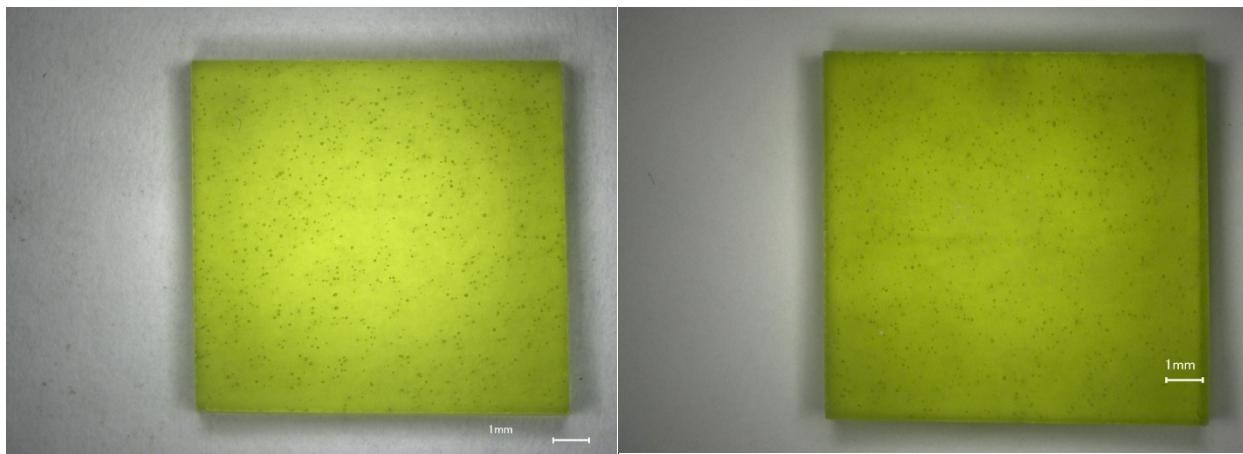


a) Glass square after (right) and before (left) VHT

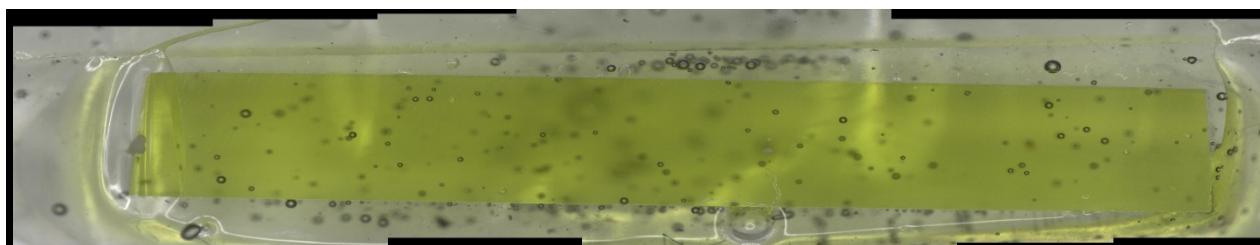


b) Glass cross section magnified after VHT

Figure I.31. Quenched Glass LP2-OL-02-1 after VHT for 11 Days

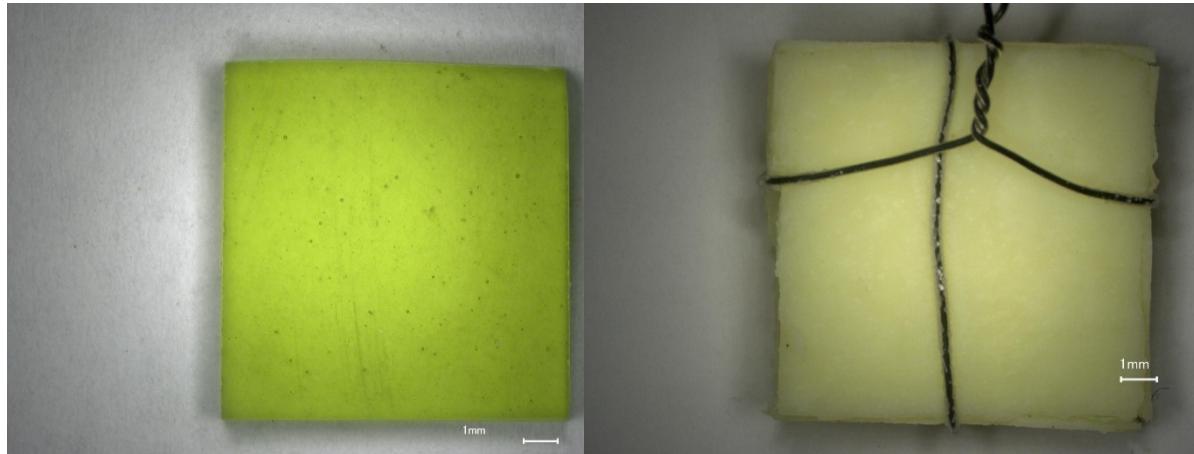


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT

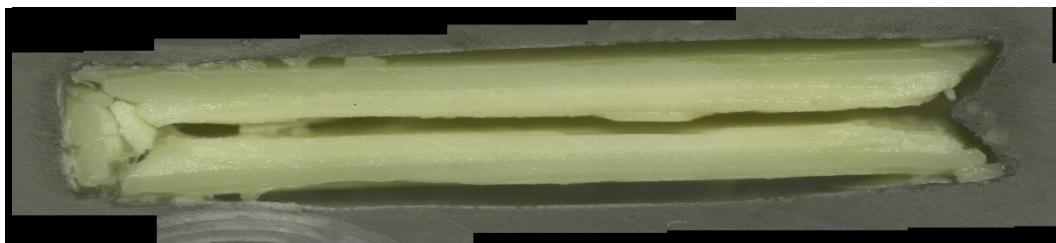


c) Glass cross section magnified after VHT

Figure I.32. Quenched Glass LP2-OL-02-1 after VHT for 24 Days

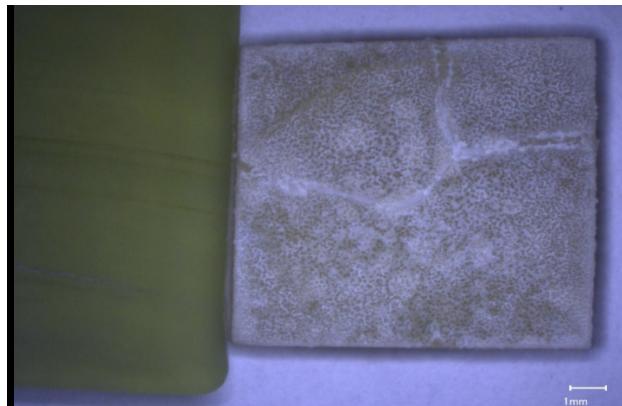


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.33. Quenched Glass LP2-OL-03 MOD2 after VHT for 24 Days

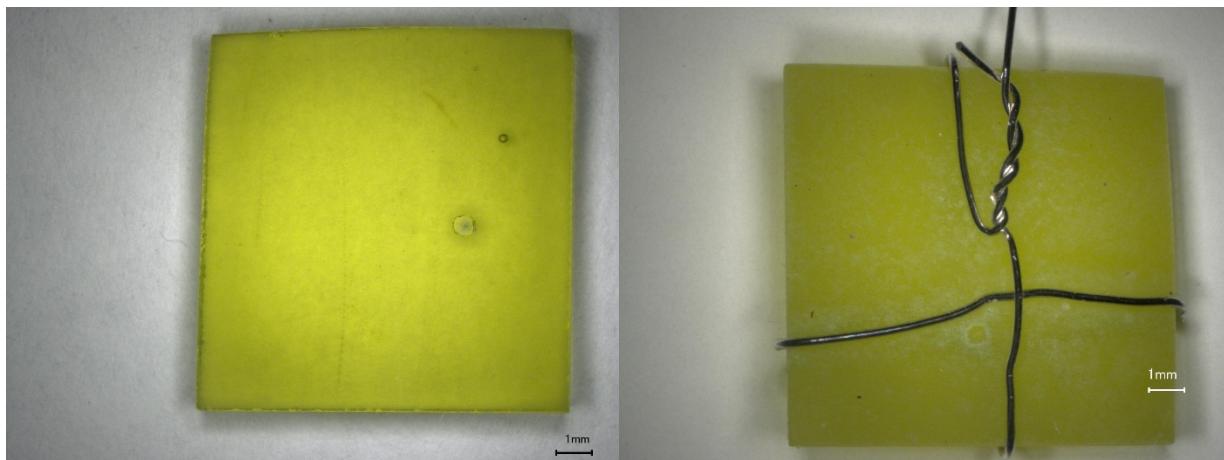


a) Glass square after (right) and before (left) VHT

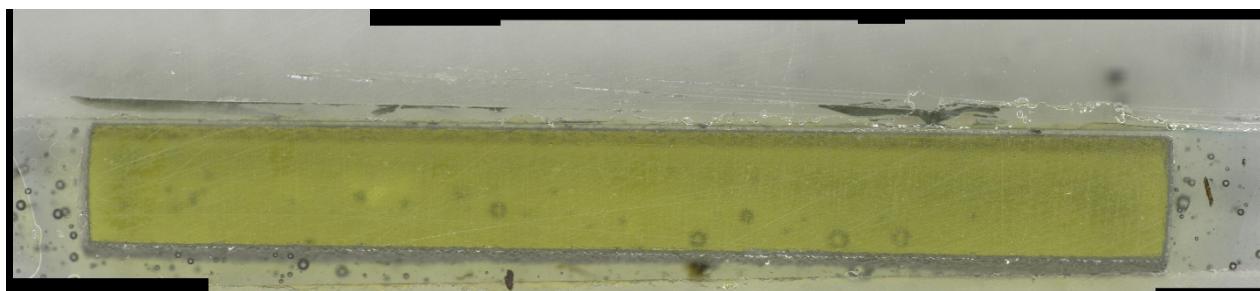


b) Glass cross section magnified after VHT

Figure I.34. Quenched Glass LP2-OL-04-1 after VHT for 11 Days



a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.35. Quenched Glass LP2-OL-04-1 after VHT for 24 Days

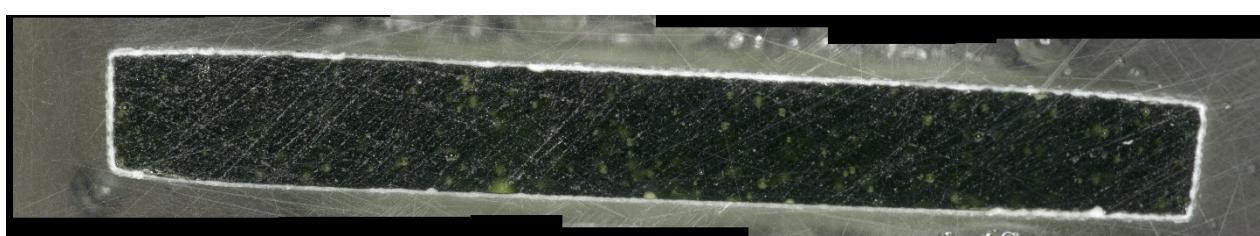
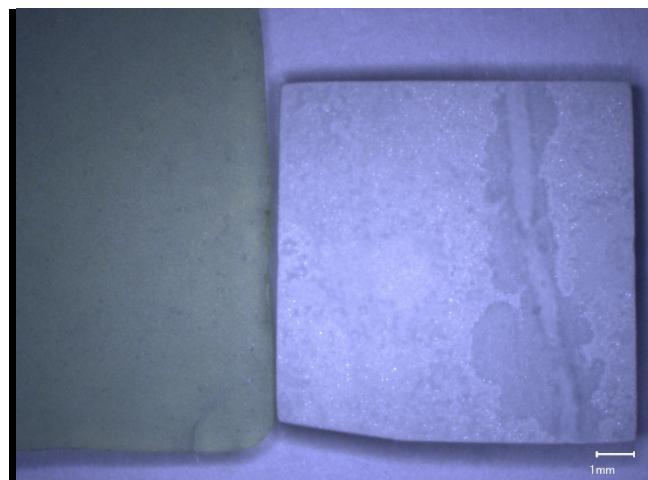


Figure I.36. Quenched Glass LP2-OL-05 after VHT for 11 Days

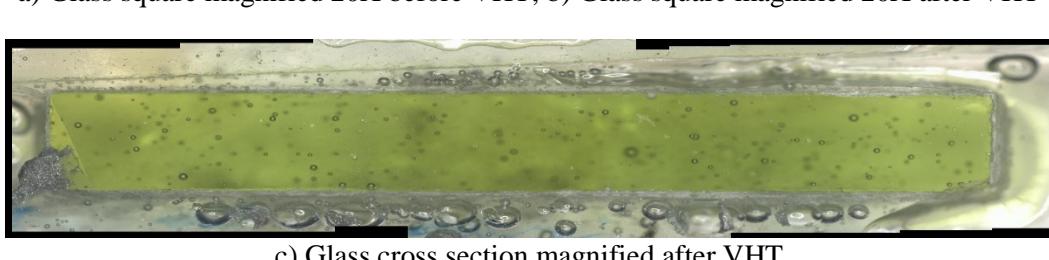


Figure I.37. Quenched Glass LP2-OL-05 after VHT for 24 Days

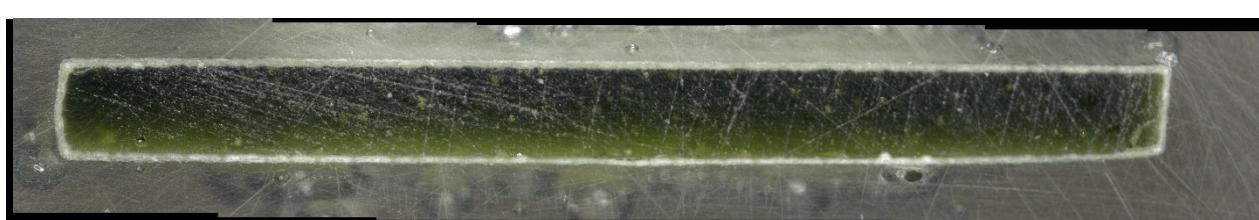
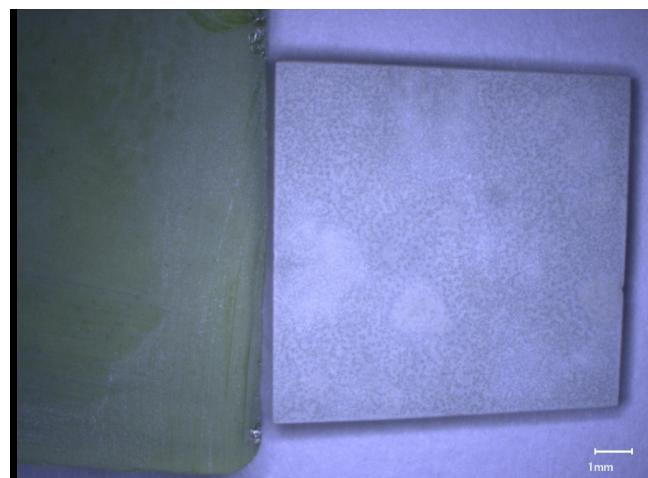


Figure I.38. Quenched Glass LP2-OL-07-1 after VHT for 11 Days

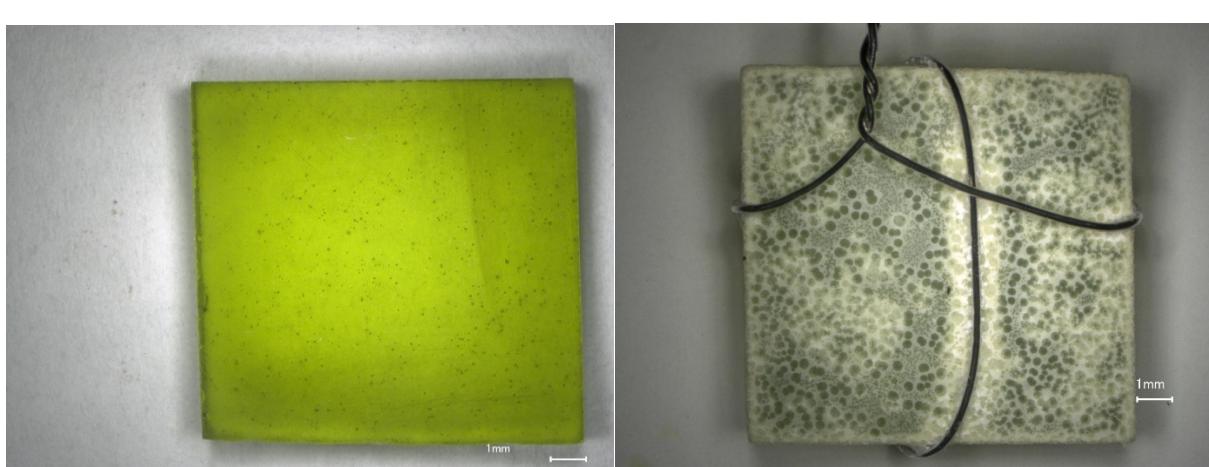
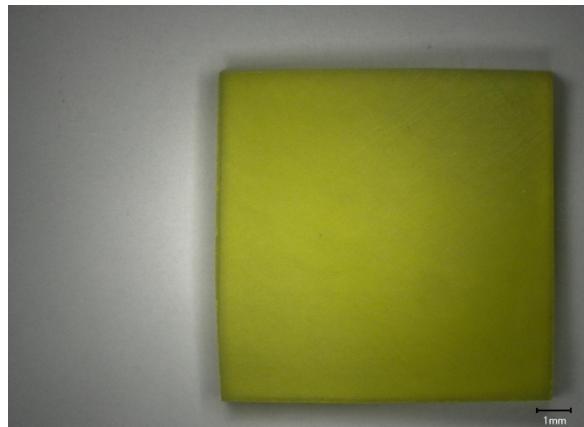
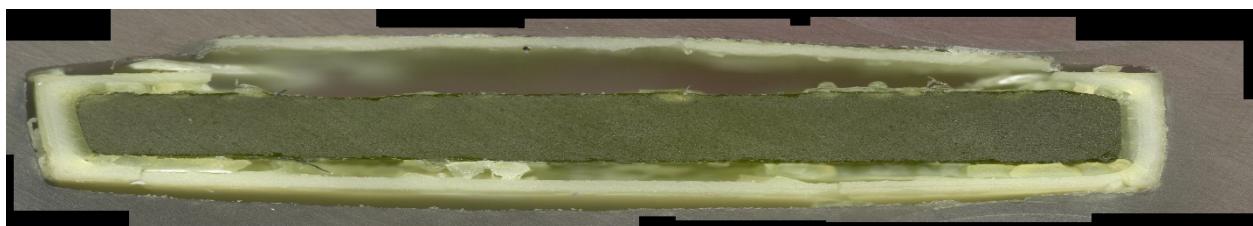


Figure I.39. Quenched Glass LP2-OL-07-1 after VHT for 24 Days

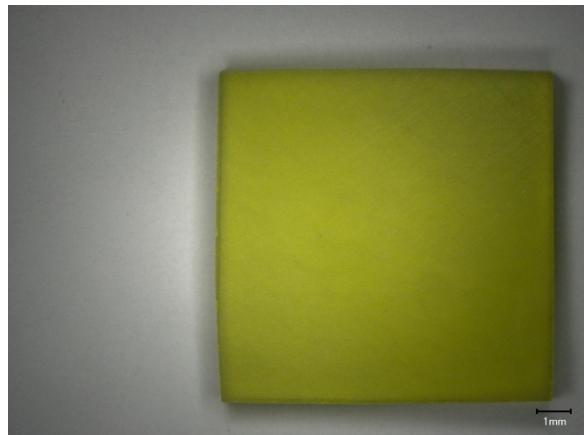


a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.40. Quenched Glass LP2-OL-08MOD after VHT for 7 Days

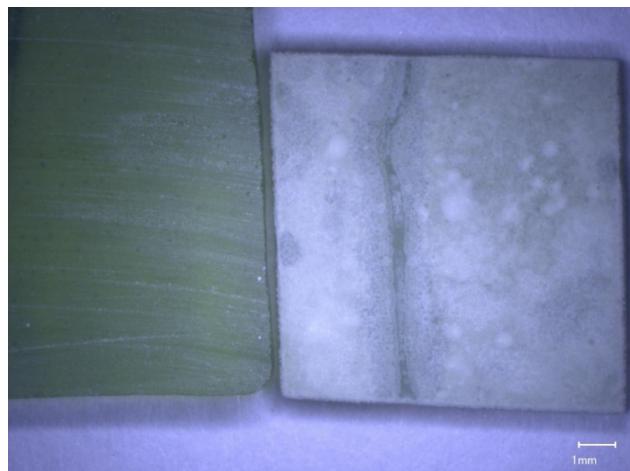


a) Glass square magnified 20X before VHT

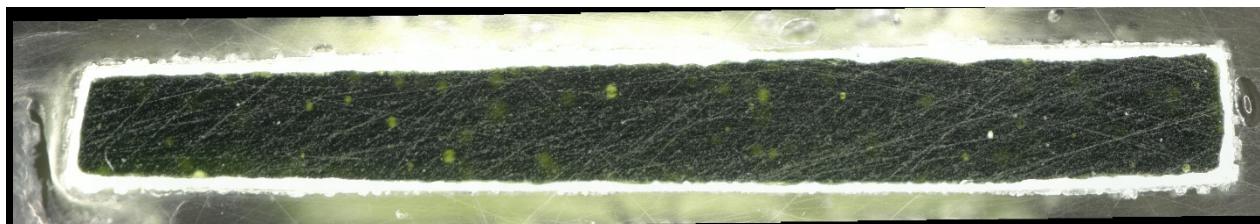


b) Glass cross section magnified after VHT

Figure I.41. Quenched Glass LP2-OL-08MOD after VHT for 24 Days

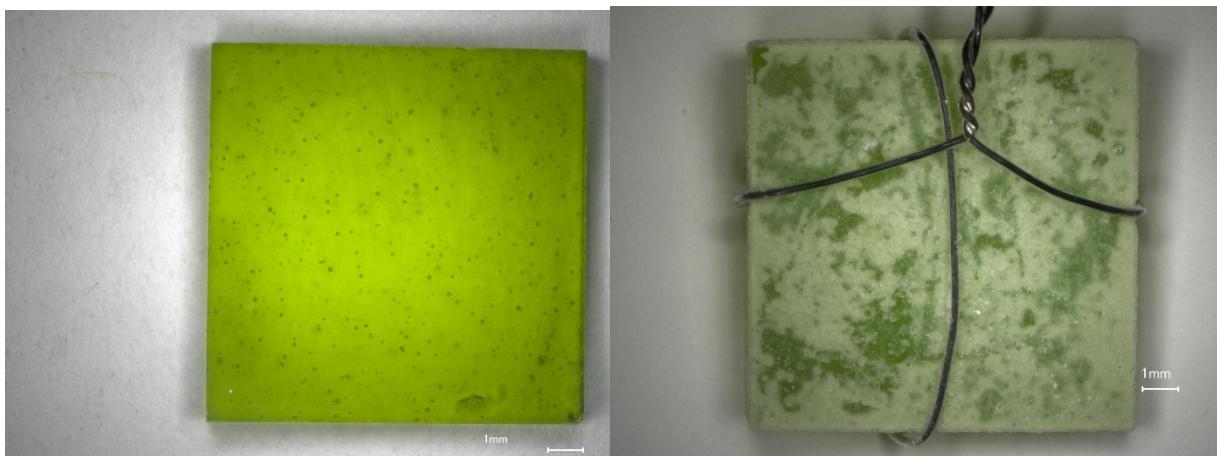


a) Glass square after (right) and before (left) VHT

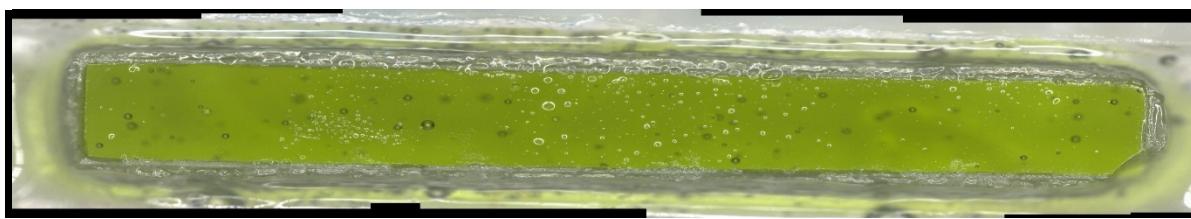


b) Glass cross section magnified after VHT

Figure I.42. Quenched Glass LP2-OL-09-1 after VHT for 11 Days



a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT

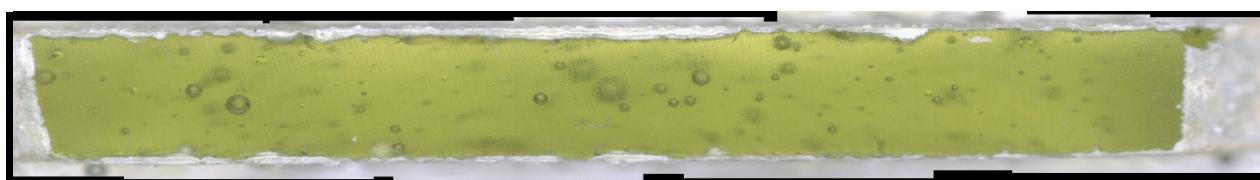


c) Glass cross section magnified after VHT

Figure I.43. Quenched Glass LP2-OL-09-1 after VHT for 24 Days

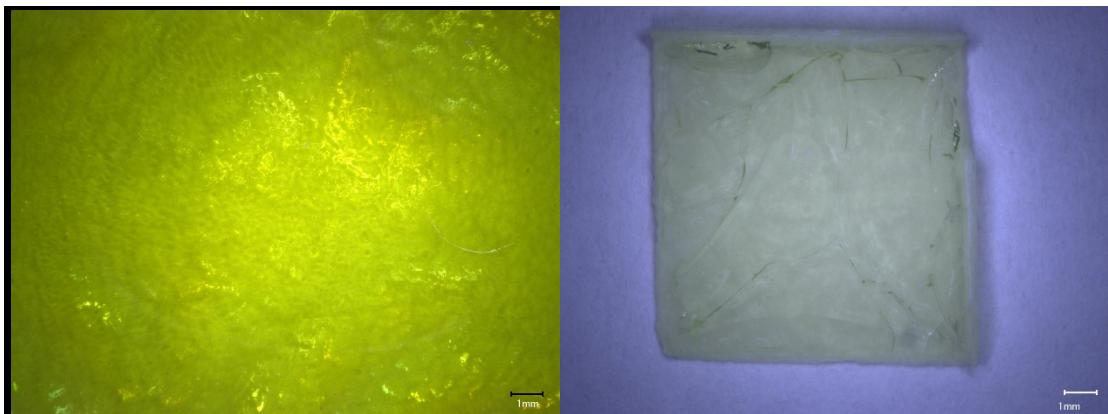


a) Glass square magnified 20X before VHT

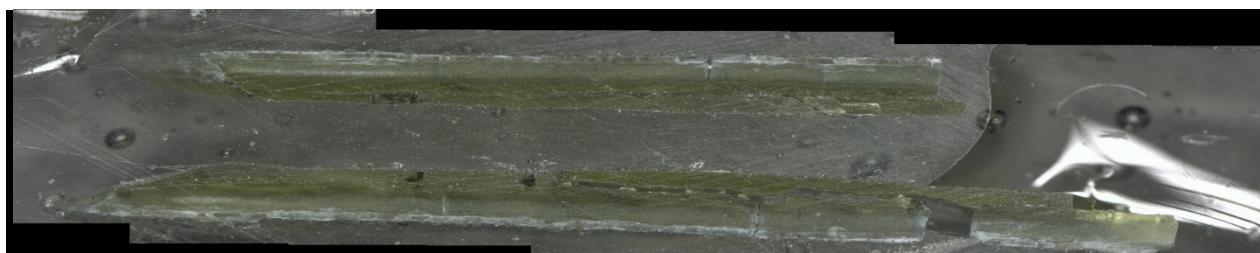


b) Glass cross section magnified after VHT

Figure I.44. Quenched Glass LP2-OL-10MOD after VHT for 24 Days

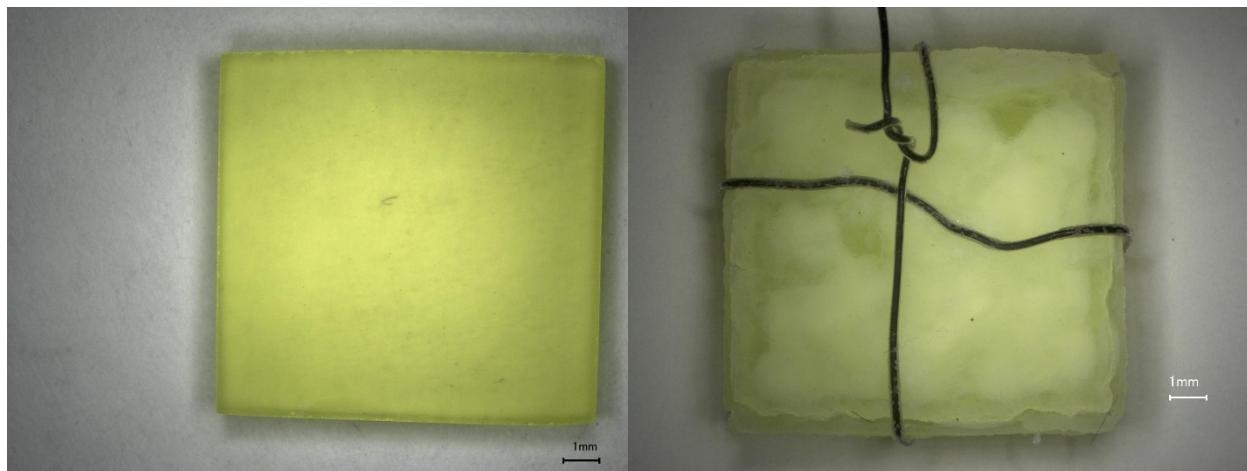


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

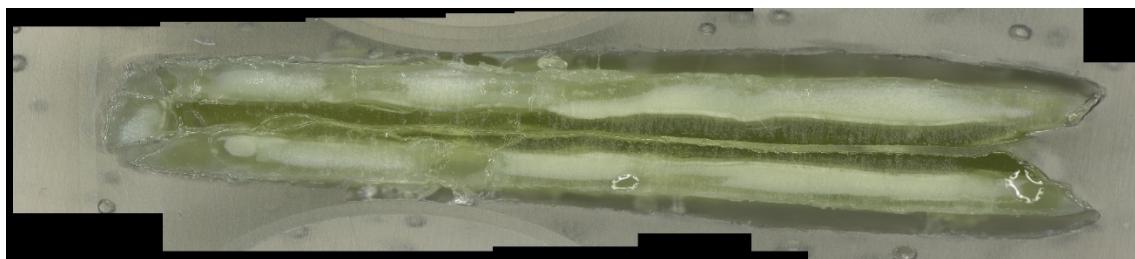


c) Glass cross section magnified after VHT

Figure I.45. Quenched Glass LP2-OL-11 after VHT for 11 Days

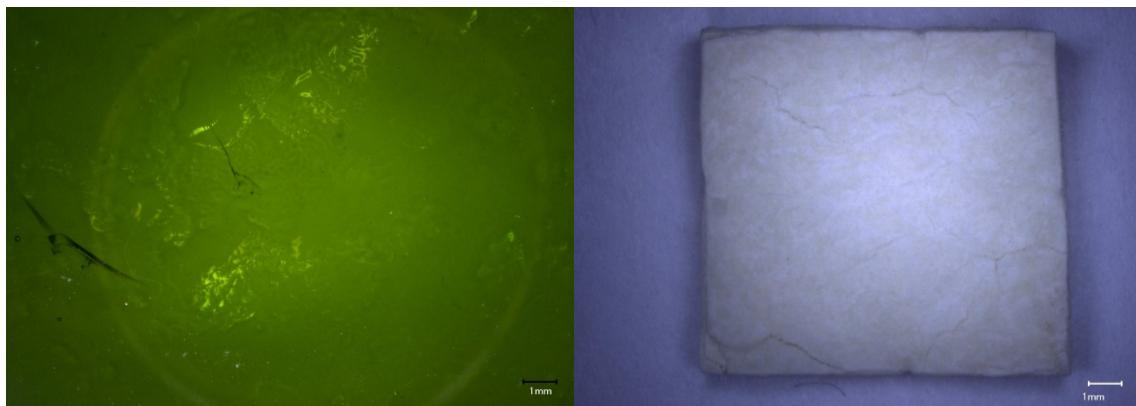


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.46. Quenched Glass LP2-OL-11 after VHT for 24 Days

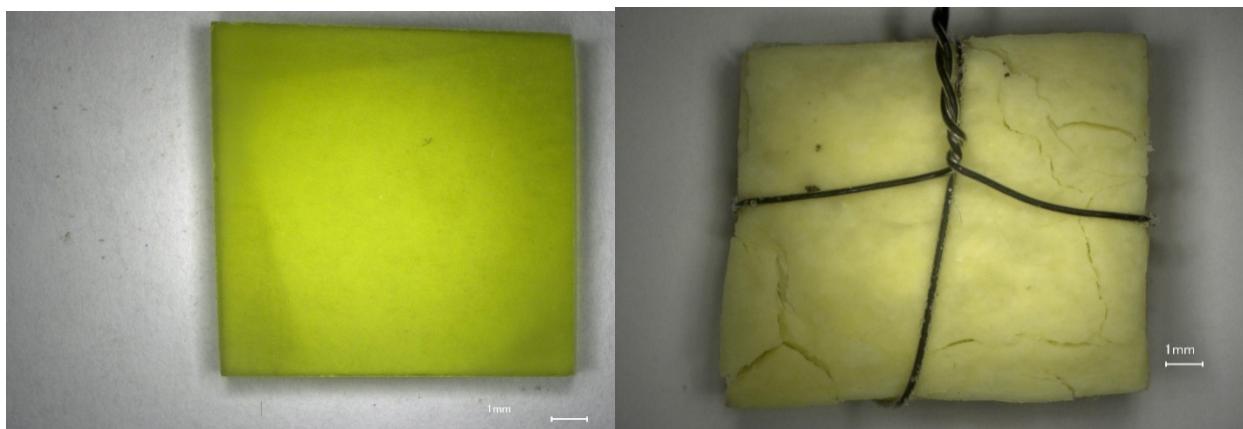


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.47. Quenched Glass LP2-OL-12 after VHT for 11 Days

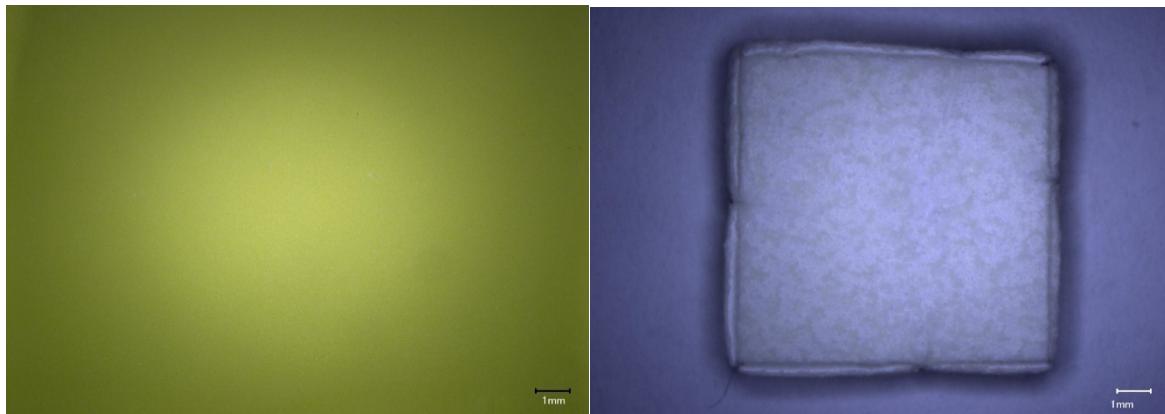


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.48. Quenched Glass LP2-OL-12 after VHT after 24 Days



a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT

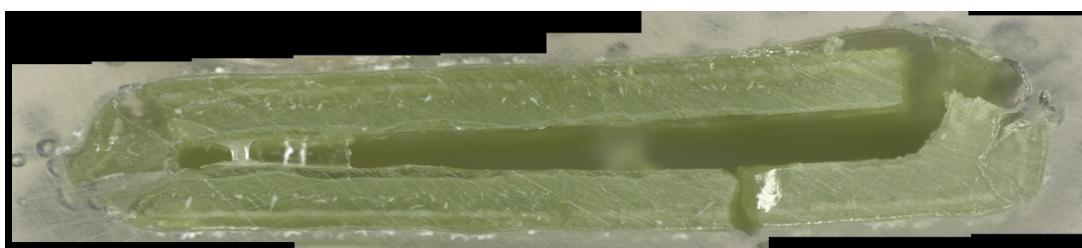


c) Glass cross section magnified after VHT

Figure I.49. Quenched Glass LP2-OL-13 after VHT after 11 Days

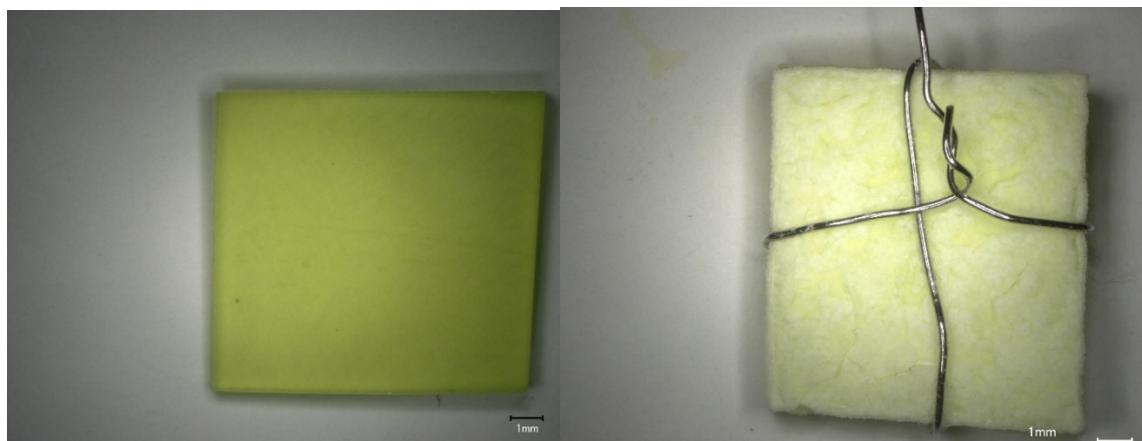


a) Glass square magnified 20X after VHT



b) Glass cross section magnified after VHT

Figure I.50. Quenched Glass LP2-OL-13 after VHT after 24 Days

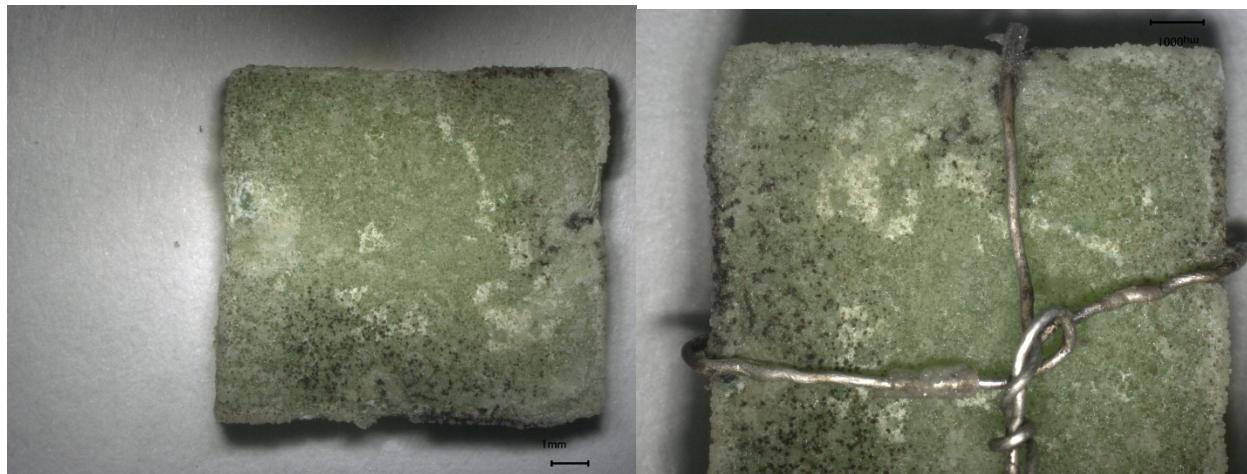


a) Glass square magnified 20X after VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.51. Quenched Glass LP2-OL-14 after VHT after 7 Days

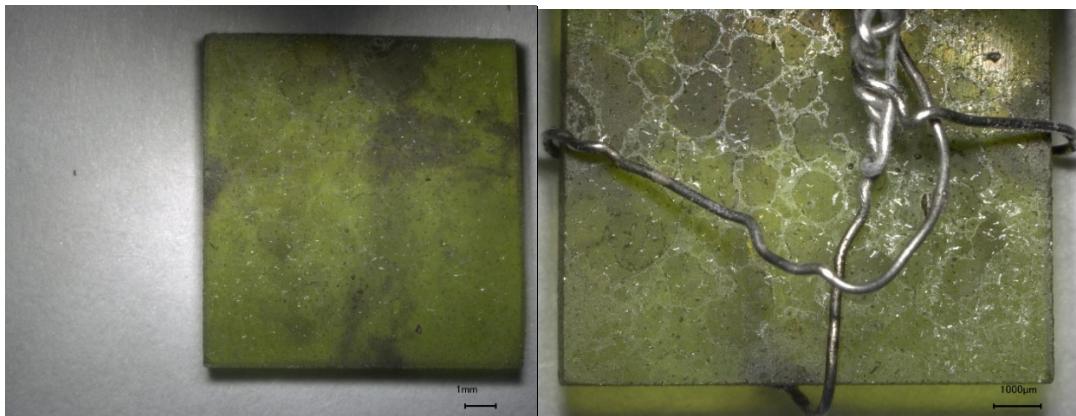


a) Glass square magnified 20X after VHT; b) Glass surface magnified 30X after VHT

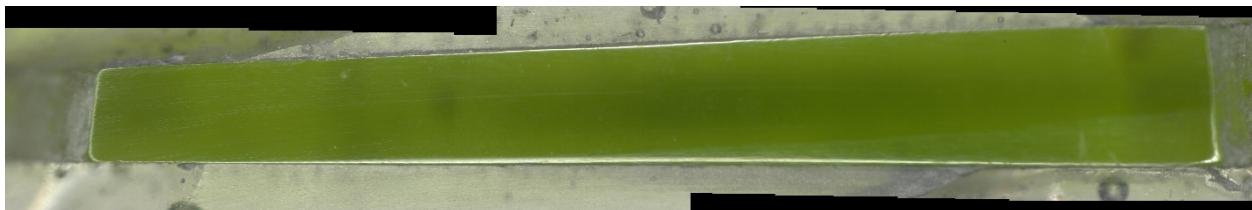


c) Glass cross section magnified after VHT

Figure I.52. Quenched Glass LP2-OL-14 after VHT after 24 Days

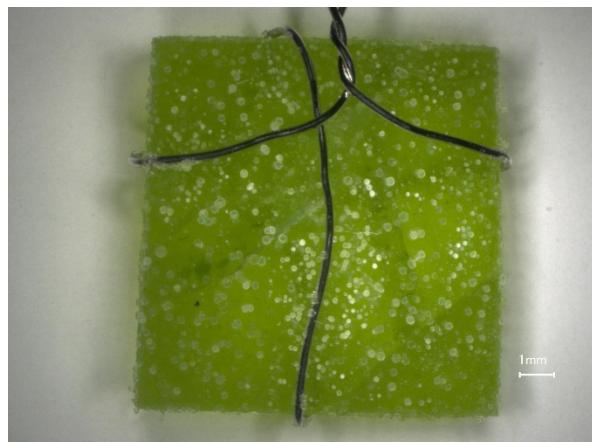


a) Glass square magnified 20X after VHT; b) Glass surface magnified 30X after VHT



c) Glass cross section magnified after VHT

Figure I.53. Quenched Glass LP2-OL-15 after VHT for 24 Days

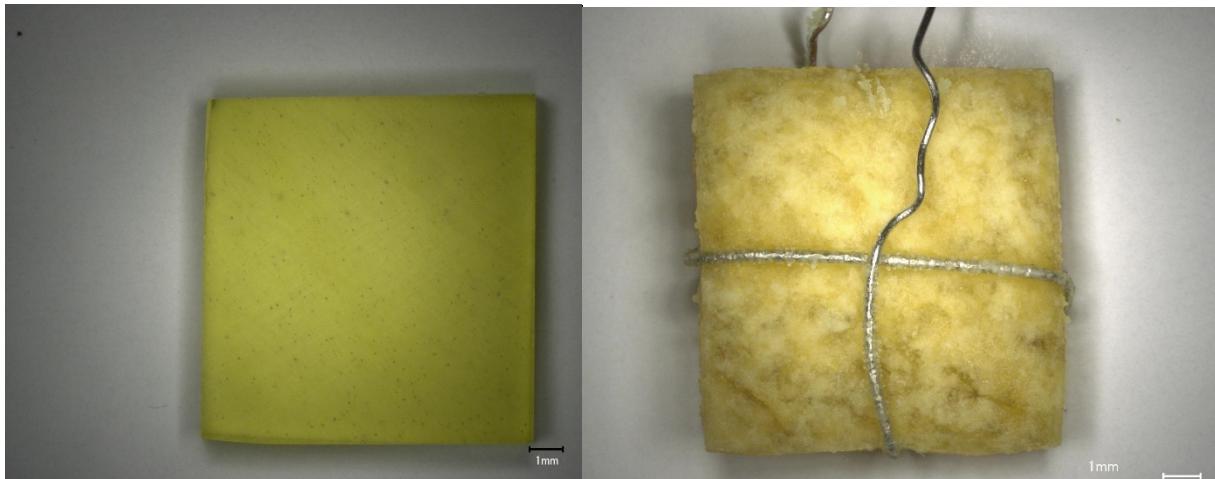


a) Glass surface magnified 20X after VHT



b) Glass cross section magnified after VHT

Figure I.54. Quenched Glass LP2-OL-16MOD after VHT for 24 Days

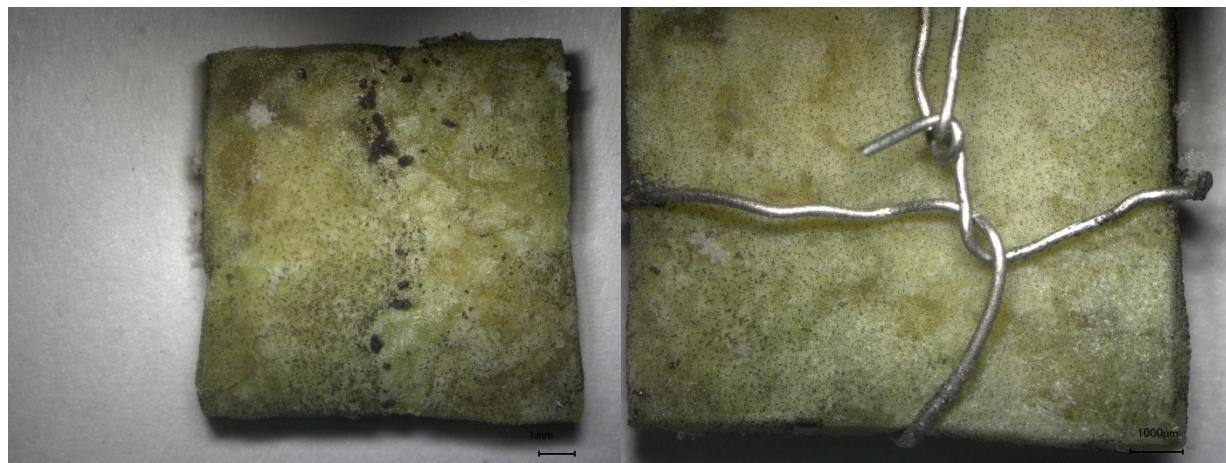


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.55. Quenched Glass LP2-OL-17 after VHT for 7 Days

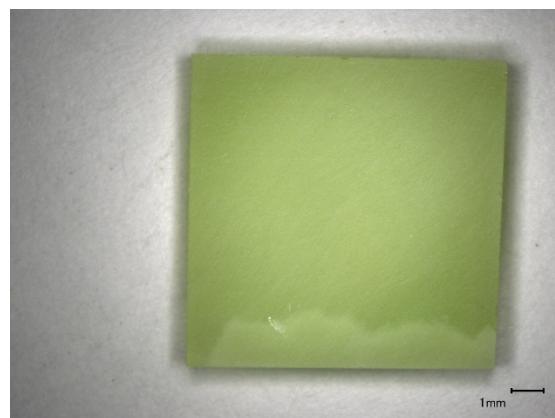


a) Glass square magnified 20X after VHT; b) Glass surface magnified 30X after VHT

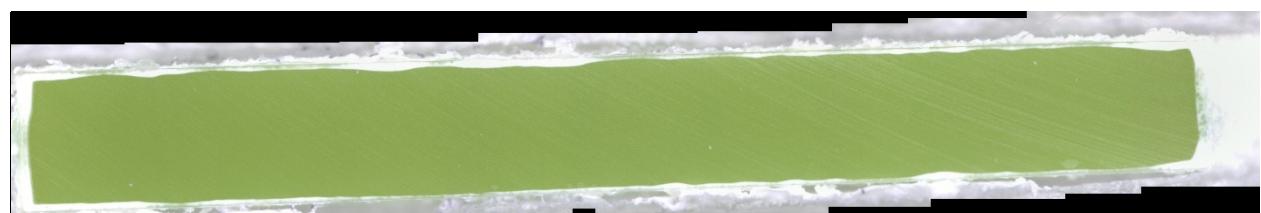


c) Glass cross section magnified after VHT

Figure I.56. Quenched Glass LP2-OL-17 after VHT for 24 Days

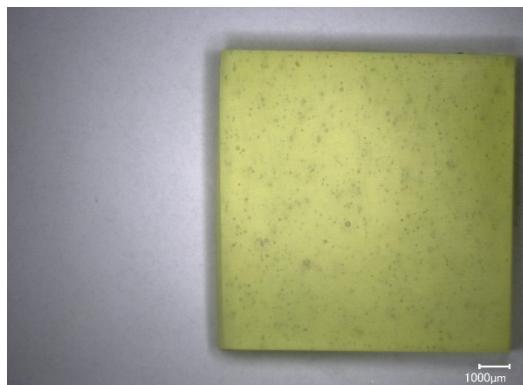


a) Glass square magnified 20X before VHT

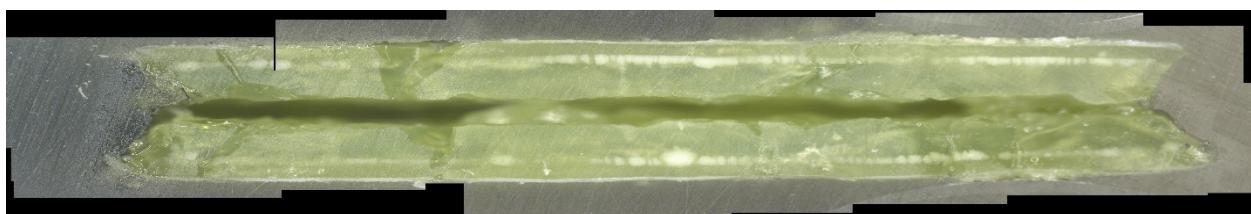


b) Glass cross section magnified after VHT

Figure I.57. Quenched Glass LP2-OL-18 after VHT for 24 Days

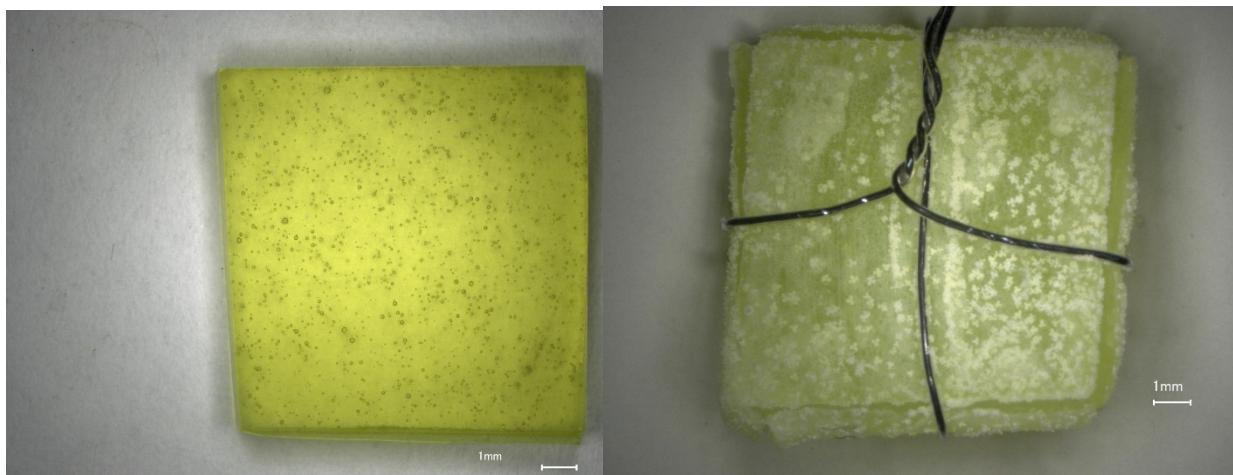


a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.58. Quenched Glass LP2-OL-19 after VHT for 7 Days

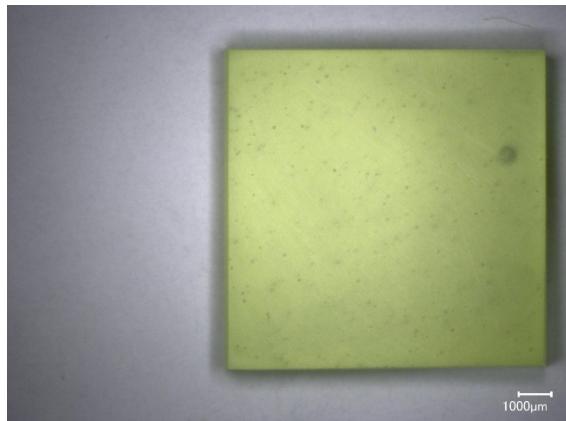


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

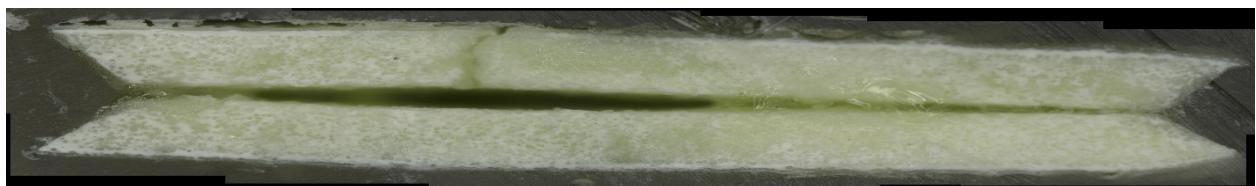


c) Glass cross section magnified after VHT

Figure I.59. Quenched Glass LP2-OL-19 after VHT for 24 Days

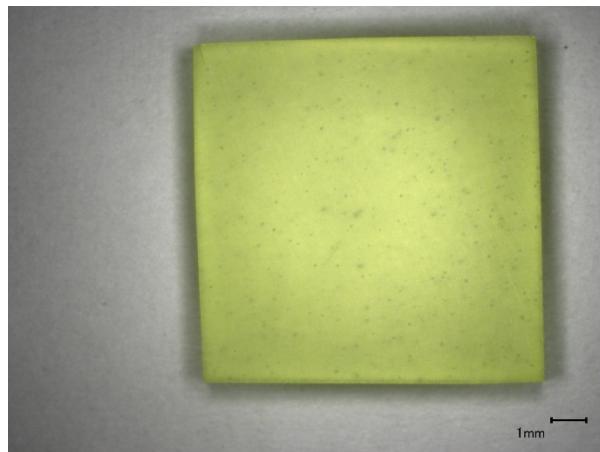


a) Glass square magnified 20X before VHT

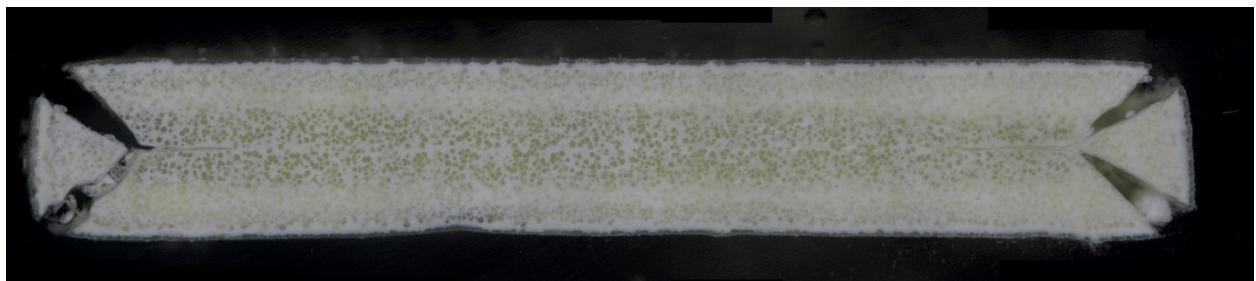


b) Glass cross section magnified after VHT

Figure I.60. Quenched Glass LP2-OL-20 after VHT for 7 Days

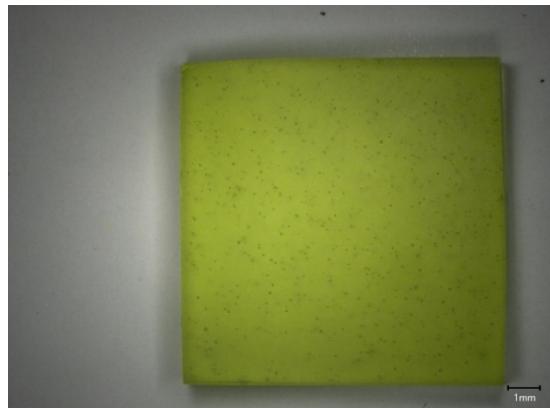


a) Glass square magnified 20X before VHT

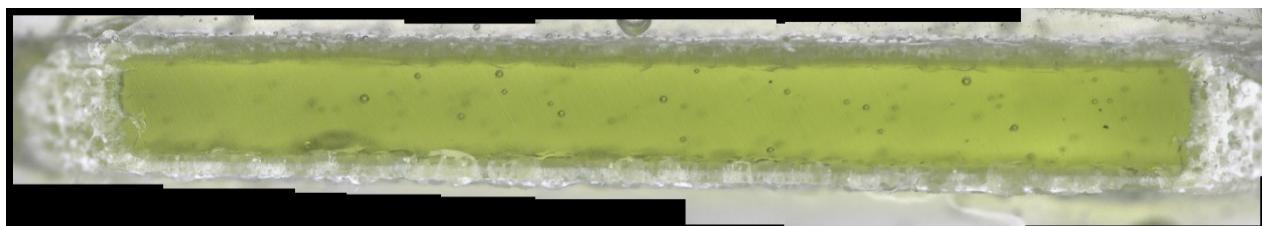


b) Glass cross section magnified after VHT

Figure I.61. Quenched Glass LP2-OL-20 after VHT for 24 Days

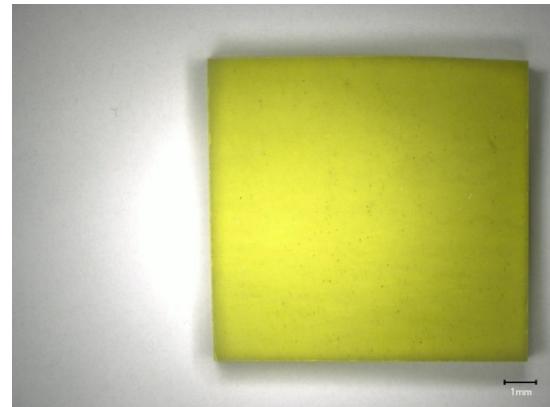


a) Glass square magnified 20X before VHT

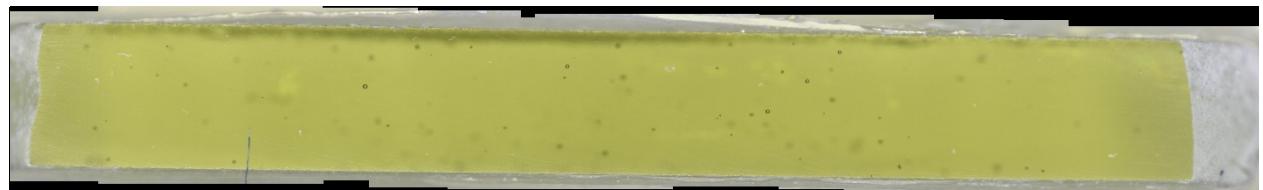


b) Glass cross section magnified after VHT

Figure I.62. Quenched Glass LP2-OL-21 after VHT for 24 Days

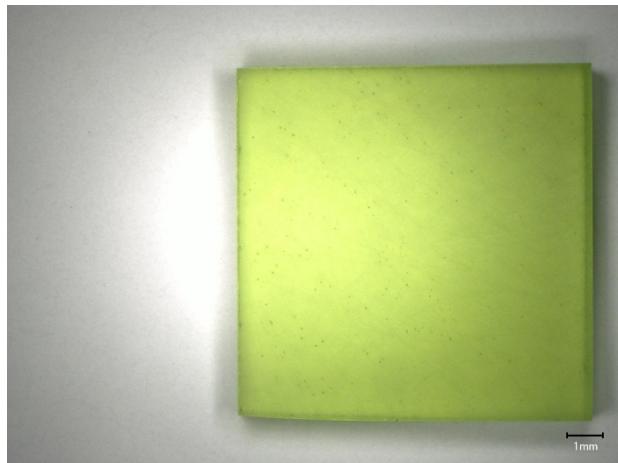


a) Glass square magnified 20X before VHT

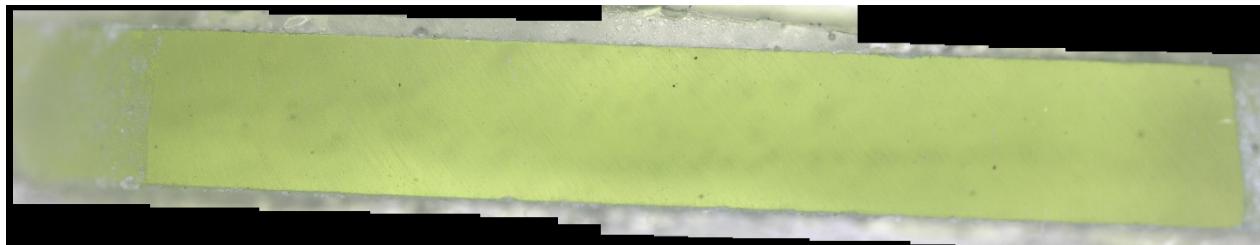


b) Glass cross section magnified after VHT

Figure I.63. Quenched Glass LP2-OL-22 after VHT for 24 Days

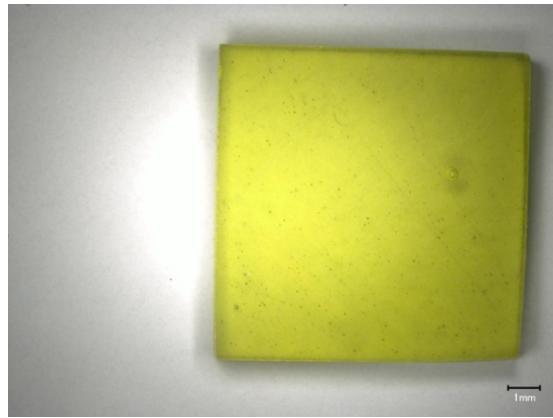


a) Glass square magnified 20X before VHT

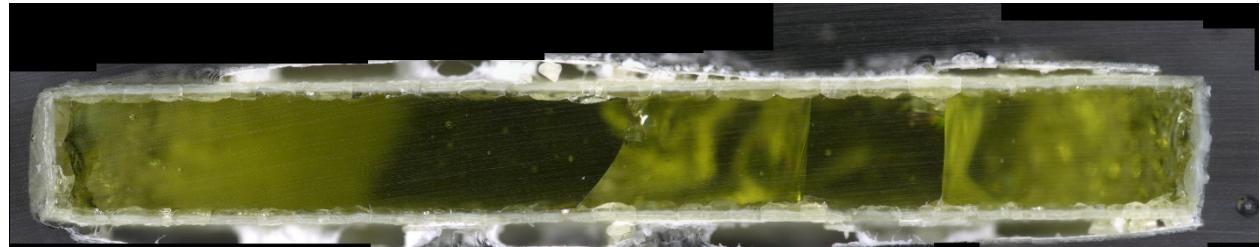


b) Glass cross section magnified after VHT

Figure I.64. Quenched Glass LP2-OL-23 after VHT for 24 Days

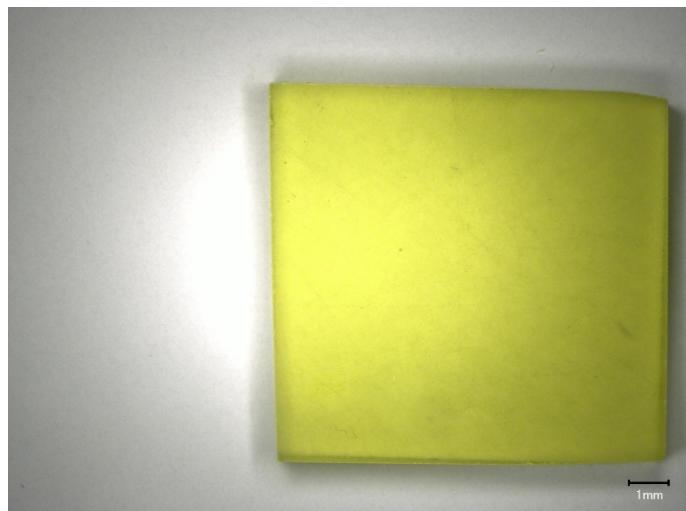


a) Glass square magnified 20X before VHT

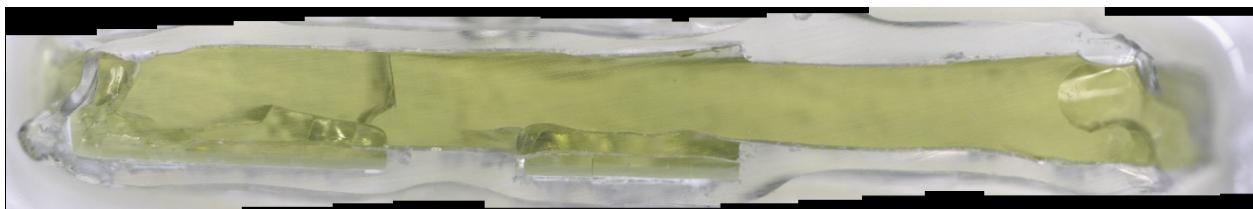


b) Glass cross section magnified after VHT

Figure I.65. Quenched Glass LP2-OL-24 after VHT for 24 Days

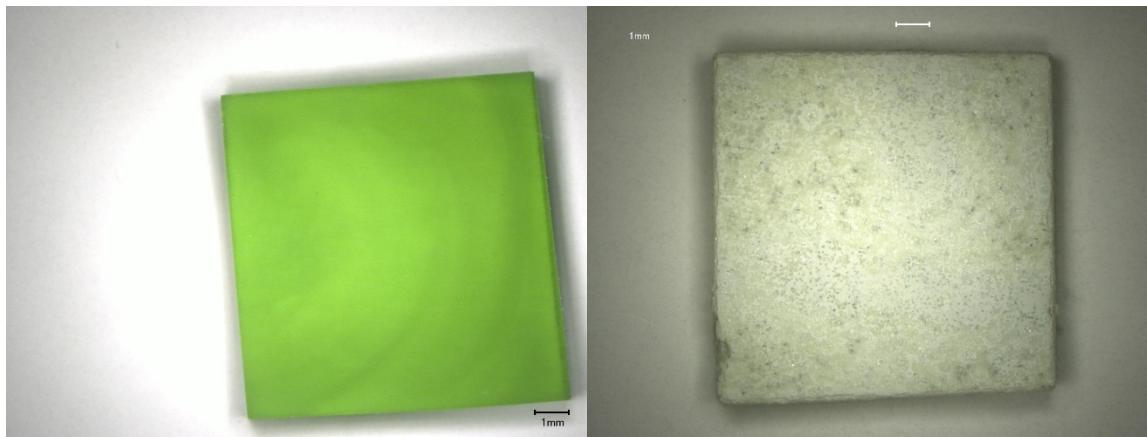


a) Glass square magnified 20X before VHT

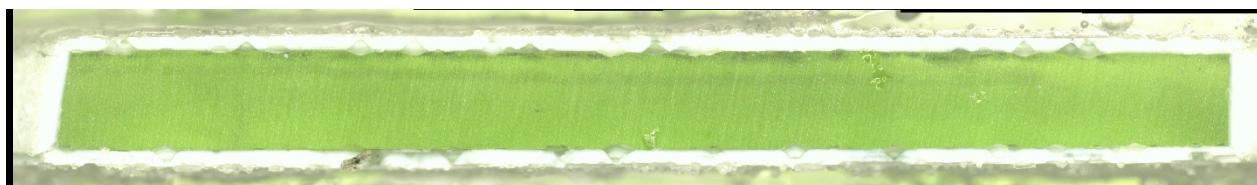


b) Glass cross section magnified after VHT

Figure I.66. Quenched Glass LP2-OL-25 after VHT for 24 Days



a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.67. ~~CCC~~-Treated Glass LP2-IL-01 after VHT for 7 Days

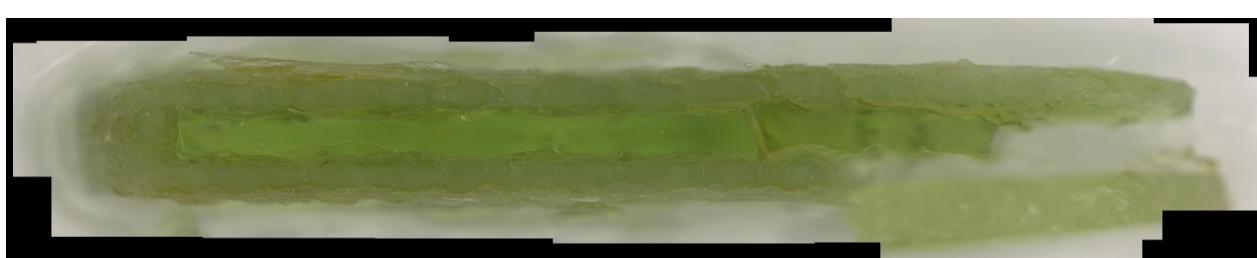
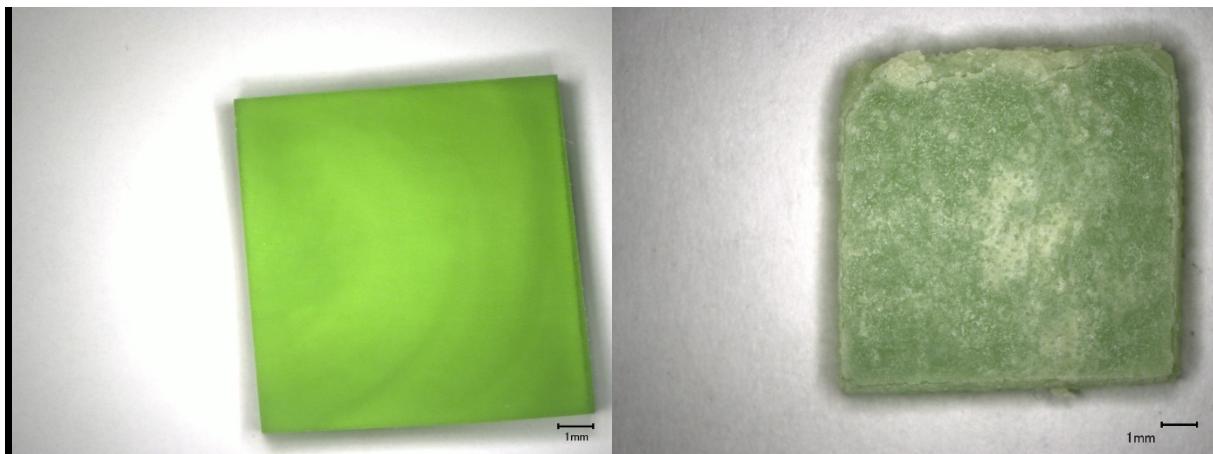


Figure I.68. ~~CCC-CCC~~-Treated Glass LP2-IL-01 after VHT for 24 Days

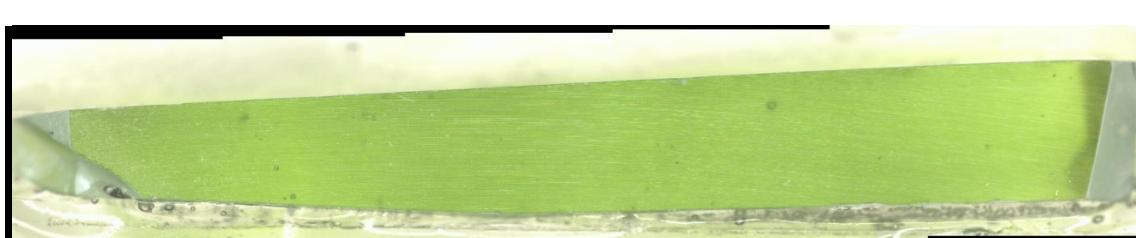
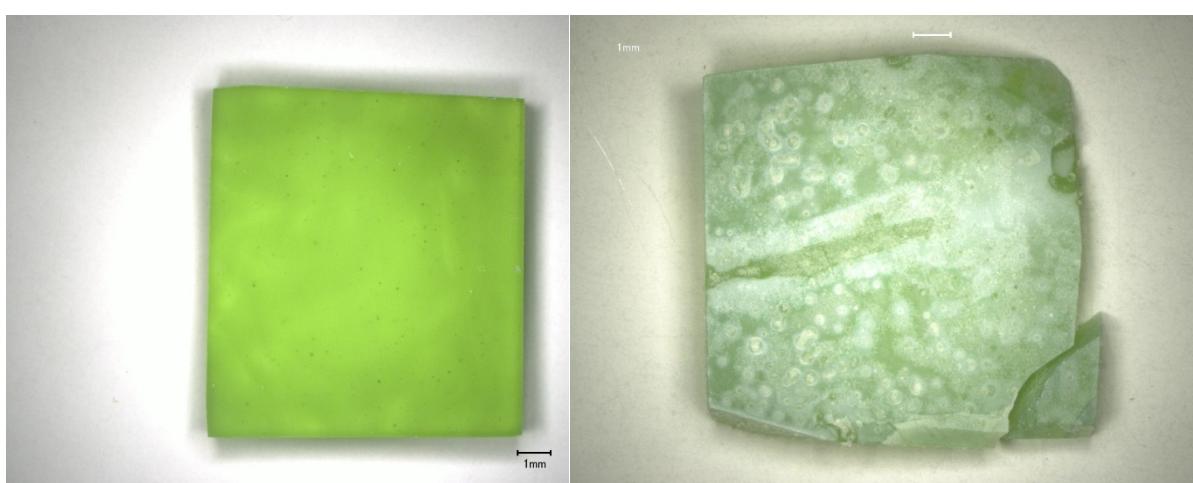
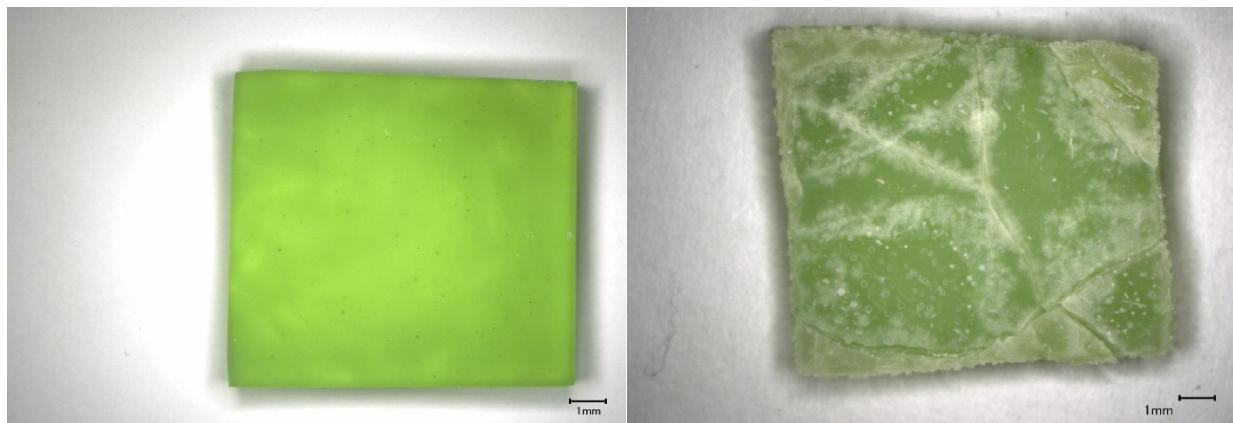
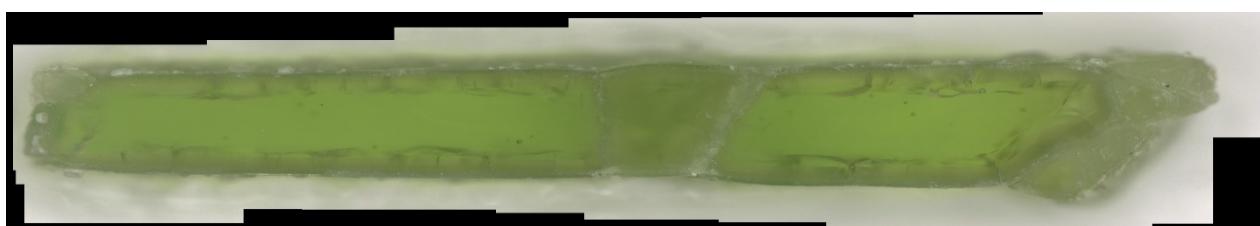


Figure I.69. ~~CCC-CCC~~-Treated Glass LP2-IL-02 after VHT for 7 Days

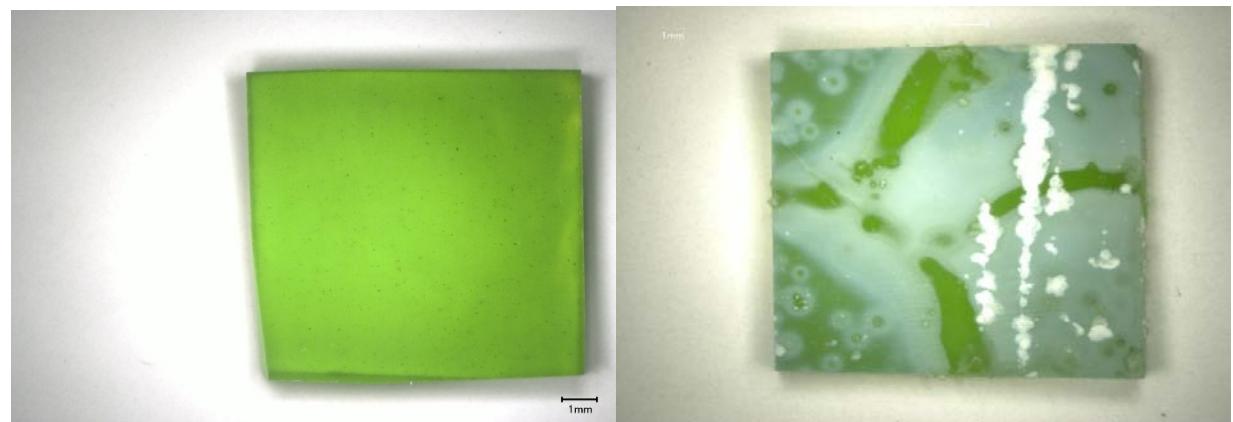


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

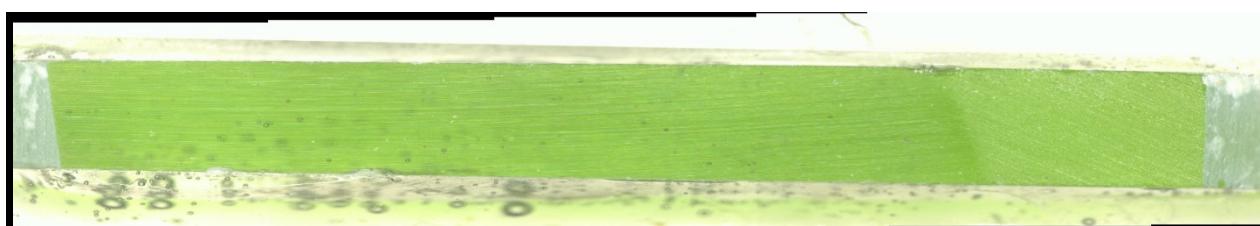


c) Glass cross section magnified after VHT

Figure I.70. ~~CCC-CCC~~-Treated Glass LP2-IL-02 after VHT for 24 Days

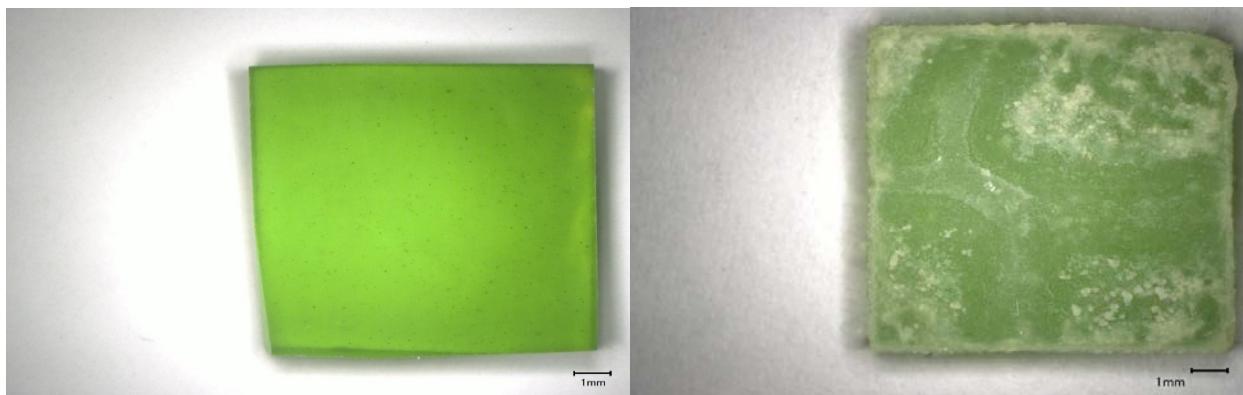


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

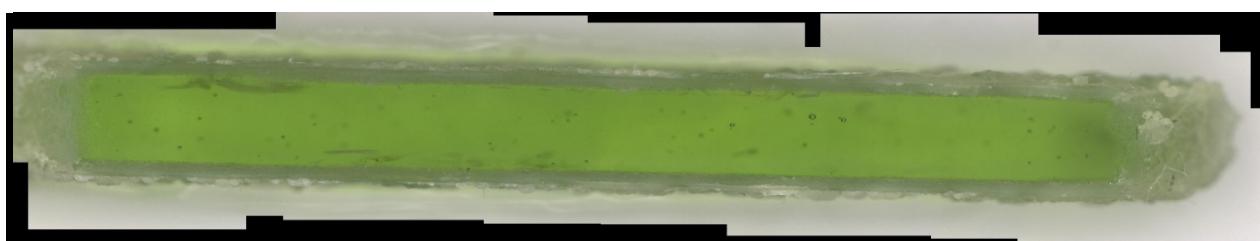


c) Glass cross section magnified after VHT

Figure I.71. ~~CCC-CCC~~-Treated Glass LP2-IL-03 after VHT for 7 Days

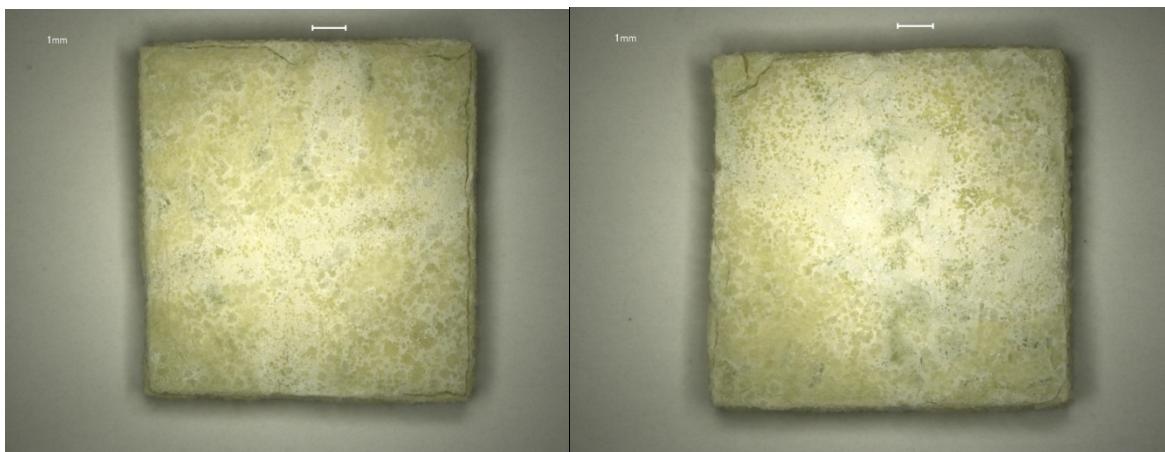


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.72. ~~CCC-CCC~~-Treated Glass LP2-IL-03 after VHT for 24 Days

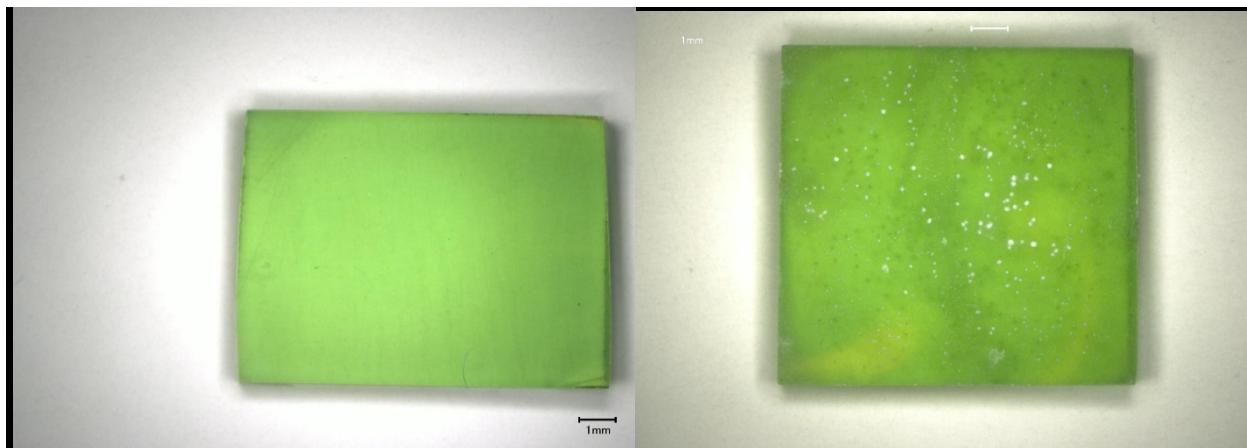


a) Glass square magnified after VHT; b) Glass square magnified after VHT

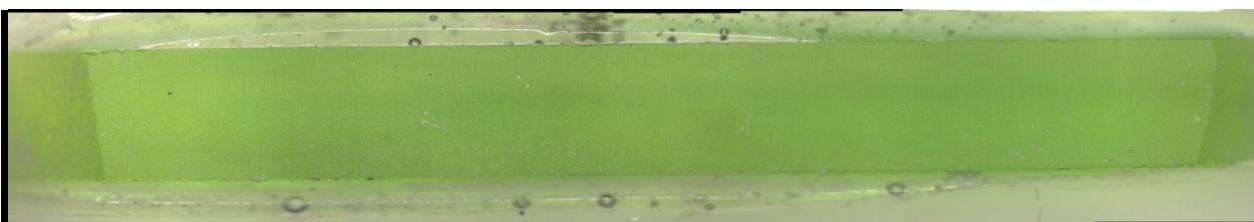


c) Glass cross section magnified after VHT

Figure I.73. ~~CCC-CCC~~-Treated Glass LP2-IL-04 after VHT for 7 Days

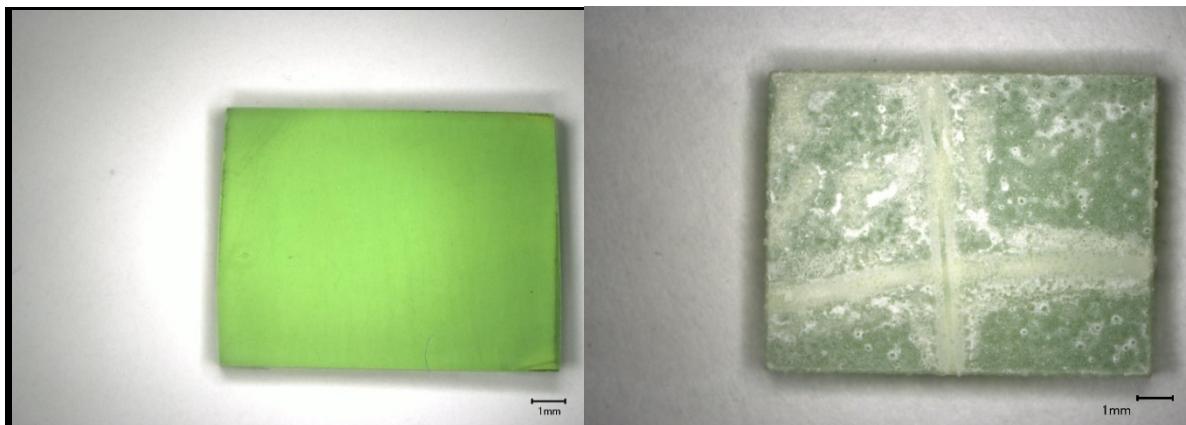


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

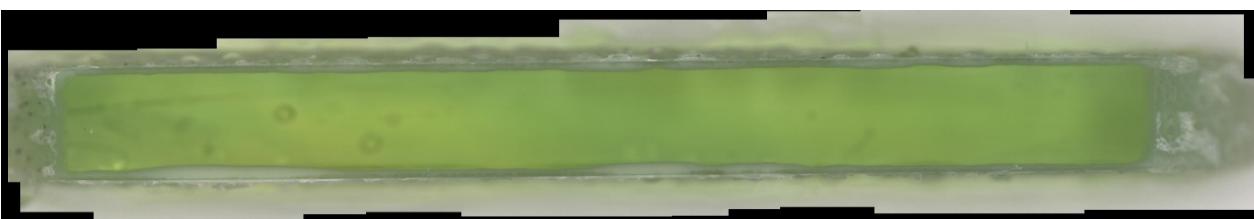


c) Glass cross section magnified after VHT

Figure I.74. ~~CCC-CCC~~-Treated Glass LP2-IL-05 after VHT for 7 Days

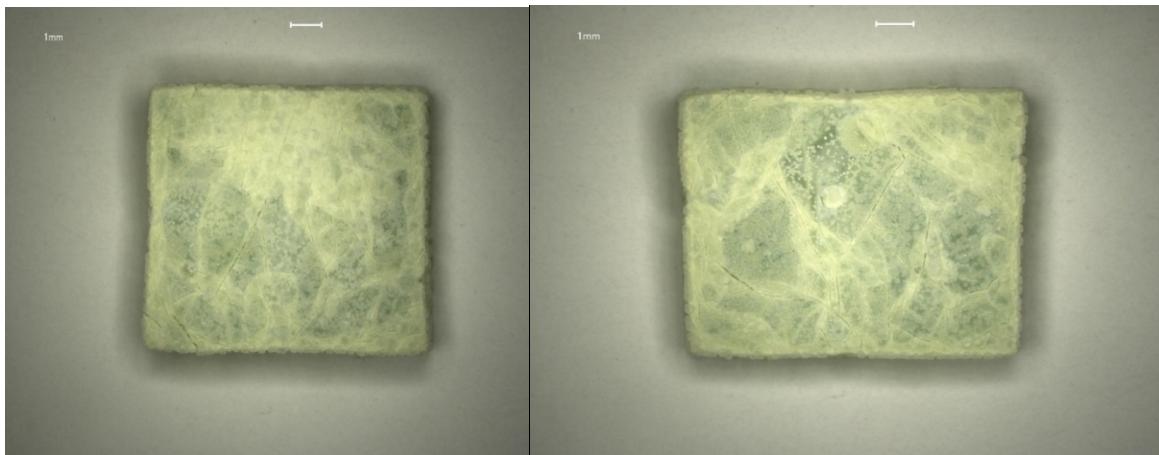


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

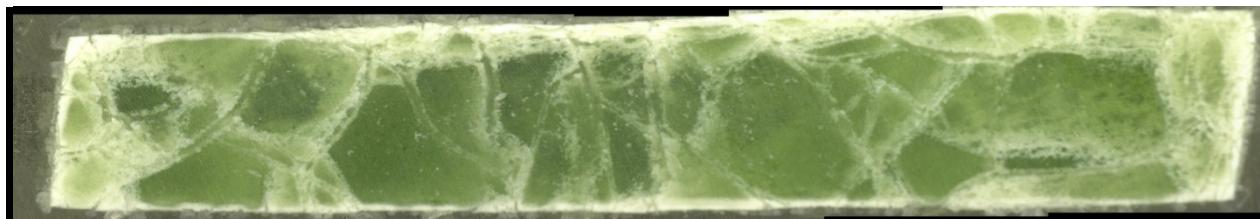


c) Glass cross section magnified after VHT

Figure I.75. ~~CCC-CCC~~-Treated Glass LP2-IL-05 after VHT for 24 Days



a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.76. ~~CCC-CCC~~-Treated Glass LP2-IL-06 after VHT for 7 Days

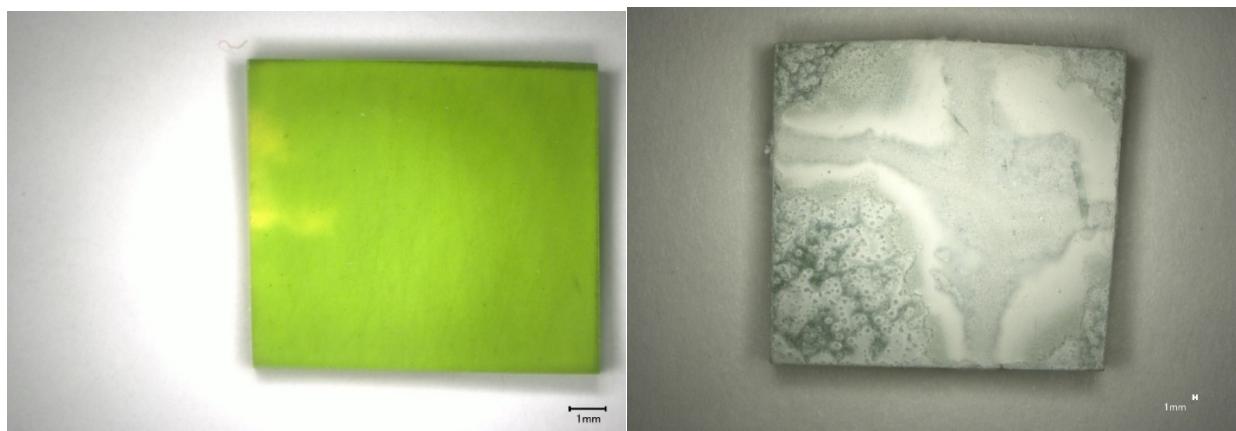


a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

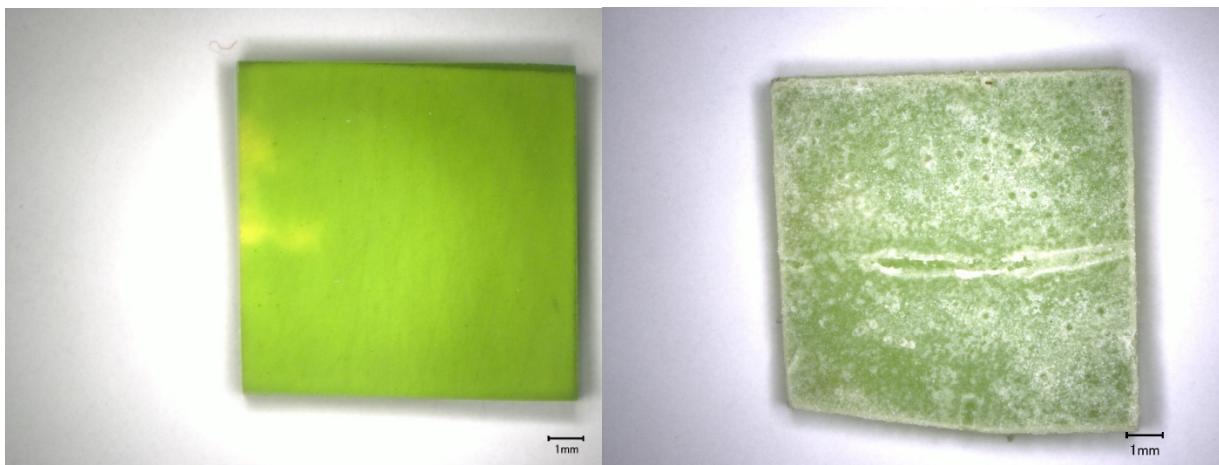
Figure I.77. ~~CCC-CCC~~-Treated Glass LP2-IL-07 after VHT for 7 Days



a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

c) Glass cross section magnified after VHT

Figure I.78. ~~CCC-CCC~~-Treated Glass LP2-IL-08 after VHT for 7 Days



a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

c) Glass cross section magnified after VHT

Figure I.79. ~~CCC-CCC~~-Treated Glass LP2-IL-08 after VHT for 24 Days

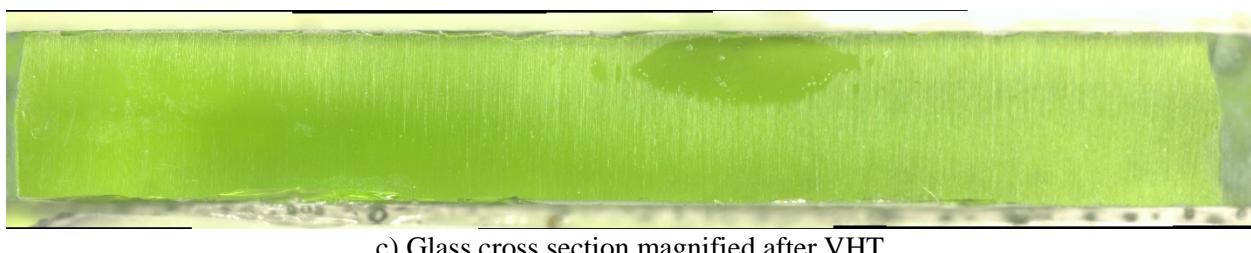
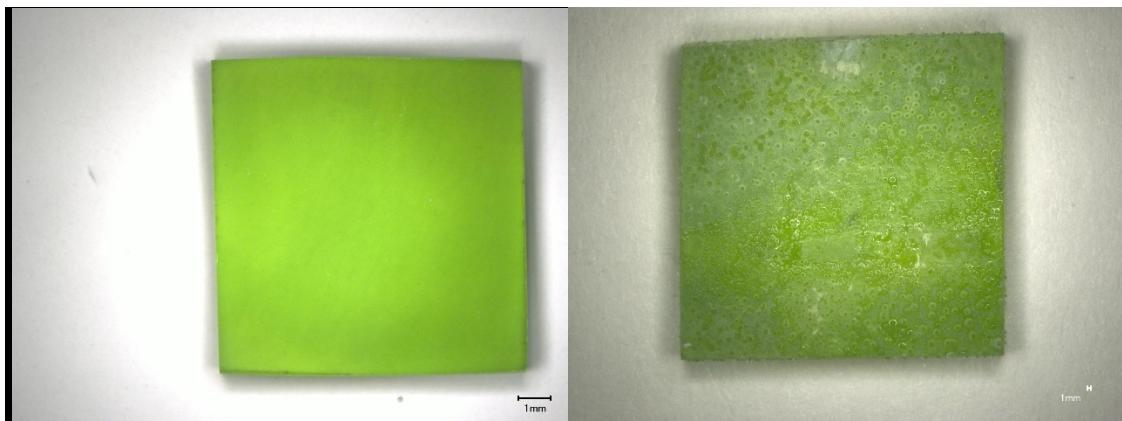


Figure I.80. ~~CCC-CCC~~-Treated Glass LP2-IL-09 after VHT for 7 Days

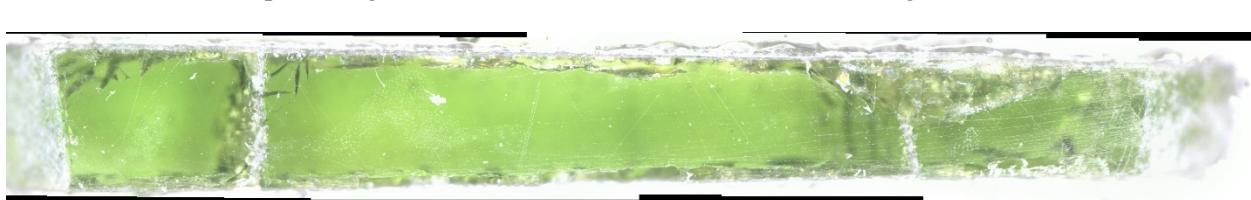
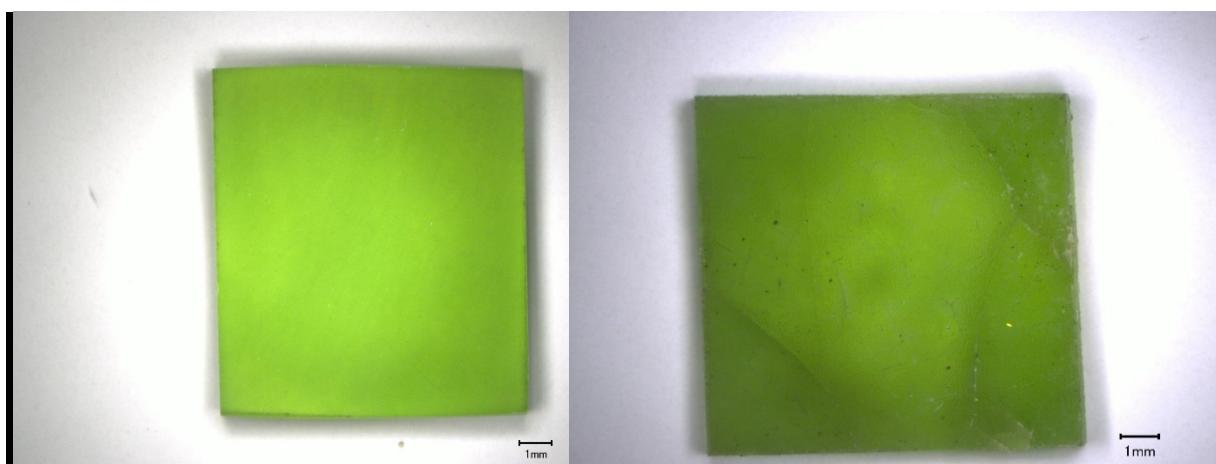


Figure I.81. ~~CCC-CCC~~-Treated Glass LP2-IL-09 after VHT for 24 Days

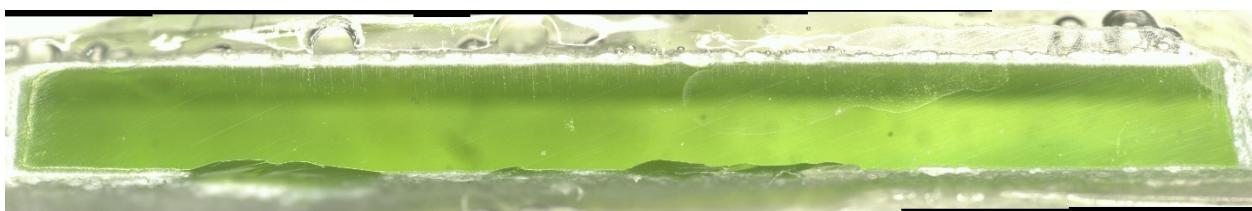
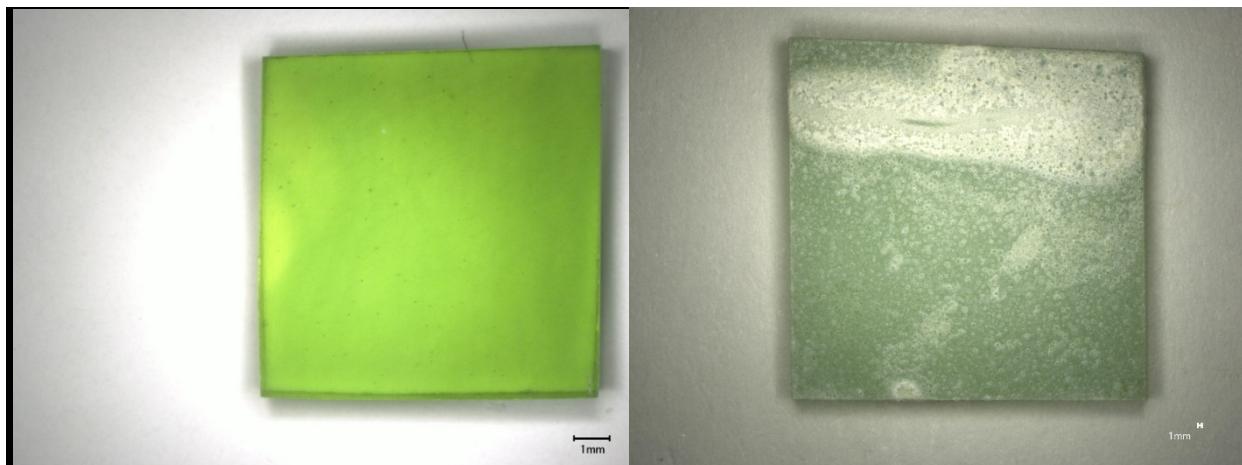


Figure I.82. ~~CCC-CCC~~-Treated Glass LP2-IL-10 after VHT for 7 Days

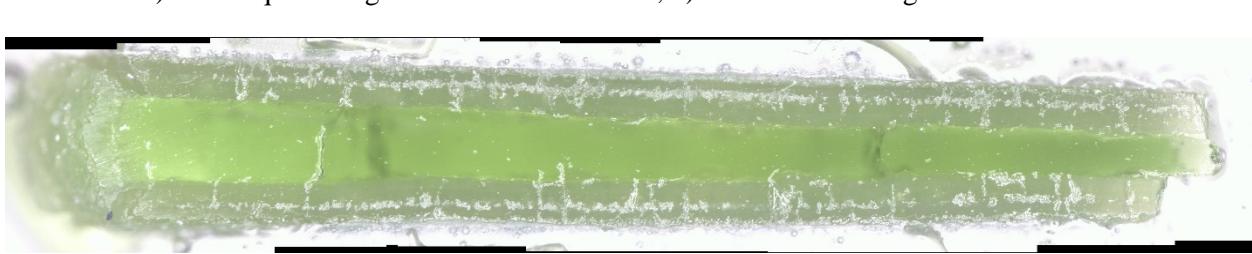
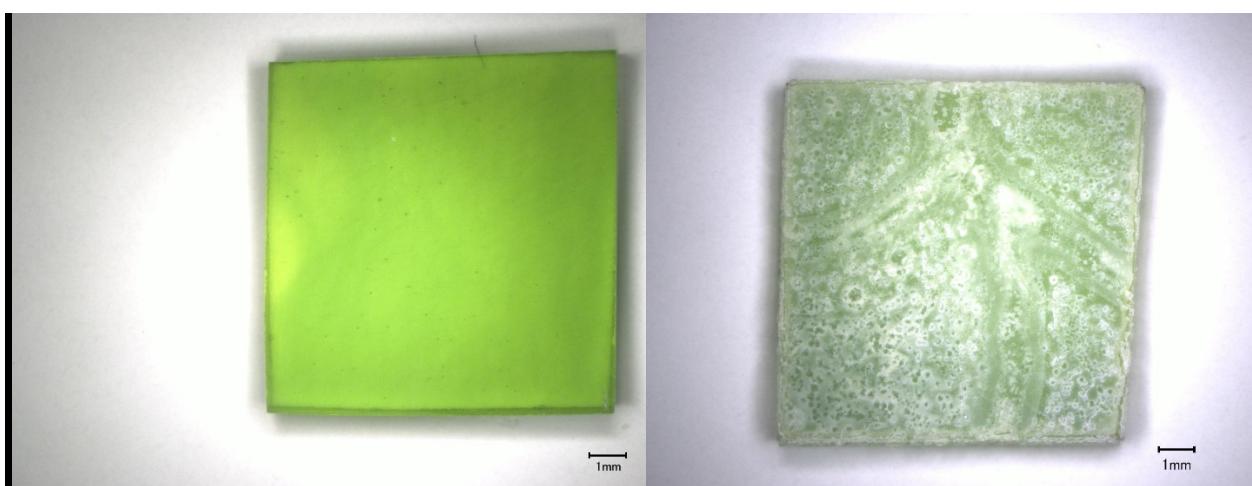
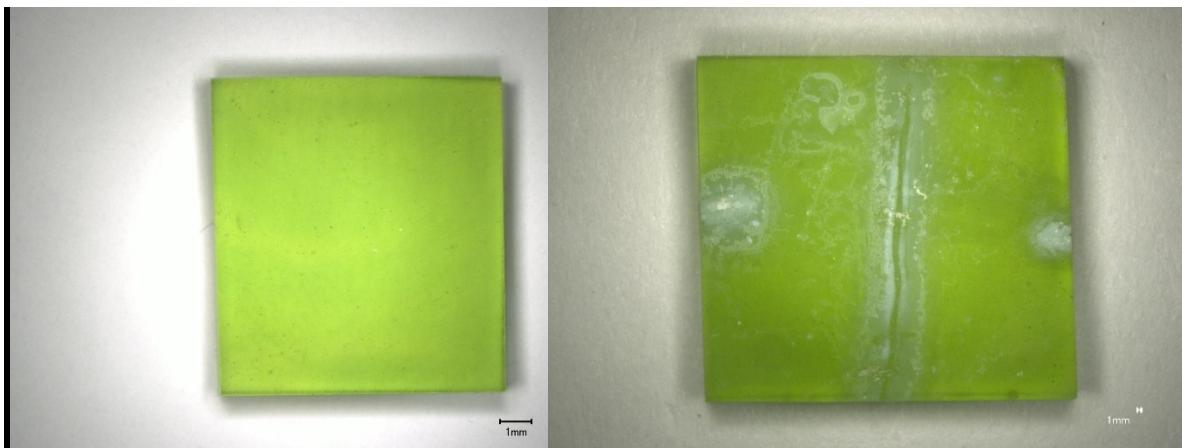


Figure I.83. ~~CCC-CCC~~-Treated Glass LP2-IL-10 after VHT for 24 Days

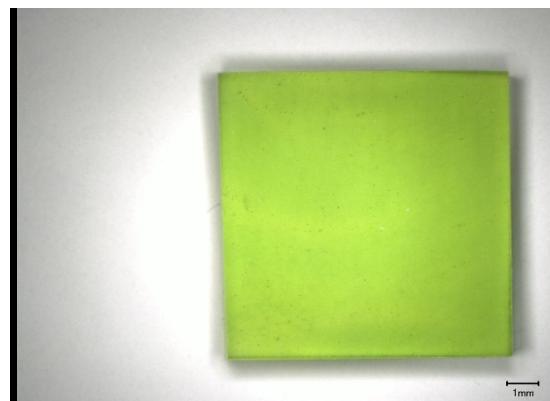


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.84. ~~CCC-CCC~~-Treated Glass LP2-IL-11 after VHT for 7 Days

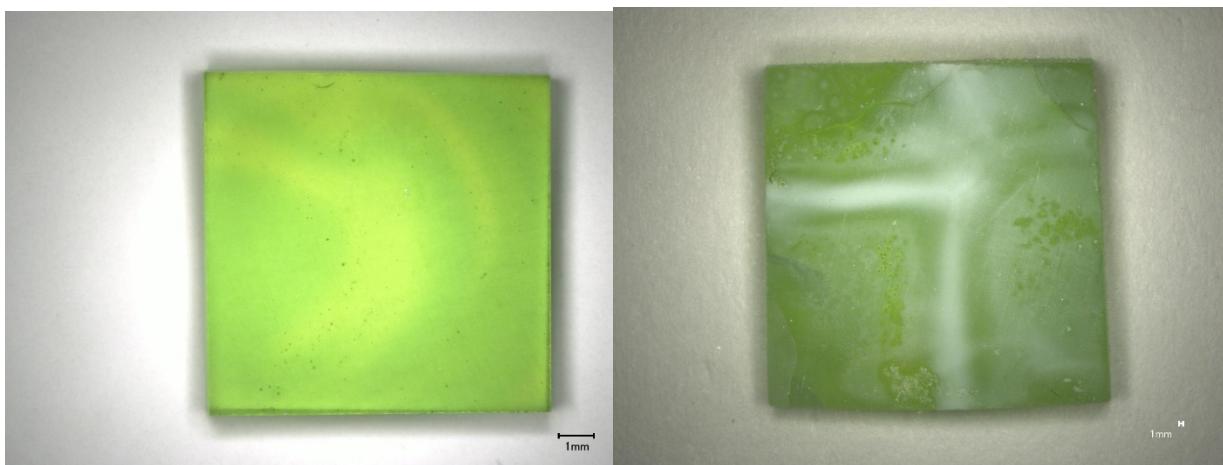


a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.85. ~~CCC-CCC~~-Treated Glass LP2-IL-11 after VHT for 24 Days

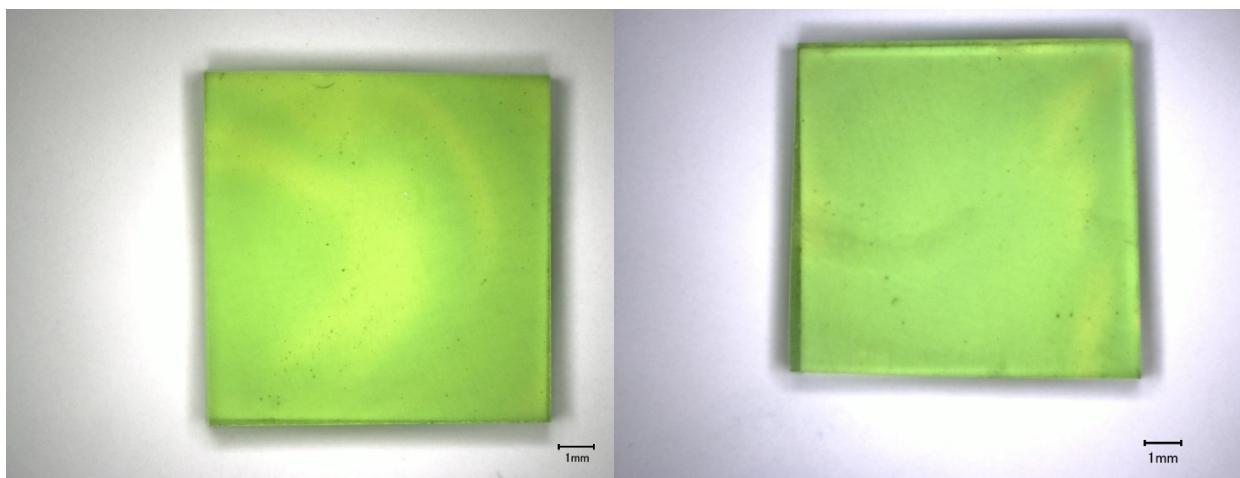


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

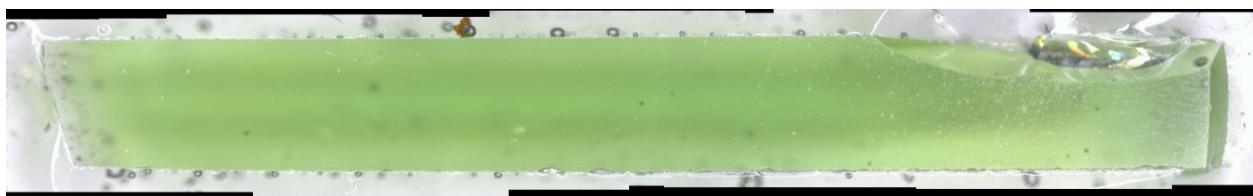


c) Glass cross section magnified after VHT

Figure I.86. ~~CCC-CCC~~-Treated Glass LP2-IL-12 after VHT for 7 Days

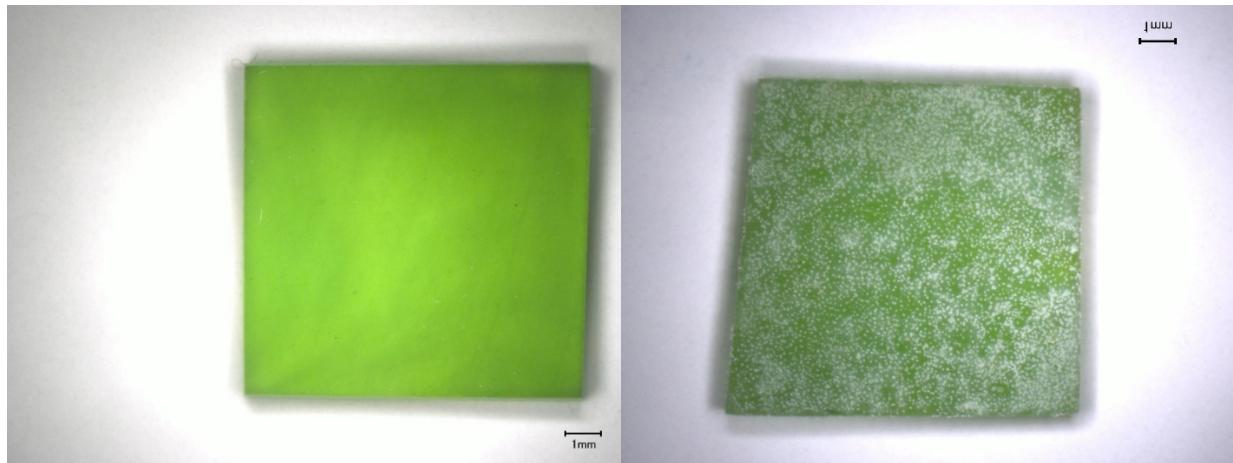


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

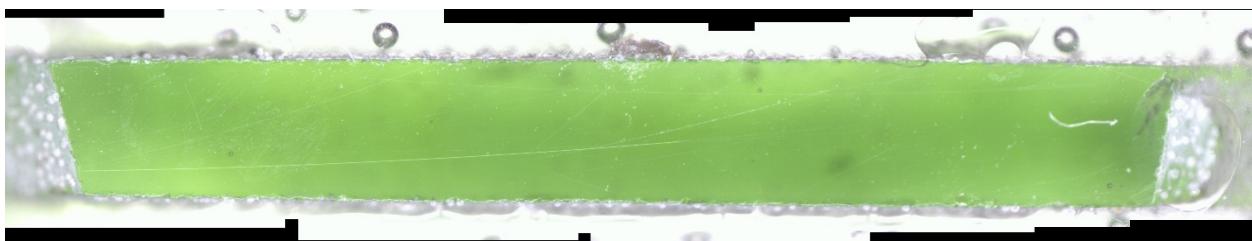


c) Glass cross section magnified after VHT

Figure I.87. ~~CCC-CCC~~-Treated Glass LP2-IL-12 after VHT for 24 Days

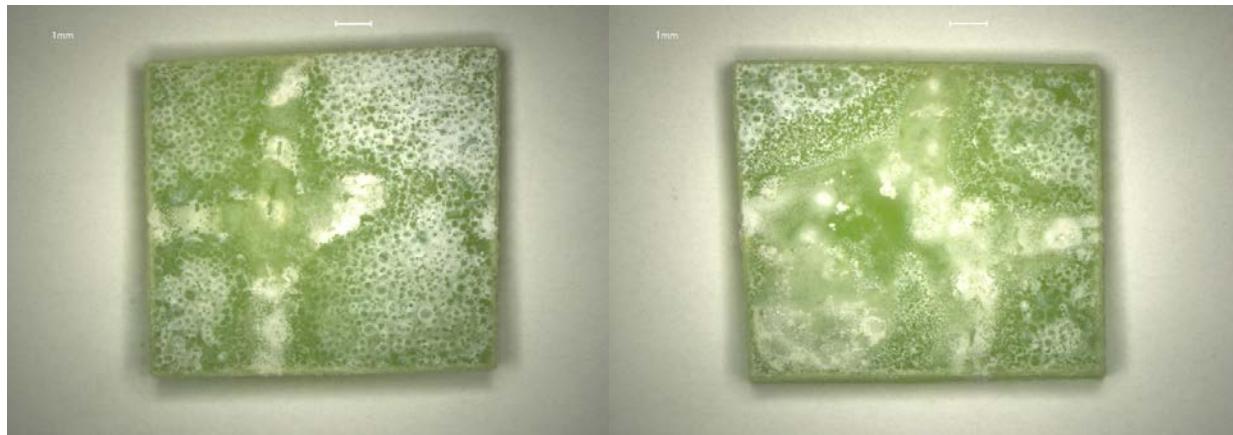


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

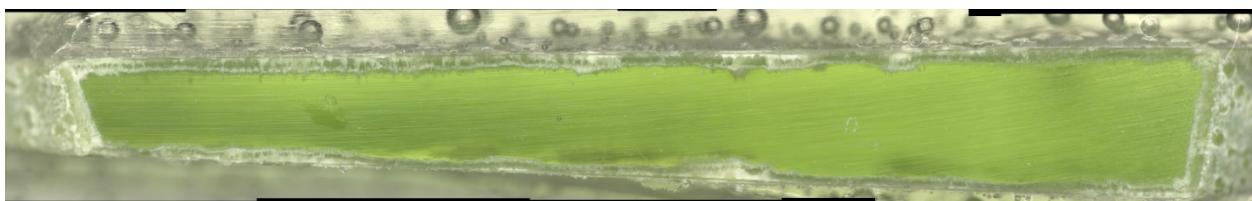


c) Glass cross section magnified after VHT

Figure I.88. ~~CCC-CCC~~-Treated Glass LP2-IL-13 after VHT for 24 Days



a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.89. ~~CCC-CCC~~-Treated Glass LP2-IL-14 after VHT for 7 Days

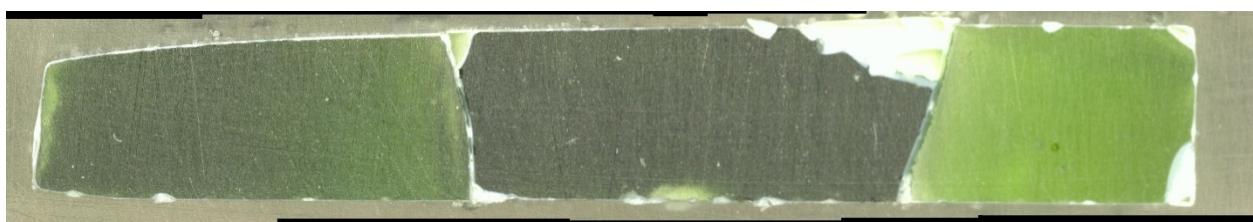
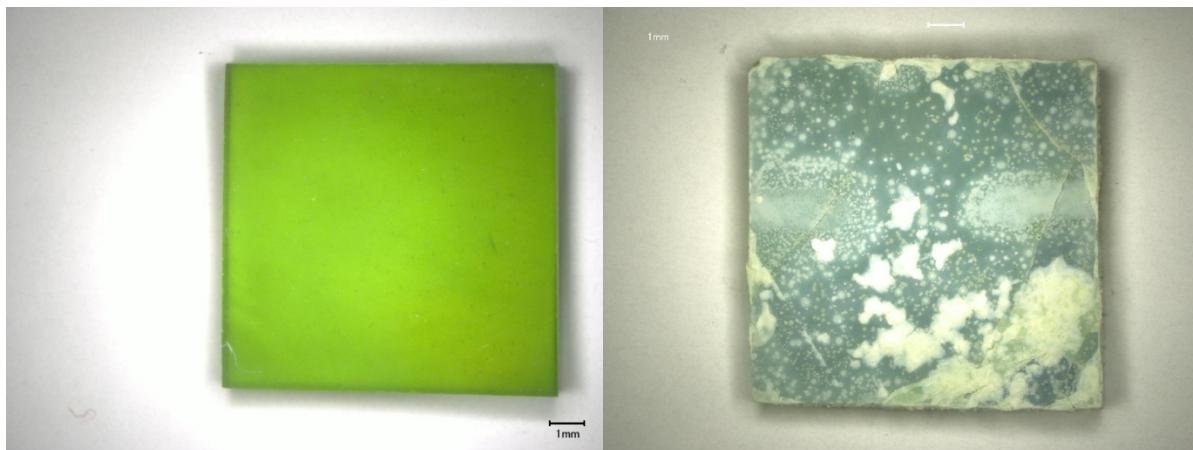


Figure I.90. ~~CCC~~-Treated Glass LP2-IL-15 after VHT for 7 Days

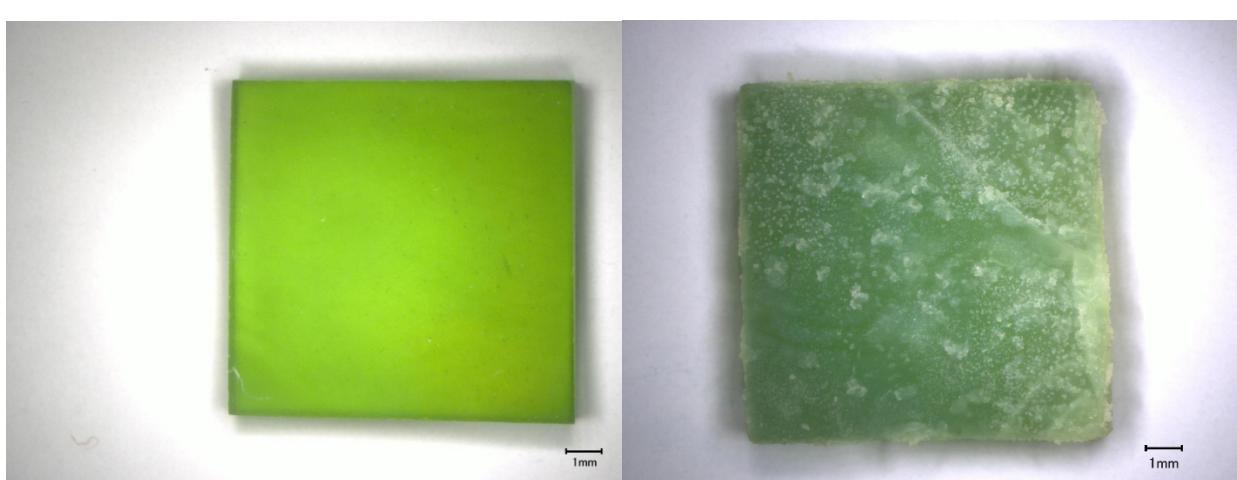
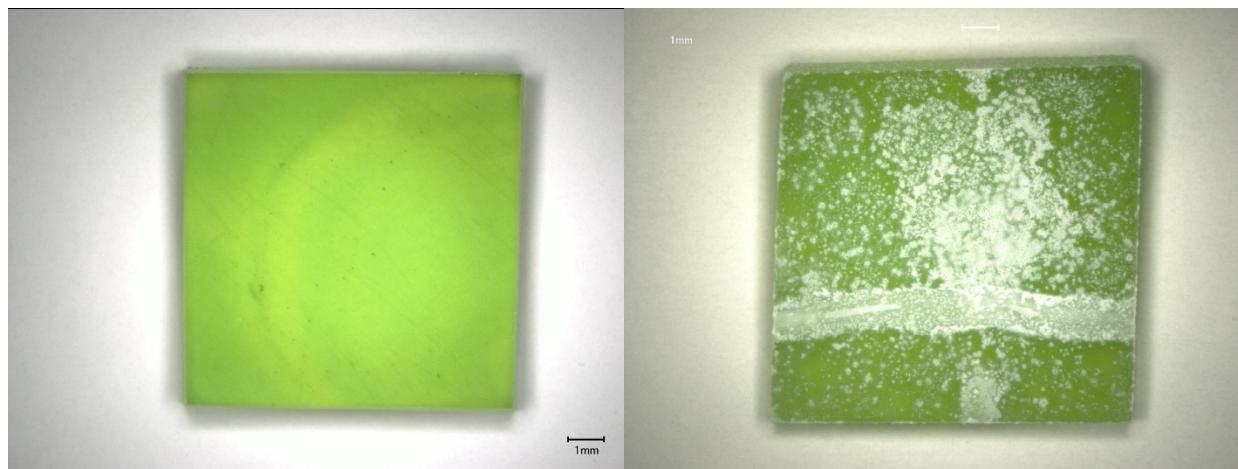


Figure I.91. ~~CCC~~-Treated Glass LP2-IL-15 after VHT for 24 Days

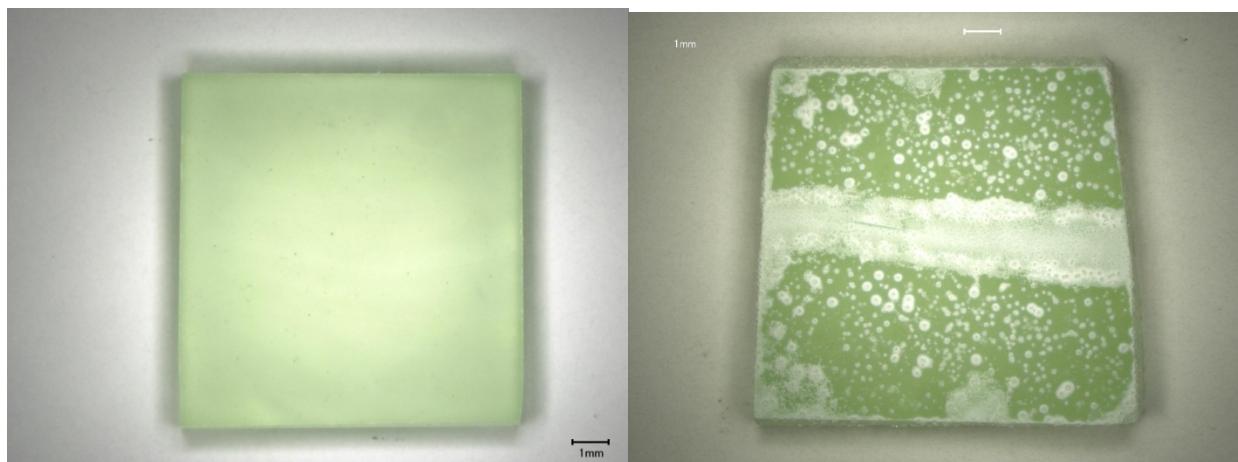


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT



c) Glass cross section magnified after VHT

Figure I.92. ~~CCC-CCC~~-Treated Glass LP2-IL-16 after VHT for 24 Days

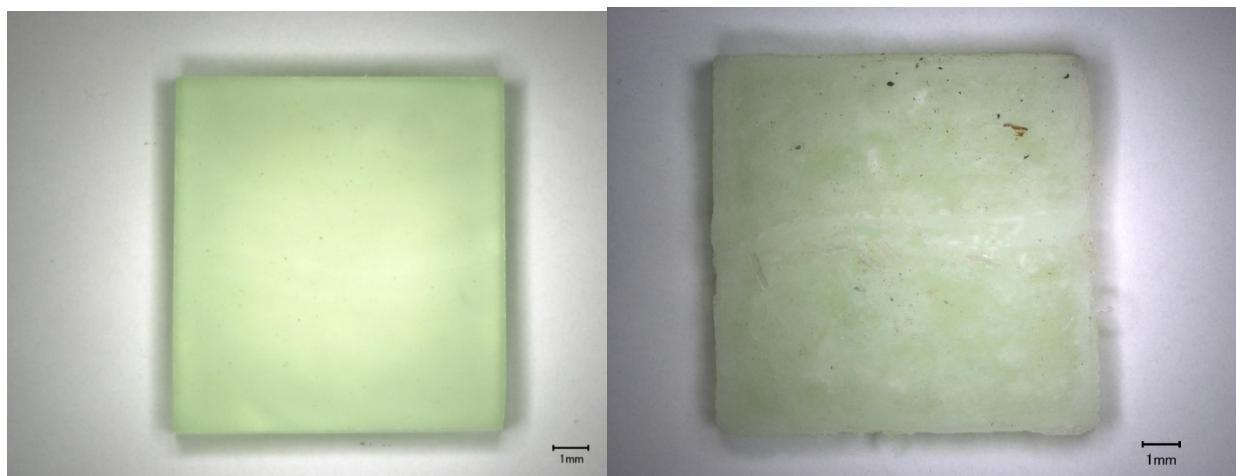


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

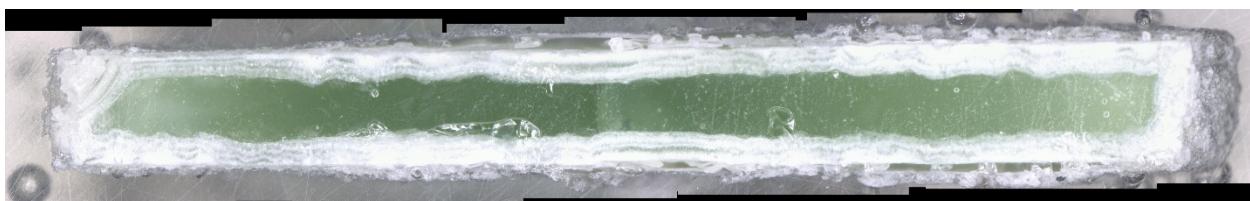


c) Glass cross section magnified after VHT

Figure I.93. ~~CCC-CCC~~-Treated Glass LP2-IL-17 after VHT for 7 Days

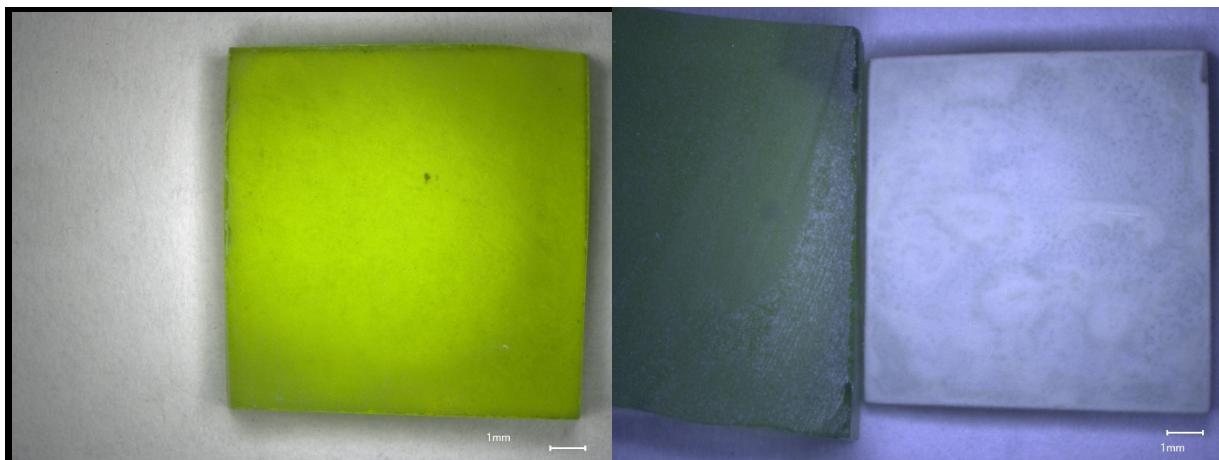


a) Glass square magnified 20X before VHT; b) Glass surface magnified after VHT

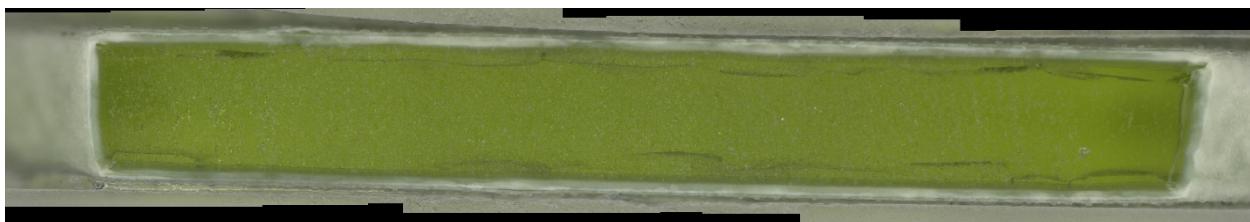


c) Glass cross section magnified after VHT

Figure I.94. ~~CCC~~-Treated Glass LP2-IL-17 after VHT for 24 Days

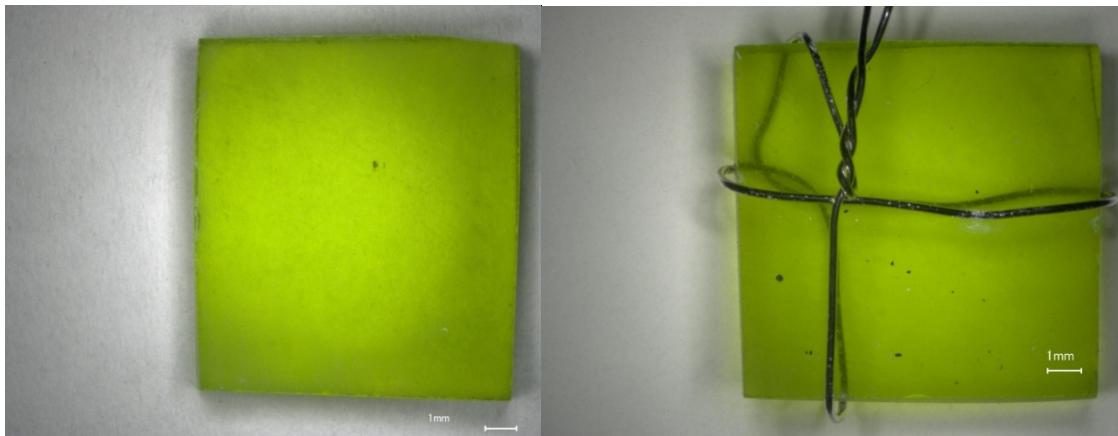


a) Glass square magnified 20X before VHT; b) Glass square after (right) and before (left) VHT

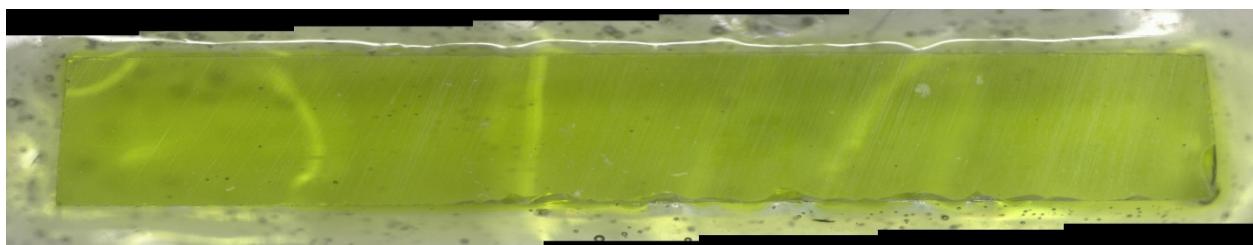


c) Glass cross section magnified after VHT

Figure I.95. ~~CCC~~-Treated Glass LP2-OL-01-3 after VHT for 11 Days

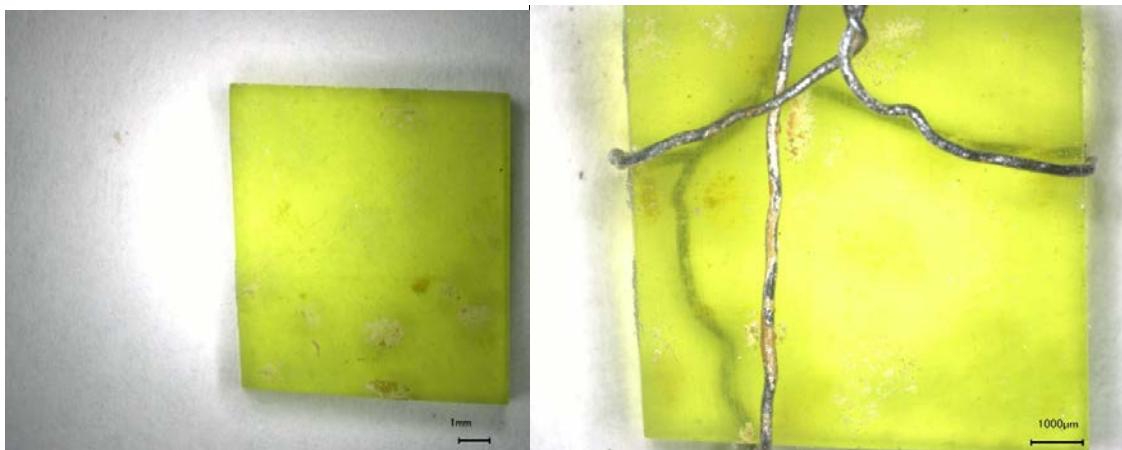


a) Glass square magnified 20X before VHT; b) Glass square magnified 20X after VHT



c) Glass cross section magnified after VHT

Figure I.96. ~~CCC-CCC~~-Treated Glass LP2-OL-01-3 after VHT for 24 Days

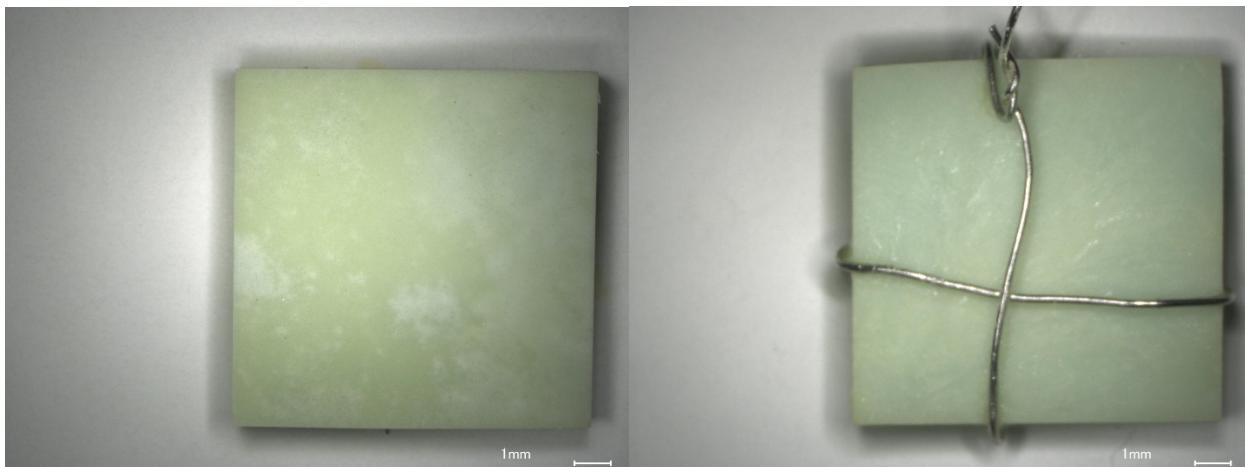


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT



c) Glass cross section magnified after VHT

Figure I.97. ~~CCC-CCC~~-Treated Glass LP2-OL-02-1 after VHT for 24 Days

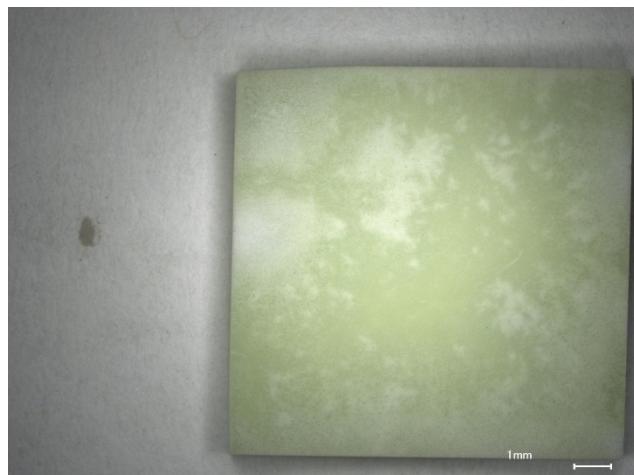


a) Glass square magnified 20X before VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.98. ~~CCC-CCC~~-Treated Glass LP2-OL-03 MOD2 after VHT for 7 Days

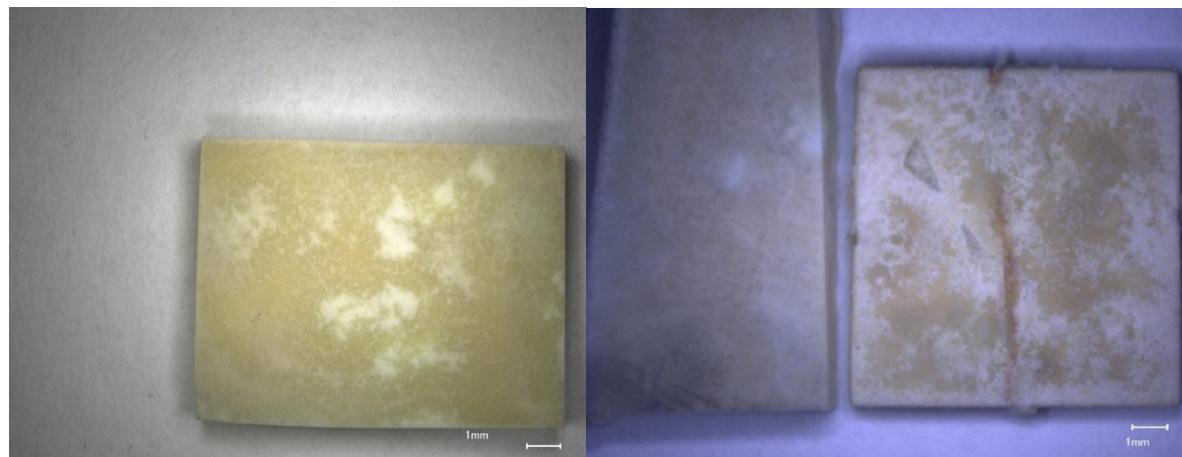


a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.99. ~~CCC-CCC~~-Treated Glass LP2-OL-03 MOD2 after VHT for 24 Days

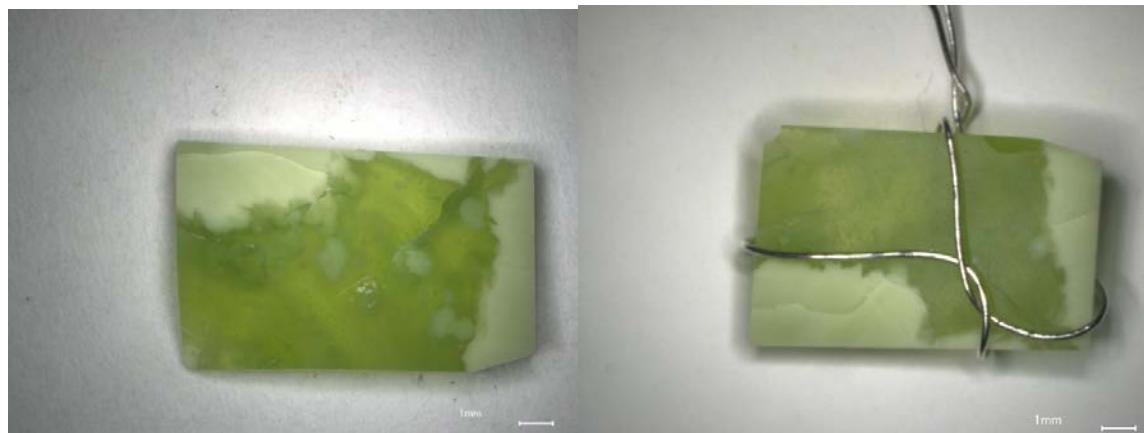


a) Glass square magnified 20X before VHT b) Glass square before (on left) and after (on right) VHT



c) Glass cross section magnified after VHT

Figure I.100. ~~CCC-CCC~~-Treated Glass LP2-OL-04-1 after VHT for 11 Days

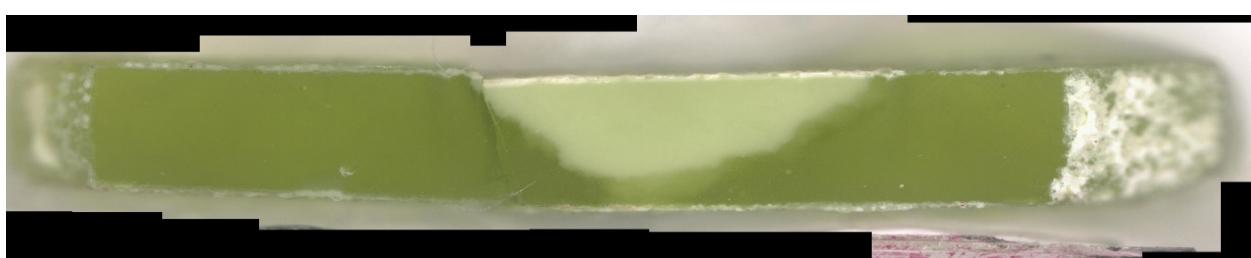
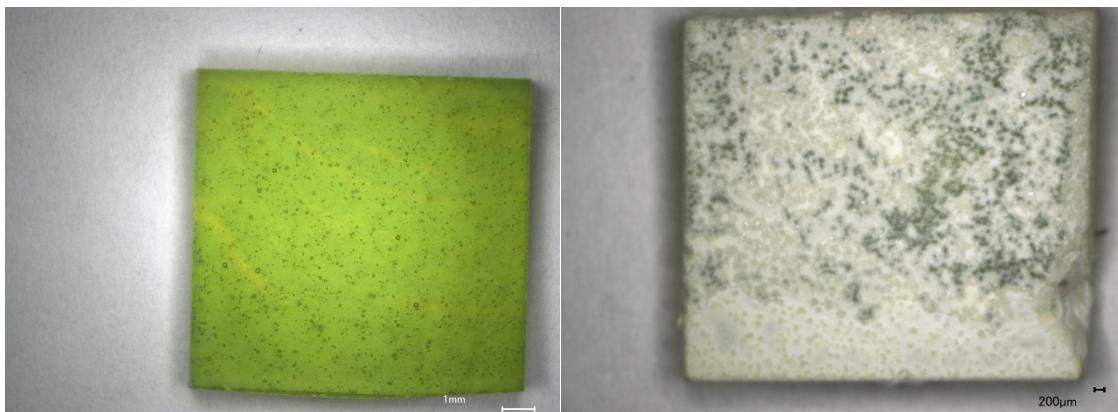


a) Glass square magnified 20X before VHT; b) Glass square magnified after VHT



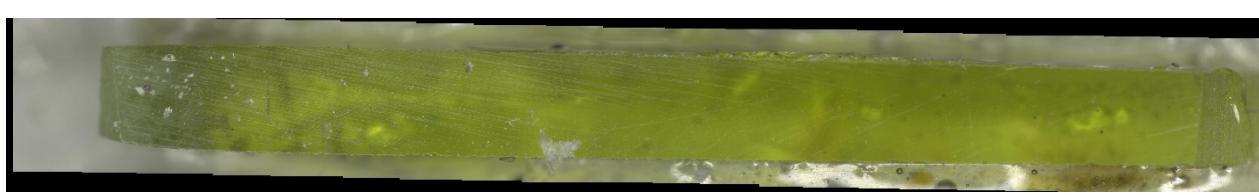
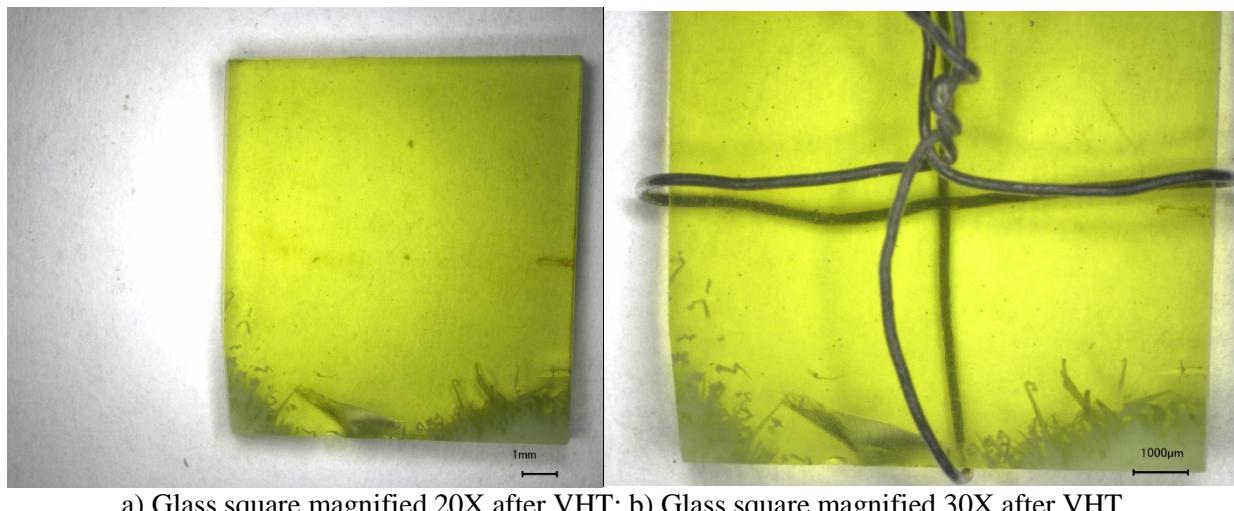
c) Glass cross section magnified after VHT

Figure I.101. ~~CCC-CCC~~-Treated Glass LP2-OL-05 after VHT for 7 Days



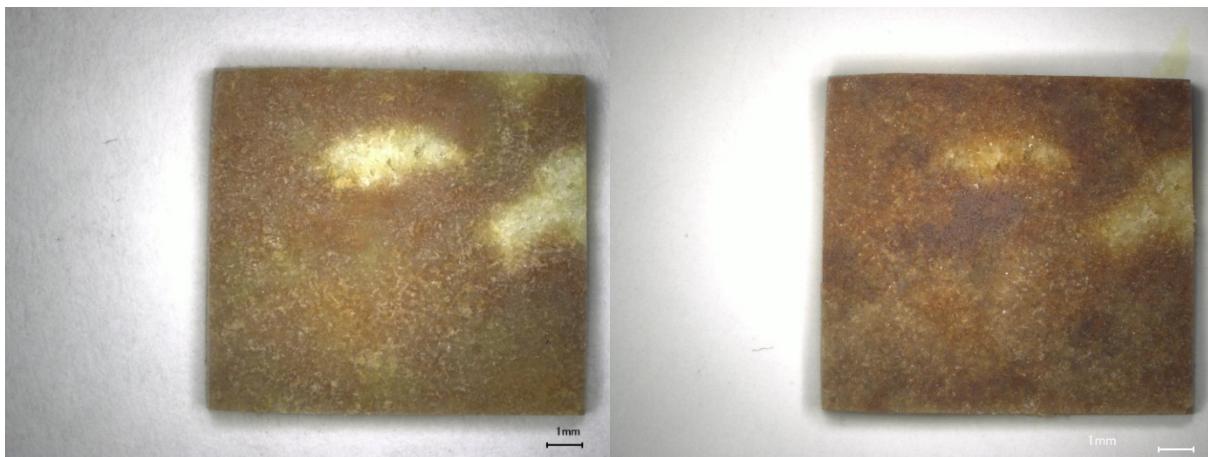
c) Glass cross section magnified after VHT

Figure I.102. ~~CCC~~-Treated Glass LP2-OL-05 after VHT for 24 Days



c) Glass cross section magnified after VHT

Figure I.103. ~~CCC~~-Treated Glass LP2-OL-07-1 after VHT for 24 Days

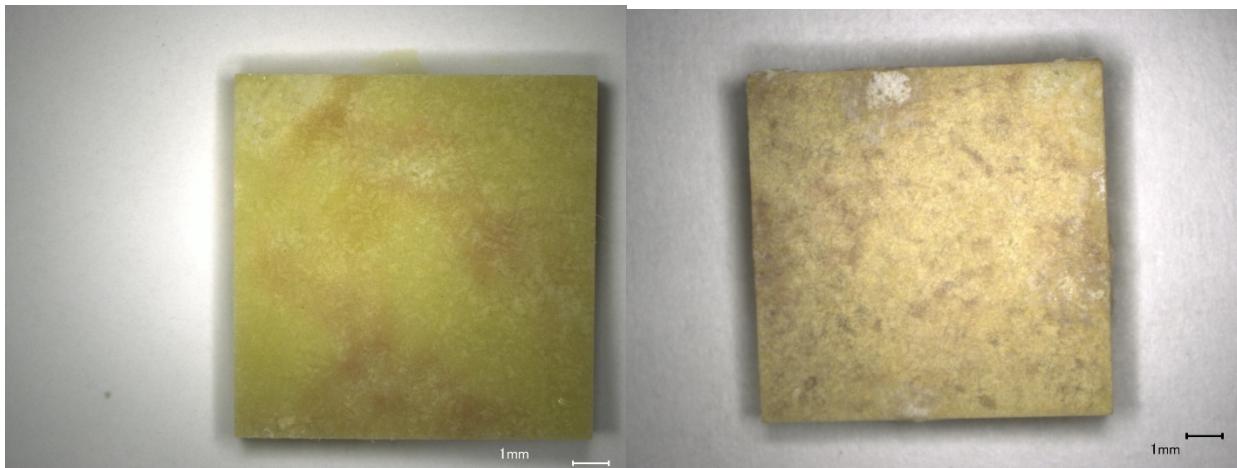


a) Glass square magnified 20X before VHT; b) Glass square magnified after VHT

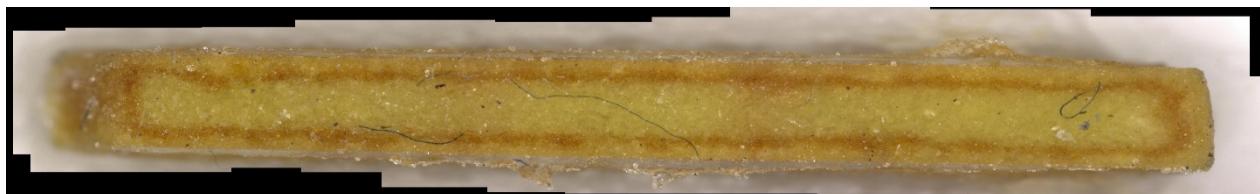


c) Glass cross section magnified after VHT

Figure I.104. CCC-CCC-Treated Glass LP2-OL-08MOD after VHT for 7 Days

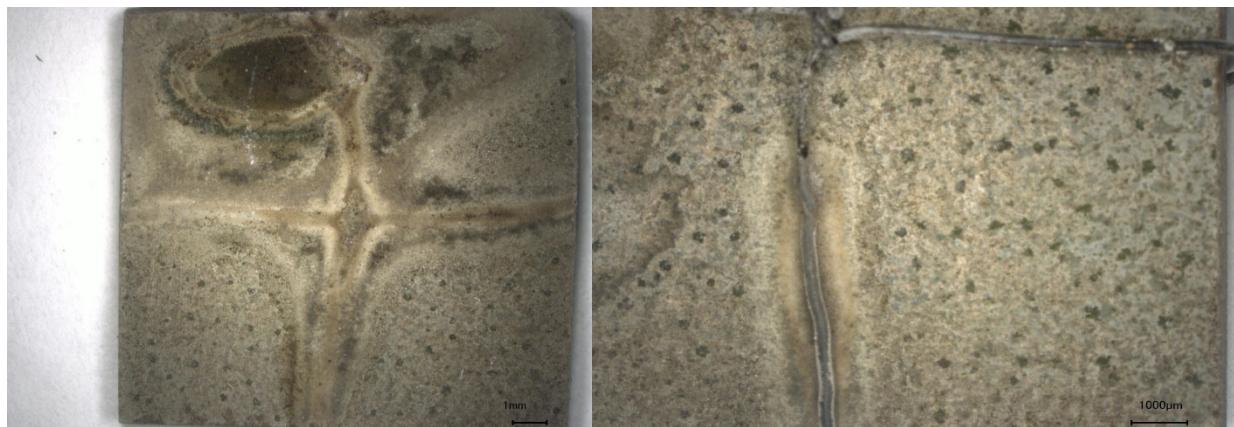


a) Glass square magnified 20X before VHT; b) Glass square magnified after VHT

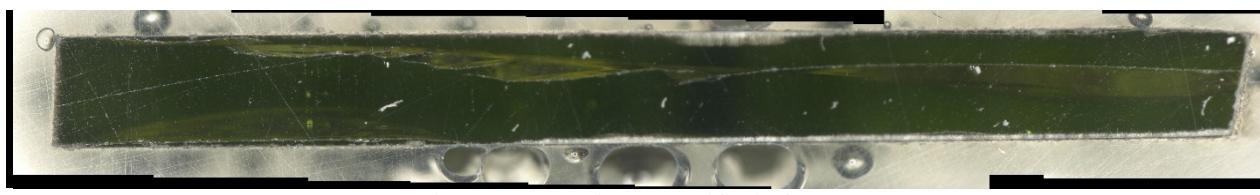


c) Glass cross section magnified after VHT

Figure I.105. CCC-CCC-Treated Glass LP2-OL-08MOD after VHT for 24 Days

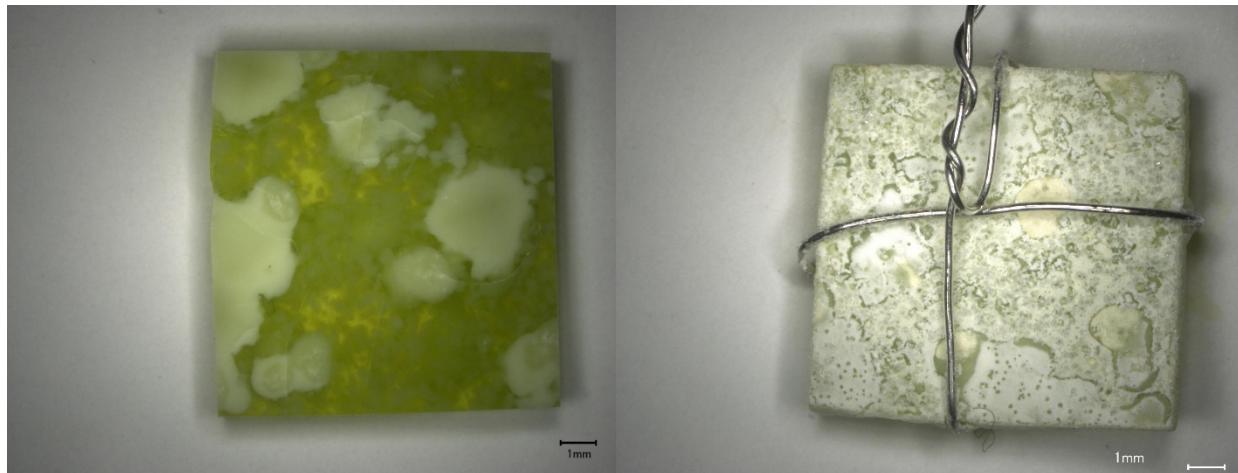


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT

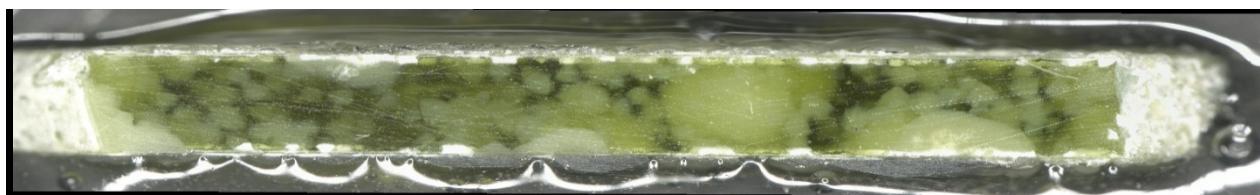


c) Glass cross section magnified after VHT

Figure I.106. ~~CCC-CCC~~-Treated Glass LP2-OL-09-1 after VHT for 24 Days

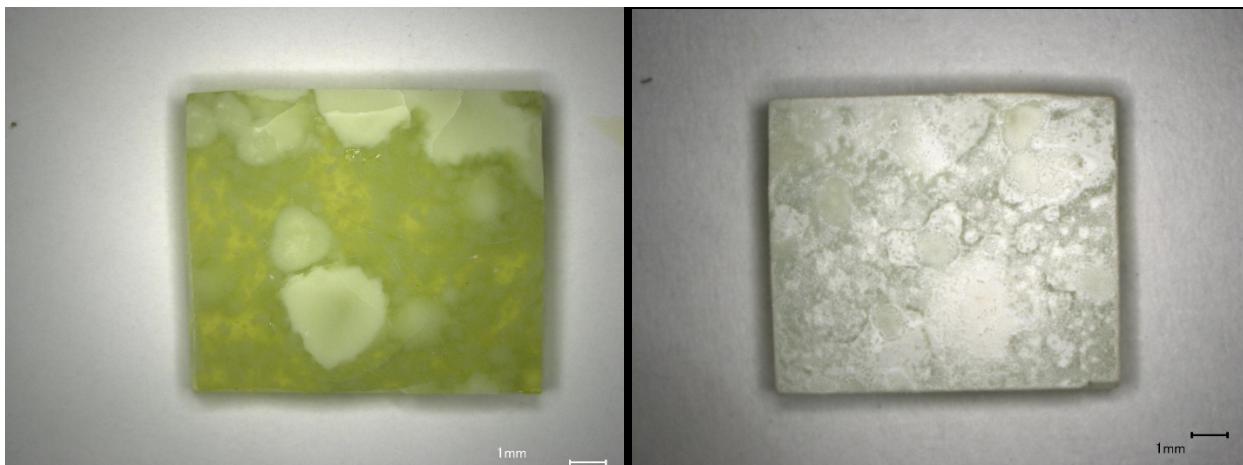


a) Glass square magnified 20X before VHT; b) Glass square magnified after VHT

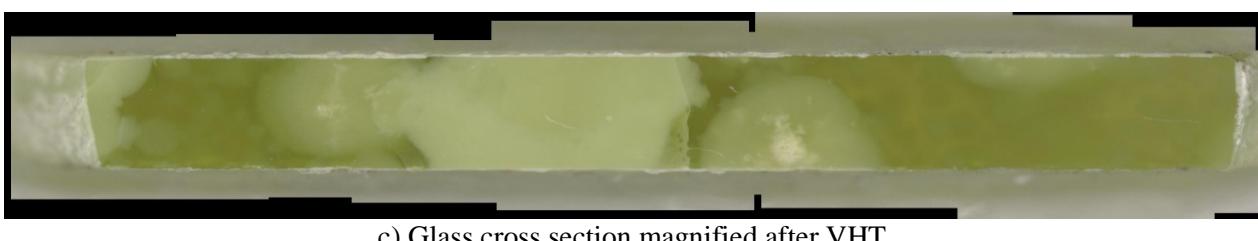


c) Glass cross section magnified after VHT

Figure I.107. ~~CCC-CCC~~-Treated Glass LP2-OL-10MOD after VHT for 7 Days

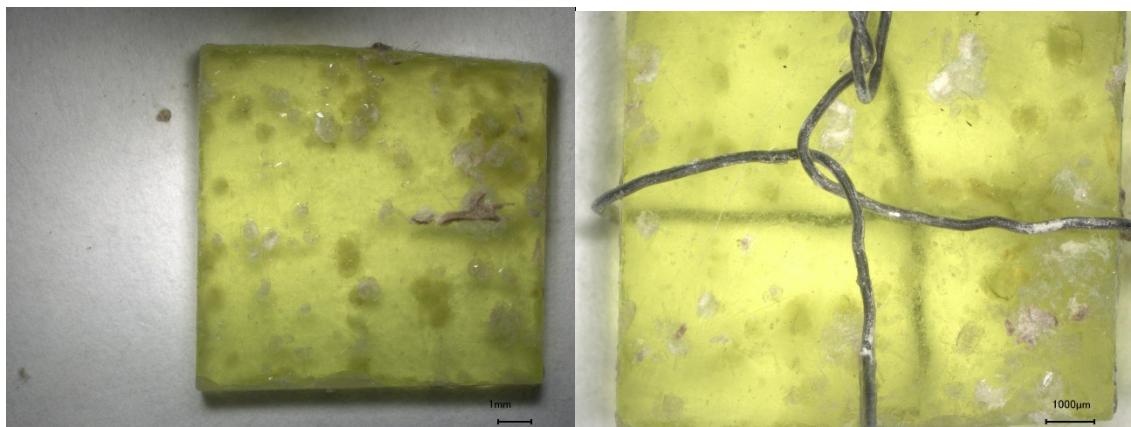


a) Glass square magnified 20X before VHT; b) Glass square magnified after VHT

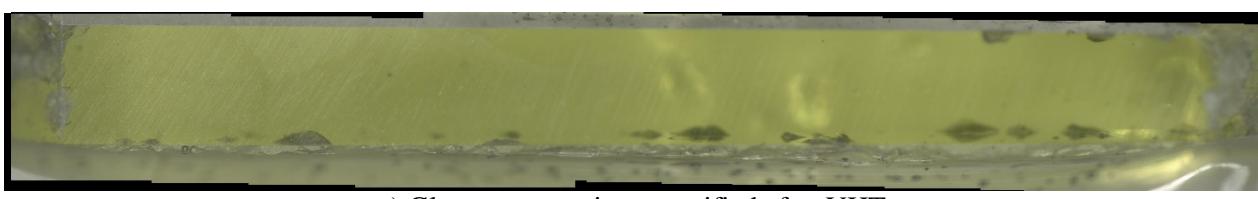


c) Glass cross section magnified after VHT

Figure I.108. CCC-CCC-Treated Glass LP2-OL-10MOD after VHT for 24 Days

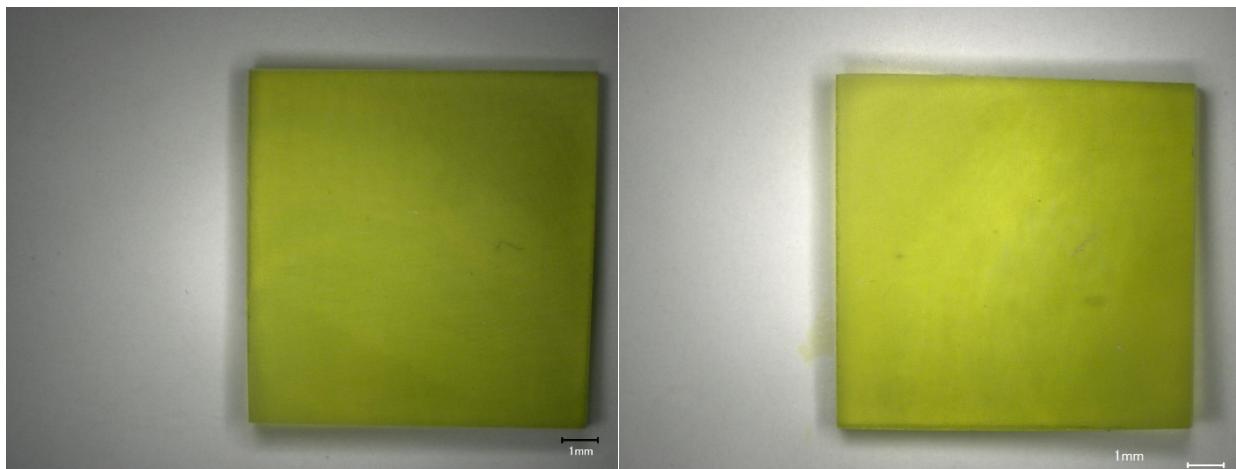


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT



c) Glass cross section magnified after VHT

Figure I.109. CCC-CCC-Treated Glass LP2-OL-11 after VHT for 24 Days

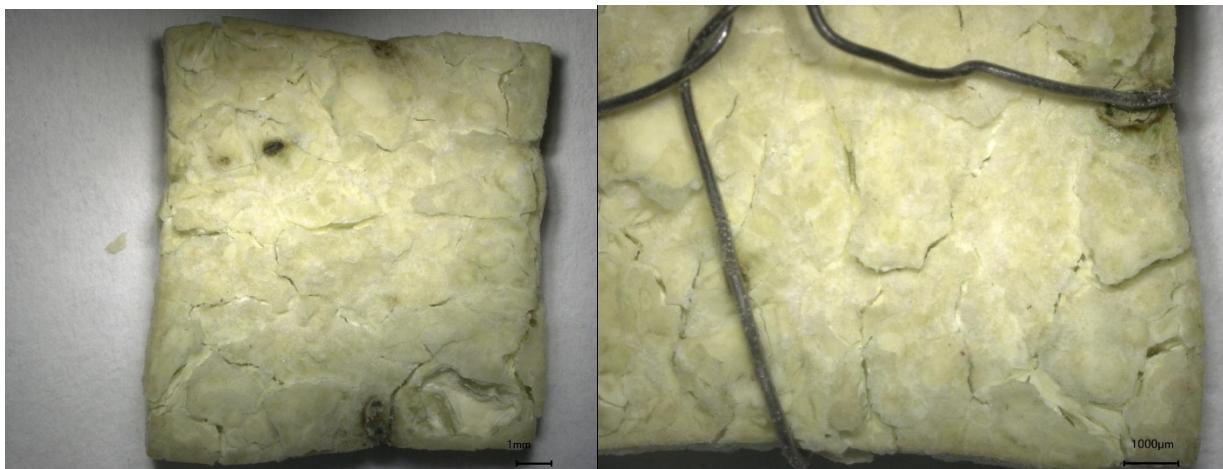


a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.110. ~~CCC-CCC~~-Treated Glass LP2-OL-12 after VHT for 7 Days

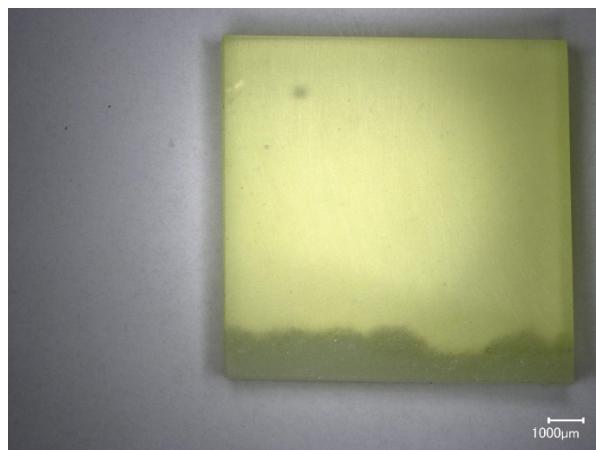


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT

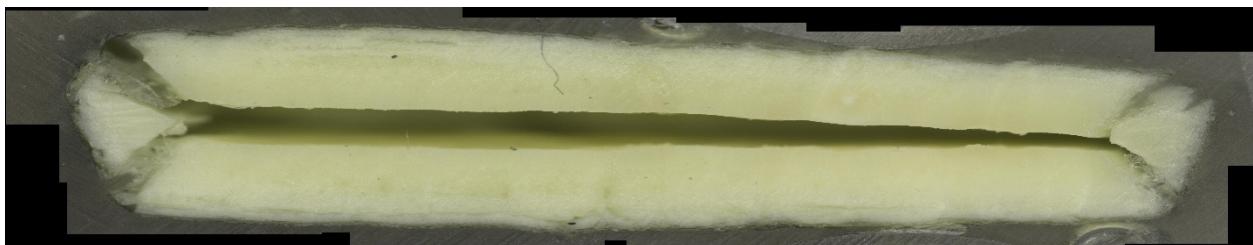


c) Glass cross section magnified after VHT

Figure I.111. ~~CCC-CCC~~-Treated Glass LP2-OL-12 after VHT for 24 Days

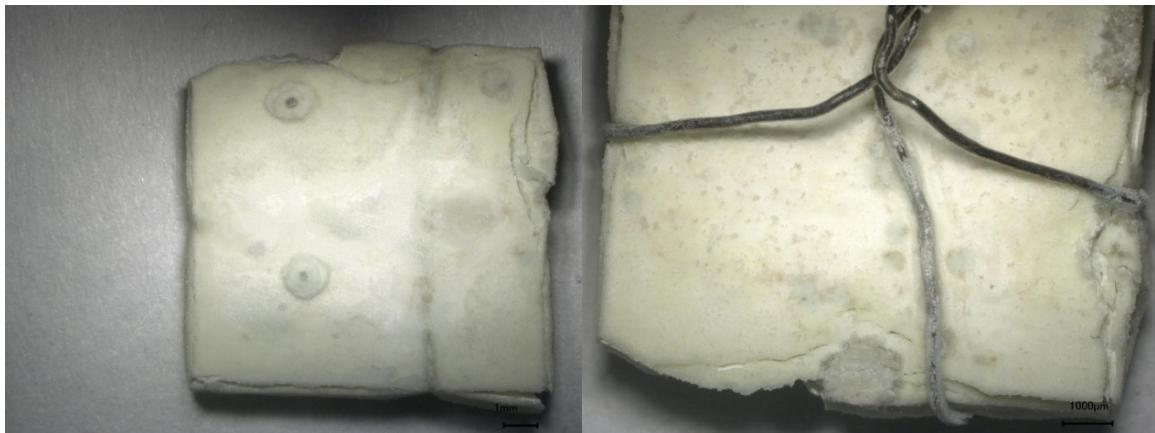


a) Glass square magnified after VHT



b) Glass cross section magnified after VHT

Figure I.112. ~~CCC-CCC~~-Treated Glass LP2-OL-13 after VHT for 7 Days

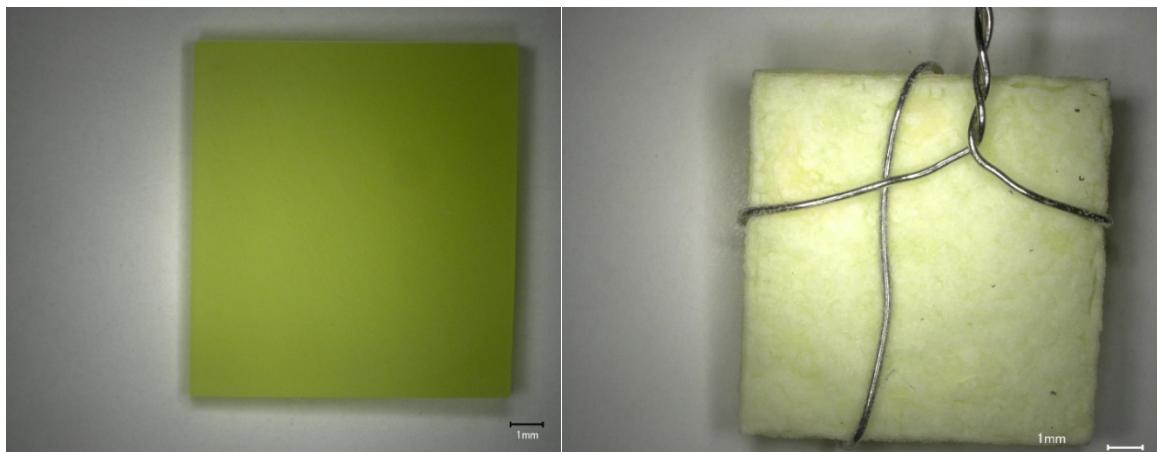


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT

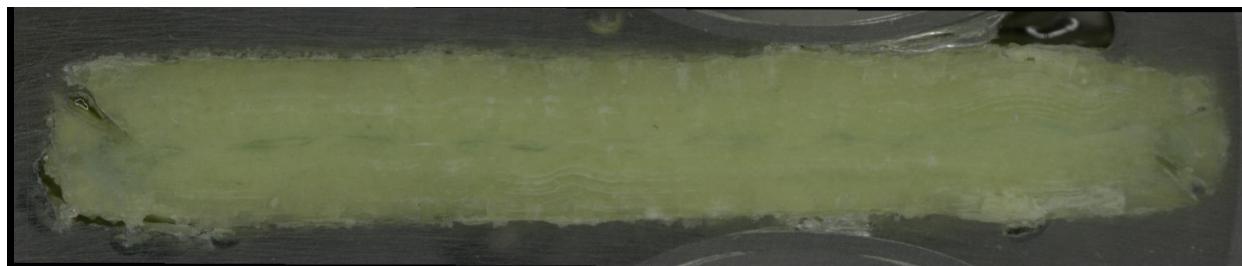


c) Glass cross section magnified after VHT

Figure I.113. ~~CCC-CCC~~-Treated Glass LP2-OL-13 after VHT for 24 Days

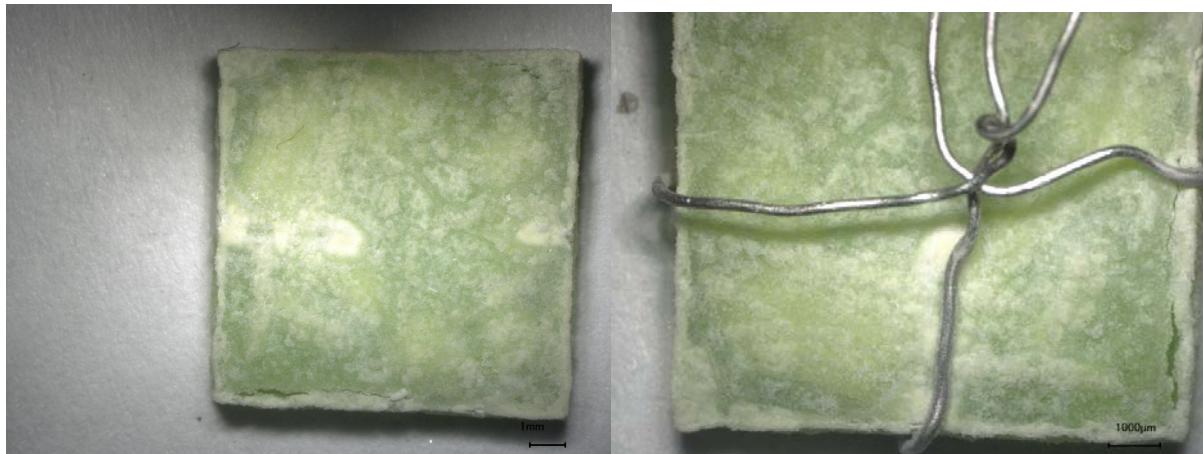


a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.114. ~~CCC-CCC~~-Treated Glass LP2-OL-14 after VHT for 7 Days

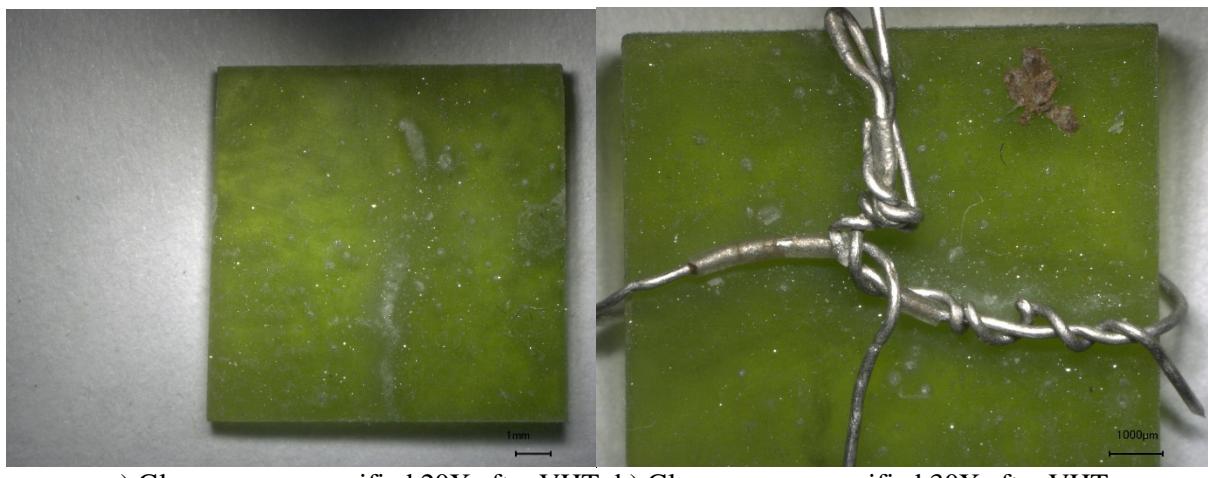


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT

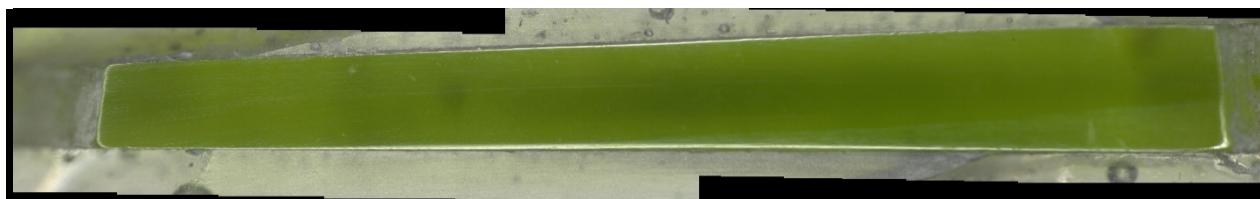


c) Glass cross section magnified after VHT

Figure I.115. ~~CCC-CCC~~-Treated Glass LP2-OL-14 after VHT for 24 Days



a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT



c) Glass cross section magnified after VHT

Figure I.116. ~~CCC~~-Treated Glass LP2-OL-15 after VHT for 24 Days

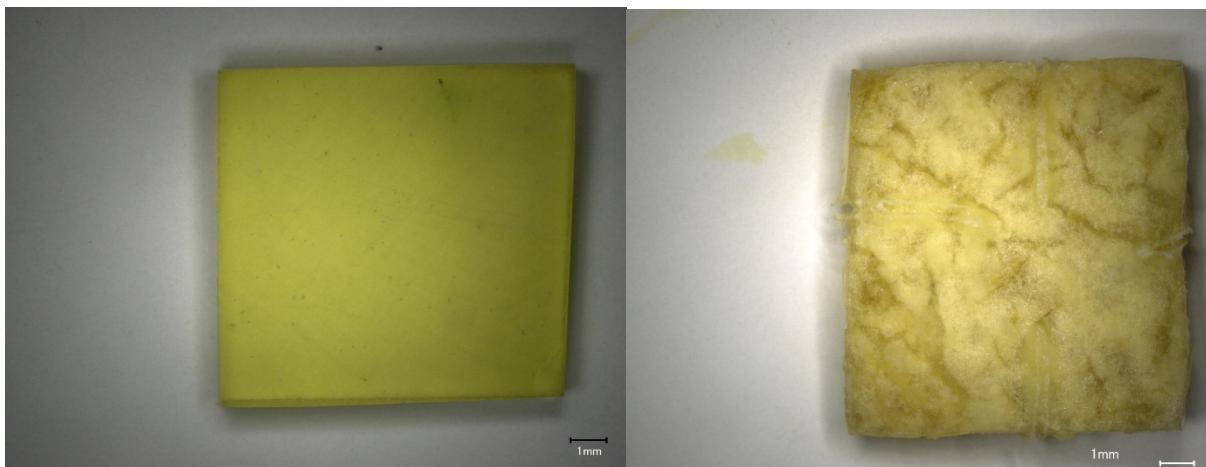


a) Glass square magnified before VHT



b) Glass cross section magnified after VHT

Figure I.117. ~~CCC~~-Treated Glass LP2-OL-16MOD after VHT for 24 Days

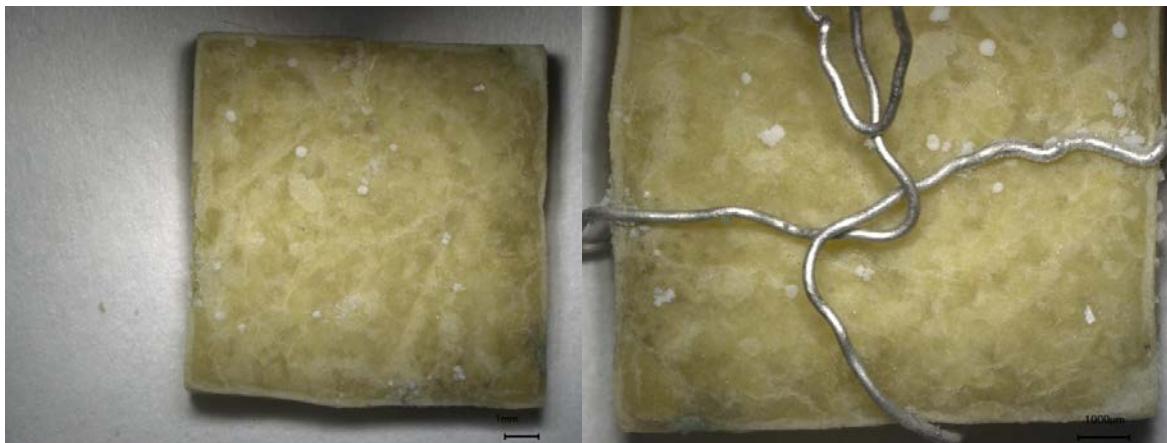


a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.118. ~~CCC-CCC~~-Treated Glass LP2-OL-17 after VHT for 7 Days

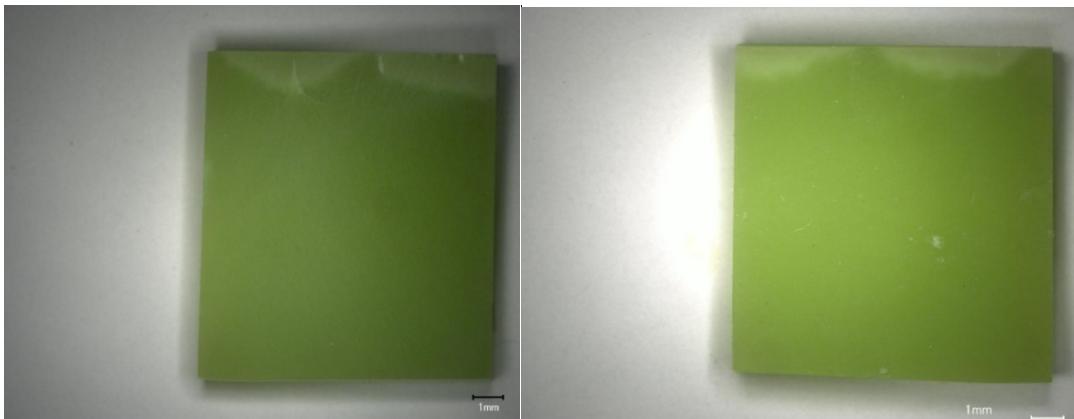


a) Glass square magnified 20X after VHT; b) Glass square magnified 30X after VHT



c) Glass cross section magnified after VHT

Figure I.119. ~~CCC-CCC~~-Treated Glass LP2-OL-17 after VHT for 24 Days

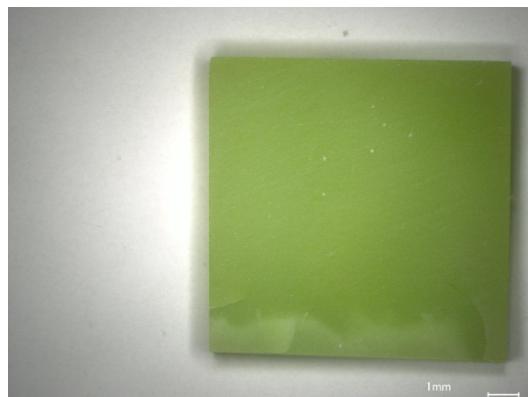


a) Glass square magnified after VHT; b) Glass square magnified after VHT



c) Glass cross section magnified after VHT

Figure I.120. ~~CCC-CCC~~-Treated Glass LP2-OL-18 after VHT for 7 Days

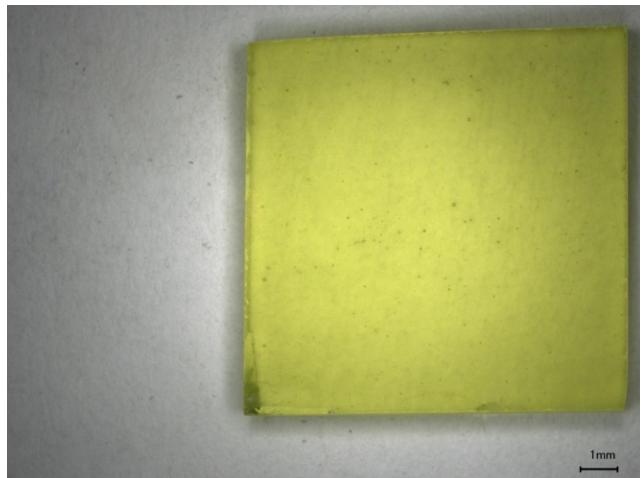


a) Glass square magnified after VHT

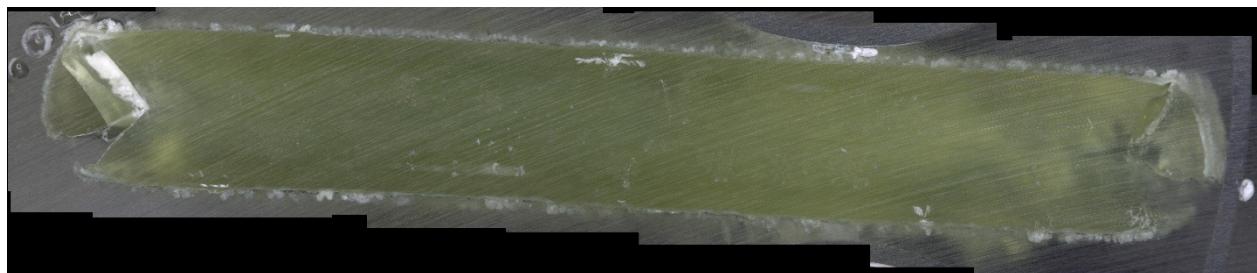


b) Glass cross section magnified after VHT

Figure I.121. ~~CCC-CCC~~-Treated Glass LP2-OL-18 after VHT for 24 Days

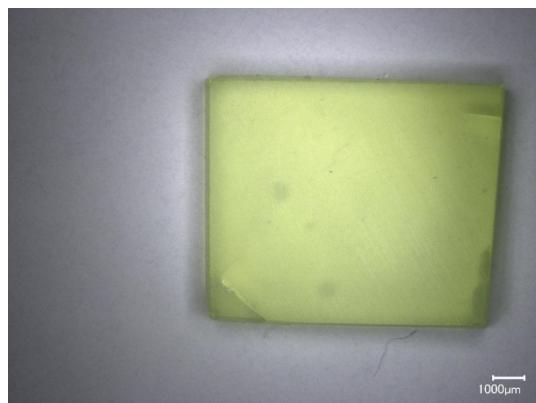


a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.122. ~~CCC~~-Treated Glass LP2-OL-19 after VHT for 24 Days

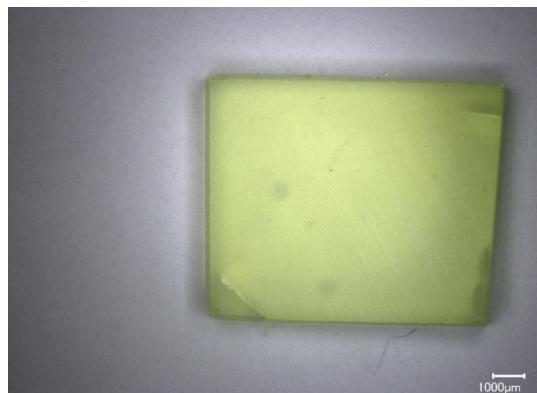


a) Glass square magnified before VHT

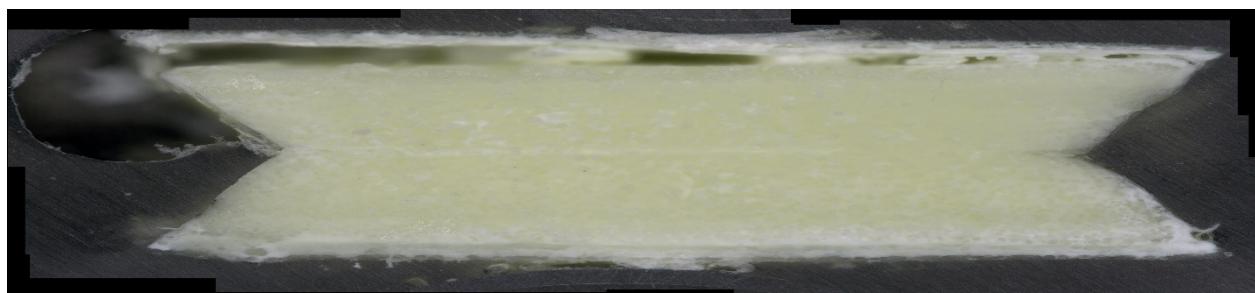


b) Glass cross section magnified after VHT

Figure I.123. ~~CCC~~-Treated Glass LP2-OL-20 after VHT for 7 Days

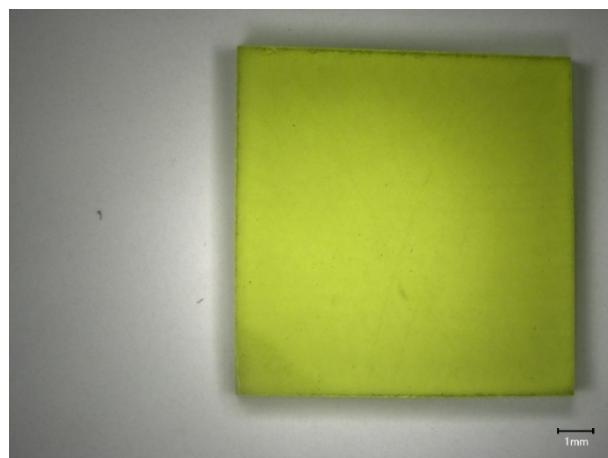


a) Glass square magnified before VHT

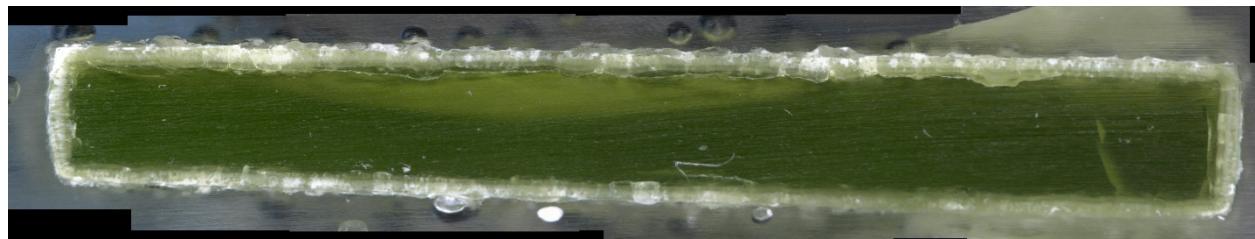


b) Glass cross section magnified after VHT

Figure I.124. ~~CCC~~-Treated Glass LP2-OL-20 after VHT for 24 Days

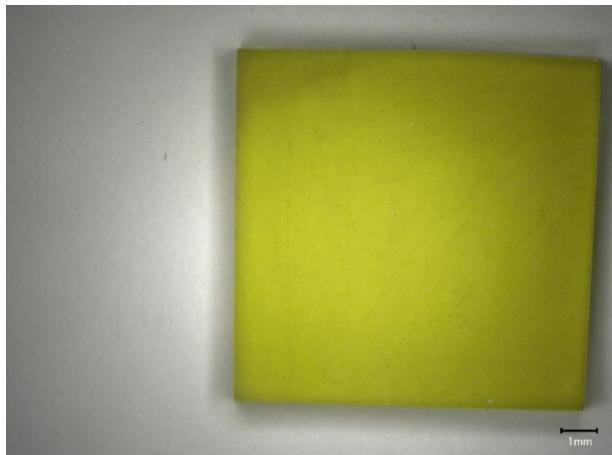


a) Glass square magnified 20X before VHT

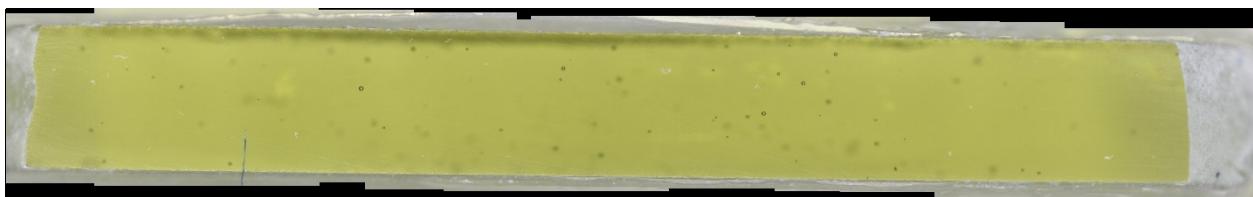


b) Glass cross section magnified after VHT

Figure I.125. ~~CCC~~-Treated Glass LP2-OL-21 after VHT for 24 Days

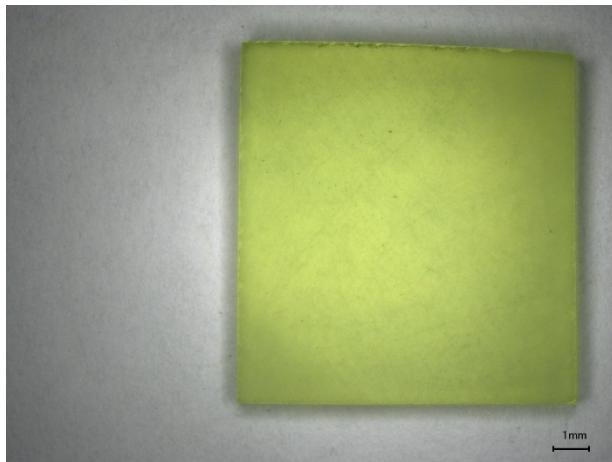


a) Glass square magnified 20X before VHT

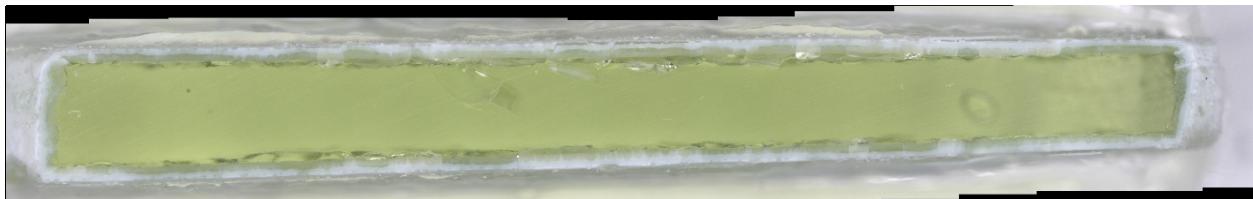


b) Glass cross section magnified after VHT

Figure I.126. ~~CCC~~-Treated Glass LP2-OL-22 after VHT for 24 Days

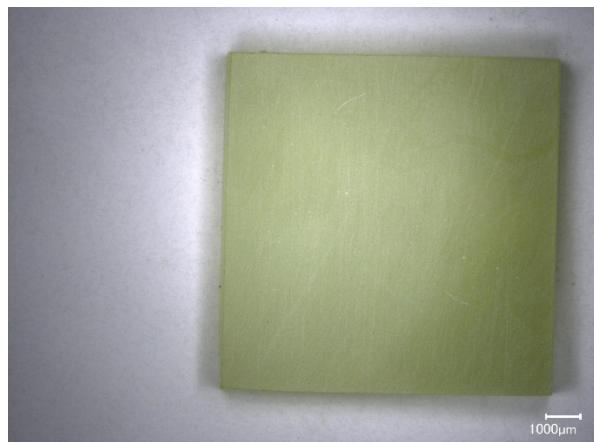


a) Glass square magnified 20X before VHT

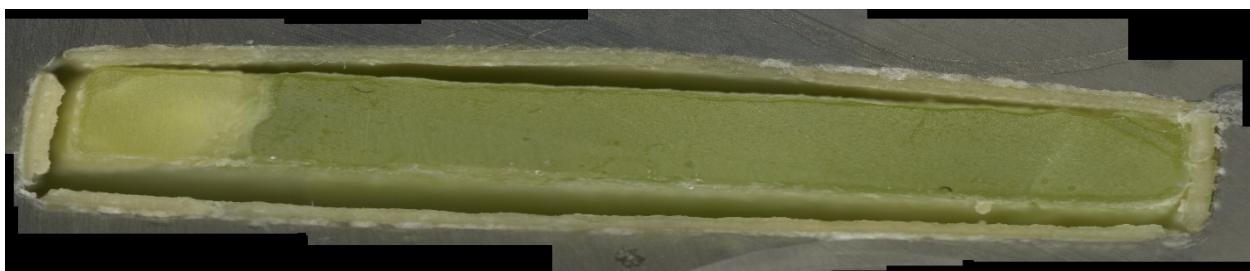


b) Glass cross section magnified after VHT

Figure I.127. ~~CCC~~-Treated Glass LP2-OL-23 after VHT for 24 Days

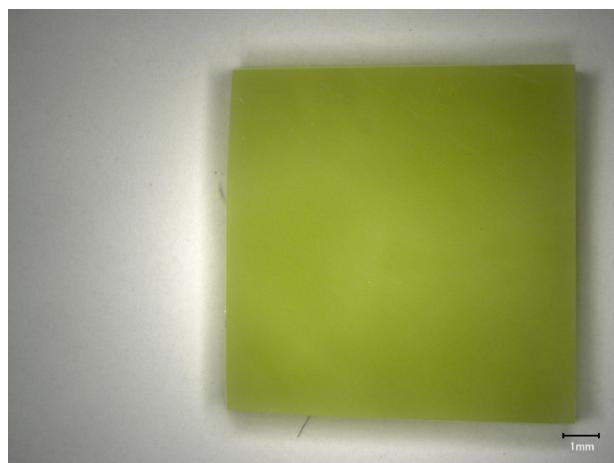


a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.128. ~~CCC-CCC~~-Treated Glass LP2-OL-24 after VHT for 7 Days

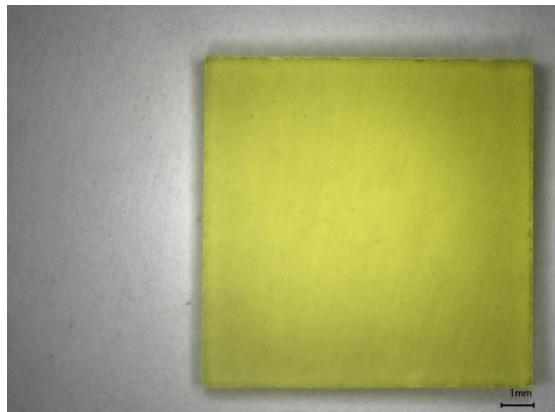


a) Glass square magnified 20X before VHT

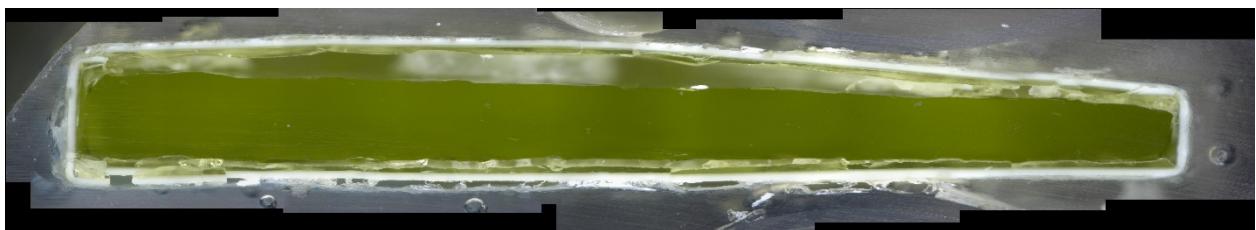


b) Glass cross section magnified after VHT

Figure I.129. ~~CCC-CCC~~-Treated Glass LP2-OL-24 after VHT for 24 Days



a) Glass square magnified 20X before VHT



b) Glass cross section magnified after VHT

Figure I.130. ~~CCC-CCC~~-Heat-Treated Glass LP2-OL-25 after VHT for 24 Days

## Appendix J – Composition Analyses for Baseline and Sulfur-Saturated Glasses and Sulfur-Wash Solutions

This appendix presents and compares the normalized compositional analyses of the baseline and sulfur-saturated Phase 2 enhanced LAW glasses and sulfur-wash solutions using ICP-AES and IC. The comparisons in the tables are shown as percentage differences (%Diff). The %Diff results show how much SO<sub>3</sub> was retained in the glass. Statistical methods to assess statistically significant differences could have been performed, but were beyond the scope of this report (which focuses on data summaries, not data analyses).

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses

Components	Glass ID											
	LP2-IL-01				LP2-IL-02				LP2-IL-03			
	Measured Baseline	Sulfur-saturated	% Diff	Measured Baseline	Sulfur-saturated	% Diff	Measured Baseline	Sulfur-saturated	% Diff	Measured Baseline	Sulfur-saturated	% Diff
Al <sub>2</sub> O <sub>3</sub>	0.07001	0.07404	5.75	0.07342	0.07801	6.26	0.08262	0.08096	-2.00	0.07263	0.07345	1.13
B <sub>2</sub> O <sub>3</sub>	0.07736	0.07793	0.74	0.08213	0.08147	-0.79	0.08749	0.08428	-3.66	0.08283	0.07990	-3.54
CaO	0.07986	0.07412	-7.18	0.02326	0.02101	-9.67	0.02392	0.02172	-9.17	0.07667	0.07125	-7.07
Cl	0.00126	0.00054	-57.12	0.00116	0.00059	-49.37	0.00268	0.00124	-53.67	0.00228	0.00090	-60.27
Cr <sub>2</sub> O <sub>3</sub>	0.00527	0.00311	-41.01	0.00375	0.00293	-22.01	0.00532	0.00396	-25.65	0.00524	0.00291	-44.42
F	0.00228	0.00196	-14.11	0.00221	0.00186	-15.65	0.00473	0.00395	-16.54	0.00465	0.00396	-14.88
Fe <sub>2</sub> O <sub>3</sub>	0.00220	0.01289	486	0.00609	0.00489	-19.59	0.00226	0.00494	118	0.01076	0.01029	-4.41
K <sub>2</sub> O	0.02012	0.01492	-25.87	0.02003	0.01492	-25.50	0.00832	0.00668	-19.70	0.01958	0.01496	-23.63
MgO	0.00319	0.00285	-10.73	0.00988	0.00935	-5.35	0.00320	0.00296	-7.45	0.00992	0.00927	-6.53
Na <sub>2</sub> O	0.22549	0.22672	0.55	0.22616	0.23456	3.71	0.22624	0.23429	3.56	0.22565	0.23256	3.06
P <sub>2</sub> O <sub>5</sub>	0.00670	0.00458	-31.62	0.00522	0.00440	-15.73	0.00847	0.00881	3.98	0.00841	0.00947	12.61
SiO <sub>2</sub>	0.39635	0.39641	0.01	0.42962	0.43239	0.64	0.43294	0.42542	-1.74	0.40010	0.39631	-0.95
SO <sub>3</sub>	0.00817	0.01558	90.68	0.00799	0.01195	49.57	0.00216	0.01232	470	0.00231	0.01542	569
SnO <sub>2</sub>	0.00511	0.00549	7.53	0.02540	0.02460	-3.16	0.02631	0.02495	-5.18	0.02652	0.02478	-6.58
V <sub>2</sub> O <sub>5</sub>	0.02036	0.01739	-14.55	0.00495	0.00446	-10.04	0.00492	0.00452	-8.17	0.00491	0.00450	-8.41
ZnO	0.02460	0.02329	-5.33	0.02651	0.02478	-6.53	0.03239	0.03115	-3.83	0.02426	0.02348	-3.21
ZrO <sub>2</sub>	0.05166	0.04817	-6.76	0.05221	0.04783	-8.40	0.04603	0.04784	3.93	0.02329	0.02661	14.24

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-IL-05			LP2-IL-06			LP2-IL-07			LP2-IL-08		
	Measured Baseline	Sulfur-saturated	% Diff									
Al <sub>2</sub> O <sub>3</sub>	0.07135	0.07312	2.48	0.10244	0.10824	5.66	0.07047	0.07224	2.51	0.07303	0.07256	-0.65
B <sub>2</sub> O <sub>3</sub>	0.11564	0.11672	0.93	0.11929	0.12035	0.89	0.12042	0.11834	-1.73	0.08590	0.07933	-7.66
CaO	0.07316	0.06700	-8.42	0.02261	0.02241	-0.92	0.05416	0.05179	-4.38	0.08193	0.08139	-0.66
Cl	0.00247	0.00119	-51.64	0.00215	0.00095	-55.95	0.00272	0.00131	-51.97	0.00208	0.00093	-55.49
Cr <sub>2</sub> O <sub>3</sub>	0.00374	0.00313	-16.08	0.00516	0.00375	-27.30	0.00371	0.00324	-12.74	0.00513	0.00367	-28.43
F	0.00446	0.00361	-19.04	0.00418	0.00359	-14.14	0.00470	0.00383	-18.50	0.00448	0.00395	-11.81
Fe <sub>2</sub> O <sub>3</sub>	0.00228	0.00299	31.35	0.00215	0.00319	48.60	0.00124	0.00217	74.89	0.00998	0.01022	2.39
K <sub>2</sub> O	0.00534	0.00461	-13.68	0.01974	0.01597	-19.08	0.02002	0.01641	-18.02	0.00543	0.00445	-17.93
MgO	0.00309	0.00311	0.86	0.00973	0.00975	0.18	0.00971	0.00981	0.97	0.00983	0.01020	3.75
Na <sub>2</sub> O	0.20913	0.21747	3.99	0.21949	0.20777	-5.34	0.22232	0.22183	-0.22	0.21148	0.21074	-0.35
P <sub>2</sub> O <sub>5</sub>	0.00758	0.00987	30.22	0.00859	0.00941	9.51	0.00752	0.00994	32.21	0.00875	0.01079	23.31
SiO <sub>2</sub>	0.39199	0.38281	-2.34	0.38627	0.39313	1.78	0.40786	0.40423	-0.89	0.40317	0.40539	0.55
SO <sub>3</sub>	0.00215	0.01520	608	0.00771	0.01076	39.66	0.00789	0.01694	115	0.00771	0.01445	87.47
SnO <sub>2</sub>	0.02638	0.02437	-7.61	0.00819	0.00849	3.74	0.00382	0.00447	17.05	0.00405	0.00464	14.57
V <sub>2</sub> O <sub>5</sub>	0.00490	0.00449	-8.31	0.01008	0.00946	-6.14	0.00490	0.00478	-2.58	0.00488	0.00490	0.30
ZnO	0.02432	0.02297	-5.52	0.02318	0.02359	1.75	0.03151	0.03193	1.31	0.03142	0.03191	1.57
ZrO <sub>2</sub>	0.05203	0.04731	-9.09	0.04905	0.04919	0.28	0.02701	0.02675	-0.96	0.05075	0.05048	-0.53

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-IL-09			LP2-IL-10			LP2-IL-11			LP2-IL-12		
	Baseline	Sulfur-saturated	% Diff									
Al <sub>2</sub> O <sub>3</sub>	0.07171	0.07125	-0.64	0.09284	0.09480	2.12	0.08736	0.08614	-1.40	0.07026	0.07232	2.93
B <sub>2</sub> O <sub>3</sub>	0.12318	0.11481	-6.80	0.10302	0.09238	-10.33	0.08531	0.07834	-8.17	0.08091	0.07834	-3.19
CaO	0.02312	0.02272	-1.70	0.05345	0.05139	-3.84	0.03365	0.03317	-1.44	0.03473	0.03331	-4.10
Cl	0.00122	0.00057	-52.99	0.00140	0.00060	-57.60	0.00208	0.00103	-50.45	0.00262	0.00116	-55.58
Cr <sub>2</sub> O <sub>3</sub>	0.00518	0.00319	-38.37	0.00445	0.00275	-38.25	0.00370	0.00266	-28.08	0.00374	0.00325	-12.95
F	0.00226	0.00183	-19.04	0.00276	0.00227	-17.80	0.00442	0.00375	-15.02	0.00464	0.00371	-19.90
Fe <sub>2</sub> O <sub>3</sub>	0.00951	0.00951	0.06	0.00566	0.00571	0.98	0.00978	0.00981	0.34	0.00122	0.00217	78.19
K <sub>2</sub> O	0.00552	0.00472	-14.55	0.01107	0.00872	-21.22	0.01946	0.01644	-15.54	0.00539	0.00486	-9.98
MgO	0.00988	0.00992	0.37	0.00642	0.00665	3.53	0.00296	0.00311	4.85	0.00987	0.01004	1.70
Na <sub>2</sub> O	0.23805	0.23367	-1.84	0.22411	0.22978	2.53	0.21512	0.21933	1.96	0.23030	0.23416	1.68
P <sub>2</sub> O <sub>5</sub>	0.00633	0.00440	-30.58	0.00618	0.00614	-0.63	0.00776	0.00994	28.01	0.00770	0.01001	30.02
SiO <sub>2</sub>	0.37725	0.39030	3.46	0.39623	0.39539	-0.21	0.39371	0.39869	1.27	0.44635	0.43373	-2.83
SO <sub>3</sub>	0.00215	0.01501	599	0.00481	0.01396	190	0.00201	0.01236	516	0.00210	0.01536	630
SnO <sub>2</sub>	0.02152	0.02075	-3.56	0.01532	0.01418	-7.44	0.02570	0.02386	-7.17	0.00417	0.00476	14.24
V <sub>2</sub> O <sub>5</sub>	0.02026	0.01854	-8.51	0.00962	0.00958	-0.49	0.02003	0.01850	-7.65	0.02042	0.01900	-6.94
ZnO	0.03170	0.03229	1.85	0.02807	0.02827	0.71	0.03116	0.03203	2.80	0.02416	0.02377	-1.59
ZrO <sub>2</sub>	0.05117	0.04652	-9.09	0.03460	0.03744	8.21	0.05579	0.05084	-8.86	0.05143	0.05004	-2.71

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-IL-13			LP2-IL-14			LP2-IL-15			LP2-IL-16		
	Baseline	Sulfur-saturated	% Diff									
Al <sub>2</sub> O <sub>3</sub>	0.07355	0.07262	-1.26	0.08276	0.08510	2.83	0.07174	0.07204	0.42	0.09590	0.09580	-0.11
B <sub>2</sub> O <sub>3</sub>	0.11142	0.10652	-4.39	0.11539	0.11371	-1.45	0.10492	0.10096	-3.78	0.09270	0.08939	-3.57
CaO	0.02617	0.02564	-2.03	0.04203	0.04136	-1.60	0.02211	0.02117	-4.23	0.05348	0.05259	-1.66
Cl	0.00129	0.00062	-51.63	0.00248	0.00096	-61.41	0.00258	0.00112	-56.57	0.00141	0.00066	-52.96
Cr <sub>2</sub> O <sub>3</sub>	0.00517	0.00443	-14.33	0.00373	0.00218	-41.51	0.00527	0.00437	-17.10	0.00445	0.00314	-29.43
F	0.00205	0.00176	-14.24	0.00431	0.00347	-19.39	0.00423	0.00339	-19.72	0.00267	0.00231	-13.56
Fe <sub>2</sub> O <sub>3</sub>	0.00969	0.01072	10.53	0.00933	0.01027	10.02	0.00956	0.01070	11.91	0.00566	0.00670	18.26
K <sub>2</sub> O	0.01958	0.01698	-13.29	0.00552	0.00450	-18.50	0.00551	0.00461	-16.36	0.01103	0.00855	-22.45
MgO	0.00296	0.00288	-2.75	0.00303	0.00293	-3.27	0.00304	0.00298	-2.06	0.00650	0.00637	-2.08
Na <sub>2</sub> O	0.21781	0.22109	1.51	0.23981	0.23442	-2.25	0.21466	0.21425	-0.19	0.22807	0.21737	-4.69
P <sub>2</sub> O <sub>5</sub>	0.00610	0.00478	-21.61	0.00793	0.00862	8.62	0.00938	0.00923	-1.56	0.00626	0.00597	-4.63
SiO <sub>2</sub>	0.44078	0.43353	-1.65	0.39041	0.39545	1.29	0.44227	0.44901	1.52	0.39722	0.40721	2.51
SO <sub>3</sub>	0.00202	0.01265	526	0.00783	0.01524	94.57	0.00753	0.01276	69.45	0.00493	0.01366	177
SnO <sub>2</sub>	0.00437	0.00554	26.71	0.00481	0.00505	5.05	0.02447	0.02448	0.04	0.01462	0.01513	3.45
V <sub>2</sub> O <sub>5</sub>	0.00488	0.00467	-4.32	0.00497	0.00453	-8.85	0.02054	0.01841	-10.37	0.00973	0.00926	-4.86
ZnO	0.02403	0.02408	0.20	0.02415	0.02453	1.61	0.02428	0.02366	-2.56	0.02800	0.02833	1.17
ZrO <sub>2</sub>	0.04812	0.05150	7.03	0.05151	0.04767	-7.44	0.02793	0.02687	-3.79	0.03735	0.03757	0.59

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-IL-17			LP2-OL-01-3			LP2-OL-02-1			LP2-OL-03 MOD2		
	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff
Al <sub>2</sub> O <sub>3</sub>	0.08765	0.08998	2.66	0.05842	0.05588	-4.35	0.09054	0.09253	2.20	0.10010	0.09978	-0.32
B <sub>2</sub> O <sub>3</sub>	0.10513	0.10534	0.21	0.06190	0.05609	-9.40	0.09156	0.09020	-1.49	0.05829	0.05673	-2.68
CaO	0.02781	0.02749	-1.13	0.08716	0.08425	-3.34	0.05031	0.05158	2.52	0.11064	0.10937	-1.15
Cl	0.00063	<0.0005	--	0.00000	<0.0005	--	0.00145	<0.0005	--	0.00069	<0.0005	--
Cr <sub>2</sub> O <sub>3</sub>	0.00088	<0.0015	--	0.00735	0.00310	-57.79	0.00555	0.00240	-56.80	0.00702	0.00227	-67.64
F	0.00088	0.00078	-11.37	0.00074	0.00060	-18.34	0.00258	0.00189	-26.72	0.00104	<0.0006	--
Fe <sub>2</sub> O <sub>3</sub>	0.00167	0.00301	80.77	0.00429	<0.0014	--	0.01003	0.00627	-37.51	0.00482	<0.0014	--
K <sub>2</sub> O	0.00564	0.00458	-18.73	0.00000	<0.0012	--	0.00970	0.00690	-28.87	0.00000	<0.0012	--
MgO	0.00980	0.00975	-0.53	0.01315	0.01303	-0.91	0.00649	0.00640	-1.38	0.01380	0.01428	3.49
Na <sub>2</sub> O	0.22943	0.22585	-1.56	0.20078	0.20383	1.52	0.22577	0.22629	0.23	0.26820	0.27679	3.20
P <sub>2</sub> O <sub>5</sub>	0.00178	<0.0023	--	0.00000	<0.0023	--	0.00573	0.00521	-9.06	0.00184	0.00167	-9.57
SiO <sub>2</sub>	0.42028	0.42201	0.41	0.49166	0.49686	1.06	0.40808	0.41159	0.86	0.34949	0.35015	0.19
SO <sub>3</sub>	0.00964	0.01354	40.48	0.00158	0.01472	832	0.00475	0.01110	134	0.00743	0.01478	99.04
SnO <sub>2</sub>	0.00128	<0.0013	--	0.00000	<0.0013	--	0.01704	0.01669	-2.08	0.03037	0.02756	-9.23
V <sub>2</sub> O <sub>5</sub>	0.02110	0.01972	-6.56	0.00000	<0.0018	--	0.00945	0.00896	-5.17	0.00000	<0.0018	--
ZnO	0.02977	0.03058	2.73	0.01972	0.01975	0.14	0.02672	0.02748	2.84	0.02139	0.02107	-1.48
ZrO <sub>2</sub>	0.04666	0.04737	1.52	0.05326	0.05190	-2.56	0.03425	0.03452	0.80	0.02490	0.02556	2.66

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-OL-04-1			LP2-OL-05			LP2-OL-07-1			LP2-OL-08 MOD		
	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff
Al <sub>2</sub> O <sub>3</sub>	0.10384	0.10117	-2.58	0.12057	0.12202	1.20	0.09726	0.09594	-1.36	0.05880	0.05839	-0.69
B <sub>2</sub> O <sub>3</sub>	0.06410	0.05760	-10.13	0.06112	0.06087	-0.41	0.12595	0.11522	-8.52	0.06160	0.05874	-4.65
CaO	0.07453	0.07589	1.82	0.11020	0.10712	-2.79	0.08235	0.07517	-8.71	0.10746	0.10819	0.68
Cl	0.00000	<0.0005	--	0.00298	0.00192	-35.73	0.00208	0.00133	-36.25	0.00061	<0.0005	--
Cr <sub>2</sub> O <sub>3</sub>	0.00643	<0.0015	--	0.00393	0.00162	-58.83	0.00596	0.00273	-54.30	0.00708	0.00358	-49.43
F	0.00081	0.00071	-12.23	0.00607	0.00496	-18.29	0.00125	0.00108	-13.29	0.00079	0.00067	-14.13
Fe <sub>2</sub> O <sub>3</sub>	0.01898	0.01486	-21.72	0.01955	0.01503	-23.12	0.01368	0.00980	-28.32	0.01929	0.01581	-18.07
K <sub>2</sub> O	0.05390	0.04039	-25.08	0.00000	<0.0012	--	0.00215	0.00139	-35.60	0.00000	<0.0012	--
MgO	0.01280	0.01328	3.74	0.00000	<0.0017	--	0.01004	0.01030	2.58	0.00000	<0.0017	--
Na <sub>2</sub> O	0.20210	0.21319	5.49	0.19398	0.19564	0.86	0.19756	0.19775	0.09	0.25410	0.25814	1.59
P <sub>2</sub> O <sub>5</sub>	0.00000	<0.0023	--	0.01491	0.00828	-44.50	0.00267	<0.0024	--	0.00232	0.00212	-8.58
SiO <sub>2</sub>	0.36880	0.38057	3.19	0.41476	0.42776	3.13	0.38301	0.40925	6.85	0.36207	0.36070	-0.38
SO <sub>3</sub>	0.00158	0.01091	592	0.00948	0.01416	49.36	0.01033	0.01620	56.86	0.00646	0.01885	192
SnO <sub>2</sub>	0.00000	<0.0013	--	0.00000	<0.0013	--	0.00000	<0.0013	--	0.00482	0.00283	-41.16
V <sub>2</sub> O <sub>5</sub>	0.00000	<0.0018	--	0.00000	<0.0018	--	0.00949	0.00961	1.34	0.04025	0.03784	-5.99
ZnO	0.03538	0.03692	4.35	0.02039	0.02016	-1.11	0.03118	0.03013	-3.36	0.02061	0.02086	1.22
ZrO <sub>2</sub>	0.05675	0.05451	-3.95	0.02205	0.02047	-7.18	0.02504	0.02410	-3.78	0.05375	0.05328	-0.88

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-OL-09-1			LP2-OL-10 MOD			LP2-OL-11			LP2-OL-12		
	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff
Al <sub>2</sub> O <sub>3</sub>	0.12079	0.11592	-4.03	0.11691	0.11888	1.69	0.05581	0.05658	1.39	0.05847	0.05673	-2.99
B <sub>2</sub> O <sub>3</sub>	0.14041	0.13041	-7.13	0.05750	0.05903	2.66	0.13417	0.13139	-2.07	0.13930	0.13156	-5.55
CaO	0.01981	0.01921	-3.06	0.10955	0.11469	4.69	0.07935	0.07791	-1.82	0.08039	0.07617	-5.25
Cl	0.00000	<0.0005	--	0.00386	0.00114	-70.36	0.00052	<0.0005	--	0.00353	0.00230	-34.68
Cr <sub>2</sub> O <sub>3</sub>	0.00703	0.00380	-45.99	0.00413	0.00123	-70.27	0.00407	0.00141	-65.28	0.00697	0.00382	-45.27
F	0.00068	<0.0006	--	0.00662	0.00512	-22.74	0.00078	0.00071	-9.37	0.00594	0.00515	-13.36
Fe <sub>2</sub> O <sub>3</sub>	0.00580	<0.0014	--	0.01961	0.01508	-23.10	0.00334	<0.0014	--	0.01888	0.01462	-22.56
K <sub>2</sub> O	0.00000	<0.0012	--	0.00000	<0.0012	--	0.05406	0.04438	-17.91	0.00000	<0.0012	--
MgO	0.00000	<0.0017	--	0.00000	<0.0017	--	0.01350	0.01309	-3.00	0.01342	0.01318	-1.83
Na <sub>2</sub> O	0.194503	0.20269	3.92	0.20971	0.20855	-0.55	0.20419	0.21275	4.19	0.24666	0.24494	-0.69
P <sub>2</sub> O <sub>5</sub>	0.00245	<0.0023	--	0.01761	0.01326	-24.66	0.00237	0.00209	-11.81	0.01451	0.01221	-15.82
SiO <sub>2</sub>	0.40663	0.42397	4.27	0.39293	0.40356	2.70	0.37129	0.37122	-0.02	0.36839	0.37624	2.14
SO <sub>3</sub>	0.00110	0.01081	884	0.00734	0.01116	52.11	0.00149	0.01485	897	0.00139	0.02354	1595
SnO <sub>2</sub>	0.01562	0.01386	-11.27	0.00268	<0.0014	--	0.00268	<0.0013	--	0.00000	<0.0013	--
V <sub>2</sub> O <sub>5</sub>	0.03841	0.03657	-4.78	0.00000	<0.0018	--	0.00000	<0.0018	--	0.00000	<0.0018	--
ZnO	0.01978	0.01976	-0.12	0.02057	0.02160	5.00	0.01983	0.01939	-2.19	0.02041	0.02037	-0.16
ZrO <sub>2</sub>	0.02645	0.02301	-12.98	0.03099	0.02671	-13.81	0.05255	0.05423	3.19	0.02178	0.01917	-11.98

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-OL-13			LP2-OL-14			LP2-OL-15			LP2-OL-16 MOD		
	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff	Baseline	Sulfur-saturated	% Diff
Al <sub>2</sub> O <sub>3</sub>	0.05757	0.05750	-0.12	0.05829	0.05714	-1.98	0.05918	0.05586	-5.62	0.05396	0.05536	2.59
B <sub>2</sub> O <sub>3</sub>	0.06076	0.05884	-3.17	0.14430	0.12904	-10.58	0.14187	0.13080	-7.80	0.07203	0.07225	0.30
CaO	0.11149	0.11173	0.22	0.07495	0.06913	-7.77	0.10887	0.09947	-8.63	0.03020	0.03130	3.64
Cl	0.00306	0.00141	-53.95	0.00000	<0.0005	--	0.00000	<0.0005	--	0.00051	<0.0005	--
Cr <sub>2</sub> O <sub>3</sub>	0.00383	0.00150	-60.75	0.00706	0.00329	-53.38	0.00707	0.00355	-49.69	0.00700	0.00335	-52.07
F	0.00609	0.00508	-16.63	0.00074	0.00056	-23.47	0.00071	0.00061	-15.29	0.00074	0.00055	-25.29
Fe <sub>2</sub> O <sub>3</sub>	0.00374	<0.0017	--	0.00301	<0.0014	--	0.02051	0.01445	-29.55	0.01853	0.01457	-2137
K <sub>2</sub> O	0.05696	0.04621	-18.88	0.05870	0.04594	-21.74	0.00000	<0.0012	--	0.00000	<0.0012	--
MgO	0.00000	<0.0017	--	0.00000	<0.0017	--	0.00000	<0.0017	--	0.01282	0.01278	-0.31
Na <sub>2</sub> O	0.21019	0.22292	6.06	0.19924	0.20788	4.34	0.1545	0.20206	3.38	0.20194	0.19897	-1.47
P <sub>2</sub> O <sub>5</sub>	0.01803	0.01754	-2.68	0.00000	<0.0023	--	0.00000	<0.0023	--	0.00201	0.00174	-13.60
SiO <sub>2</sub>	0.36058	0.35975	-0.23	0.35491	0.38266	7.82	0.37227	0.38387	3.12	0.49174	0.49760	1.19
SO <sub>3</sub>	0.00104	0.01555	1389	0.01581	0.02619	65.67	0.00122	0.01975	1525	0.00883	0.01195	35.31
SnO <sub>2</sub>	0.00284	<0.0019	--	0.00000	<0.0013	--	0.03536	0.03202	-9.44	0.00434	0.00271	-37.48
V <sub>2</sub> O <sub>5</sub>	0.04059	0.03757	-7.43	0.04181	0.03768	-9.88	0.00000	<0.0018	--	0.03717	0.03634	-2.23
ZnO	0.03764	0.03784	0.55	0.02122	0.02023	-4.67	0.03626	0.03452	-4.79	0.03389	0.03503	3.36
ZrO <sub>2</sub>	0.02559	0.02654	3.70	0.01997	0.02026	1.45	0.02124	0.02305	8.51	0.02429	0.02550	4.98

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-OL-17			LP2-OL-18			LP2-OL-19			LP2-OL-20		
	Baseline	Sulfur-saturated	% Diff									
Al <sub>2</sub> O <sub>3</sub>	0.05860	0.05800	-1.04	0.05964	0.06124	2.68	0.05998	0.06054	0.94	0.05705	0.05664	-0.72
B <sub>2</sub> O <sub>3</sub>	0.06334	0.05781	-8.73	0.06122	0.06237	1.87	0.06362	0.06162	-3.14	0.05947	0.05695	-4.25
CaO	0.04452	0.04505	1.19	0.08913	0.09224	3.48	0.03694	0.03724	0.82	0.08273	0.08171	-1.23
Cl	0.00337	0.00190	-43.55	0.00329	0.00100	-69.45	0.00058	<0.0005	--	0.00066	<0.0005	--
Cr <sub>2</sub> O <sub>3</sub>	0.00387	<0.0015	--	0.00679	0.00259	-61.81	0.00447	0.00129	-71.17	0.00444	0.00190	-57.14
F	0.00618	0.00516	-16.52	0.00651	0.00543	-16.64	0.00085	0.00072	-15.19	0.00083	0.00080	-3.91
Fe <sub>2</sub> O <sub>3</sub>	0.01812	0.01475	-18.61	0.00477	<0.0014	--	0.02075	0.01610	-22.42	0.00549	<0.0014	--
K <sub>2</sub> O	0.05520	0.04621	-16.29	0.00000	<0.0012	--	0.05945	0.04915	-17.31	0.00000	<0.0012	--
MgO	0.01320	0.01315	-0.35	0.01324	0.01339	1.19	0.00000	<0.0017	--	0.00000	<0.0017	--
Na <sub>2</sub> O	0.21027	0.22342	6.26	0.20963	0.20648	-1.50	0.20207	0.21311	5.47	0.26211	0.27016	3.07
P <sub>2</sub> O <sub>5</sub>	0.01499	0.01196	-20.22	0.01320	0.01033	-21.71	0.00255	0.00212	-16.93	0.00220	0.00181	-17.47
SiO <sub>2</sub>	0.38970	0.39368	1.02	0.35247	0.36750	4.26	0.45472	0.46307	1.84	0.45702	0.44846	-1.87
SO <sub>3</sub>	0.00141	0.01789	1165	0.01036	0.01249	20.56	0.00653	0.01018	55.77	0.00123	0.01915	1455
SnO <sub>2</sub>	0.03482	0.03300	-5.24	0.03975	0.03796	-4.50	0.03820	0.03679	-3.68	0.00265	<0.0019	--
V <sub>2</sub> O <sub>5</sub>	0.03928	0.03669	-6.58	0.04104	0.03862	-5.90	0.00000	<0.0018	--	0.00000	<0.0018	--
ZnO	0.02015	0.02054	1.92	0.03829	0.03976	3.83	0.02118	0.02160	1.98	0.03813	0.03731	-215
ZrO <sub>2</sub>	0.02297	0.02080	-9.44	0.05066	0.04859	-4.10	0.02812	0.02646	-5.90	0.02599	0.02510	-3.41

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID											
	LP2-OL-21			LP2-OL-22			LP2-OL-23			LP2-OL-24		
	Baseline	Sulfur-saturated	% Diff									
Al <sub>2</sub> O <sub>3</sub>	0.09221	0.09287	0.71	0.06779	0.06749	-0.44	0.05545	0.05433	-2.01	0.11546	0.11707	1.40
B <sub>2</sub> O <sub>3</sub>	0.09296	0.09166	-1.40	0.06123	0.05988	-2.21	0.13342	0.12699	-4.82	0.05877	0.05568	-5.25
CaO	0.05053	0.05065	0.23	0.11149	0.10966	-1.64	0.10498	0.10592	0.90	0.07516	0.07456	-0.80
Cl	0.00160	0.00072	-54.87	0.00000	<0.0005	--	0.00056	<0.0005	--	0.00062	<0.0005	--
Cr <sub>2</sub> O <sub>3</sub>	0.00545	0.00213	-60.89	0.00391	0.00147	-62.40	0.00425	0.00220	-48.32	0.00426	0.00146	-65.81
F	0.00274	0.00232	-15.26	0.00078	0.00067	-13.72	0.00072	0.00055	-24.10	0.00096	0.00072	-25.32
Fe <sub>2</sub> O <sub>3</sub>	0.00939	0.00603	-35.75	0.01975	0.01552	-21.43	0.00602	<0.0014	--	0.01940	0.01478	-23.83
K <sub>2</sub> O	0.01041	0.00810	-22.12	0.00000	<0.0012	--	0.00000	<0.0012	--	0.00000	<0.0012	--
MgO	0.00634	0.00661	4.38	0.00000	<0.0017	--	0.01313	0.01363	3.75	0.01368	0.01377	0.68
Na <sub>2</sub> O	0.21651	0.22456	3.72	0.20025	0.20704	3.39	0.20573	0.20888	1.53	0.25558	0.25489	-0.27
P <sub>2</sub> O <sub>5</sub>	0.00623	0.00549	-11.80	0.00286	0.00252	-12.03	0.00196	0.00195	-0.36	0.00194	0.00195	030
SiO <sub>2</sub>	0.41480	0.41268	-0.51	0.37796	0.37600	-0.52	0.36620	0.37287	1.82	0.34382	0.34754	1.08
SO <sub>3</sub>	0.00495	0.01128	128	0.00108	0.01180	990	0.01167	0.01737	48.92	0.00130	0.01421	997
SnO <sub>2</sub>	0.01770	0.01607	-9.20	0.03716	0.03551	-4.43	0.03565	0.03392	-4.85	0.00253	<0.0019	--
V <sub>2</sub> O <sub>5</sub>	0.00937	0.00895	-4.44	0.04064	0.03749	-7.74	0.00000	<0.0018	--	0.04135	0.03775	-8.72
ZnO	0.02702	0.02730	1.06	0.02082	0.02044	-1.84	0.03437	0.03512	2.20	0.03857	0.03839	-0.46
ZrO <sub>2</sub>	0.03181	0.03257	2.39	0.05426	0.05450	0.45	0.02588	0.02626	1.47	0.02660	0.02724	2.39

Table J.1. Normalized Measured Compositions (mass fractions) for Baseline and Sulfur-Saturated Versions of the LAW Phase 2 Glasses (cont.)

Components	Glass ID		
	Baseline	Sulfur-saturated	% Diff
Al <sub>2</sub> O <sub>3</sub>	0.05918	0.05884	-0.58
B <sub>2</sub> O <sub>3</sub>	0.13734	0.13380	-2.58
CaO	0.02686	0.02783	3.64
Cl	0.00059	<0.0005	--
Cr <sub>2</sub> O <sub>3</sub>	0.00411	0.00150	-63.5
F	0.00078	0.00073	-6.75
Fe <sub>2</sub> O <sub>3</sub>	0.02038	0.01574	-22.76
K <sub>2</sub> O	0.00000	<0.0012	--
MgO	0.00000	<0.0017	--
Na <sub>2</sub> O	0.24420	0.24933	2.10
P <sub>2</sub> O <sub>5</sub>	0.00286	0.00261	-8.55
SiO <sub>2</sub>	0.36664	0.36533	-0.36
SO <sub>3</sub>	0.00809	0.01293	59.94
SnO <sub>2</sub>	0.03797	0.03622	-4.62
V <sub>2</sub> O <sub>5</sub>	0.00000	<0.0018	--
ZnO	0.03618	0.03776	4.37
ZrO <sub>2</sub>	0.05482	0.05739	4.68

Table J.2. Measured Concentrations for the Sulfur-Wash Solutions from Phase 2 Enhanced LAW Glasses (mg/L)

Component	LP2-IL-01	LP2-IL-02	LP2-IL-03	LP2-IL-04	LP2-IL-05	LP2-IL-06	LP2-IL-07	LP2-IL-08	LP2-IL-09	LP2-IL-10
Al	<1.00	<1.00	1.29	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
B	21.1	26.4	27.3	19.0	24.4	32.6	27.2	16.8	27.6	20.1
Ca	2.30	1.41	<1.00	1.96	<1.00	2.30	2.99	1.61	1.31	3.53
Cr	34.5	21.9	36.0	617	12.9	37.7	14.3	43.6	39.5	44.7
Fe	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
K	82.5	106	40.6	110	23.5	103	90.5	32.1	15.0	53.1
Li	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Mg	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Na	653	957	1030	793	698	996	775	885	602	819
P	5.95	15.0	32.0	16.1	7.10	21.1	10.2	7.73	8.48	9.88
S	373	606	561	487	414	604	495	544	332	508
Si	19.7	13.0	15.8	8.38	9.56	6.17	8.67	6.70	17.8	8.06
Sn	<1.00	<1.00	1.28	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
V	22.7	6.06	7.83	5.69	3.73	16.1	4.30	4.80	19.2	10.7
Zn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Zr	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Cl	<10.0	12.0	30.3	16.7	20.4	27.4	24.3	19.7	<10.0	10.9
F	<10.0	<10.0	13.7	<10.1	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
PO <sub>4</sub>	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
SO <sub>4</sub>	1130	1780	1680	1450	1240	1780	1450	1600	996	1503.33

Table J.2. Measured Concentrations for the Sulfur-Wash Solutions from LAW Phase 2 Glasses (mg/L) (cont)

Component	LP2-IL-11	LP2-IL-12	LP2-IL-13	LP2-IL-14	LP2-IL-15	LP2-IL-16	LP2-IL-17	LP2-OL-01-3	LP2-OL-02-1	LP2-OL-03MOD2
Al	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	9.47	1.42
B	17.3	19.5	25.3	24.7	23.0	23.0	26.8	10.3	23.4	13.4
Ca	1.36	1.58	2.60	2.66	<1.00	1.63	5.16	7.42	5.73	4.33
Cr	28.2	17.1	18.9	31.3	21.5	35.5	1.79	63.6	50.4	88.0
Fe	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
K	79.3	18.7	88.3	20.1	22.2	56.9	25.2	<1.00	46.7	<1.00
Li	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Mg	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Na	774	814	770	779	939	853	883	767	774	852
P	20.9	20.5	10.2	16.0	21.7	9.45	5.06	<1.00	8.21	3.69
S	546	464	503	410	542	521	587	457	422	418
Si	7.61	16.9	9.67	7.92	9.81	7.61	10.1	5.50	36.3	6.09
Sn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
V	31.7	28.4	4.22	4.90	27.1	11.0	21.7	<1.00	10.0	<1.00
Zn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Zr	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Cl	23.0	21.5	11.5	15.9	28.7	12.8	<10.0	<10.0	<10.0	<10.0
F	<1.00	<10.0	<10.0	<10.0	<1.00	<10.0	<10.0	<10.0	<10.0	<10.0
PO <sub>4</sub>	<100	<100	<100	<100	<100	<100	<100	<10.0	17.1	<10.0
SO <sub>4</sub>	1360	1360	1490	1360	1620	1540	1730	1450	1360	1430

Table J.2. Measured Concentrations for the Sulfur-Wash Solutions from LAW Phase 2 Glasses (mg/L) (cont)

Component	LP2-OL-04-1	LP2-OL-05	LP2-OL-07-1	LP2-OL-08MOD	LP2-OL-09-1	LP2-OL-10MOD	LP2-OL-11	LP2-OL-12	LP2-OL-13	LP2-OL-14
Al	1.79	1.31	1.01	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
B	15.1	14.1	24.5	17.0	33.1	9.91	75.3	40.2	103	44.7
Ca	<1.00	<1.00	19.5	11.9	10.2	4.78	10.6	<1.00	<1.00	9.13
Cr	108	32.0	61.1	68.7	56.0	42.1	73.5	57.0	204	57.3
Fe	<1.00	<1	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
K	397	<1.00	10.8	<1.00	<1.00	<1.00	523	<1.00	1430	243
Li	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Mg	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Na	642	1090	1030	830	913	910	1060	744	3240	669
P	2.60	3.03	<1.00	2.27	5.33	9.24	2.05	8.93	25.3	<1.00
S	470	656	609	382	497	513	699	324	1770	387
Si	6.01	6.46	6.72	19.0	7.13	2.74	27.2	29.1	154	26.9
Sn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
V	<1.00	<1.00	8.46	63.5	56.4	<1.00	<1.00	<1.00	387	49.9
Zn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Zr	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Cl	<10.0	46.8	21.8	<10.0	<10.0	21.8	<10.0	23.9	117	<10.0
F	<10.0	26.4	<10.0	<10.0	<10.0	20.6	<10.0	17.8	107	<10.0
PO <sub>4</sub>	<10.0	<10.0	<10.0	<10.0	<10.0	18.4	<10.0	18.1	56.6	<10.0
SO <sub>4</sub>	1440	2090	1830	1210	1600	1620	2160	1040	5480	1230

Table J.2. Measured Concentrations for the Sulfur-Wash Solutions from LAW Phase 2 Glasses (mg/L) (cont)

Component	LP2-OL-15	LP2-OL-16MOD	LP2-OL-17	LP2-OL-18	LP2-OL-19	LP2-OL-20	LP2-OL-21	LP2-OL-22	LP2-OL-23	LP2-OL-24	LP2-OL-25
Al	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	1.51	<1.00
B	23.3	11.0	19.0	13.0	20.0	10.8	21.9	18.2	28.6	12.4	69.2
Ca	13.0	10.3	<1.00	8.05	2.26	<1.00	<1.00	23.7	20.6	8.19	1.82
Cr	46.2	59.2	39.2	82.4	52.5	27.9	53.0	51.6	27.3	36.3	54.3
Fe	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
K	<1.00	<1.00	256	<1.00	358	<1.00	46.0	2.21	<1.00	<1.00	<1.00
Li	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Mg	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Na	673	935	726	1020	880	623	807	1157	777	718	1330
P	<1.00	4.65	28.0	9.12	6.24	1.99	8.26	1.44	2.10	3.05	8.12
S	369	514	377	510	627	349	449	646	447	372	737
Si	11.4	5.84	25.2	8.11	12.0	16.3	10.2	17.3	12.7	8.85	16.1
Sn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
V	<1.00	42.4	90.1	79.6	<1.00	<1.00	11.0	78.6	<1.00	67.5	<1.00
Zn	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Zr	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00	<1.00
Cl	<10.0	<10.0	27.6	23.1	<10.0	<10.0	13.8	<10.0	<10.0	<10.0	<10.0
F	<10.0	<10.0	24.9	19.2	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
PO <sub>4</sub>	<10.0	<10.0	64.2	20.2	13.6	<10.0	15.7	<10.0	<10.0	<10.0	17.9
SO <sub>4</sub>	1200	1620	1160	1690	1930	1130	1360	2020	1380	1160	2270

# **Pacific Northwest National Laboratory**

902 Battelle Boulevard  
P.O. Box 999  
Richland, WA 99354  
1-888-375-PNNL (7665)

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