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Corrosion Testing of Refractory in Contact with Molten Glasses Designed for Waste Vitrification - VSL Touchpoint Matrix Glasses

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PREFACE AND ACKNOWLEDGEMENTS

This document serves to convey the refractory loss measurement results from corrosion testing of Monofrax® K-3 refractory by molten glass to support the enhanced waste glass program being led by Pacific Northwest National Laboratory (PNNL). Any discussion or conclusions to be drawn from the data are not presented in this report. The refractory corrosion data is intended to be used in the development, validation, and implementation of enhanced property/composition models for waste glass vitrification at Hanford. Funding for this work by the U.S. Department of Energy Office of River Protection Waste Treatment & Immobilization Plant Project through Department of Energy Work Authorization M0SRV00101 managed by Albert A. Kruger is gratefully acknowledged.

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LIST OF ABBREVIATIONS

DOE	Department of Energy
DWPF	Defense Waste Processing Facility
HF	Hydrofluoric
HLW	High-level waste
INL	Idaho National Laboratory
LAW	Low activity waste
PNNL	Pacific Northwest National Laboratory
SA/V	Surface area to volume ratio
SRNL	Savannah River National Laboratory
WTP	Waste Treatment and Immobilization Plant

1.0 Introduction

It is known that the predictive life of the refractory ceramic liner of nuclear waste glass melters is conservative, as demonstrated by performance of these materials such as in the Defense Waste Processing Facility (DWPF).[1] The motivation for this task is to maximize the useful life of the melters that will be operated at the Waste Treatment and Immobilization Plant (WTP), which will in turn minimize procurement and disposal costs and melter outage times, as well as to identify maximum loadings in the waste glass of those species that corrode melter components. This task was initiated jointly with Pacific Northwest National Laboratory (PNNL) with the objective to develop a methodology and model to enable more accurate prediction of refractory service life under prototypic conditions from laboratory-scale material corrosion tests.

Refractory corrosion is generally reported as physical material loss, measured in units of distance (e.g., inch) or as physical material loss rate, measured in units of distance per time (e.g., inch/day). In post-operational melters, the refractory corrosion is measured directly, sometimes reported as corrosion depth. Crucible tests are used in the laboratory to accelerate the refractory corrosion to facilitate a meaningful measurement in a commensurate amount of time. Crucible tests are particularly useful in understanding refractory corrosion across a large glass composition space, where operational testing would be prohibitive. Some of the critical parameters that are known to influence refractory corrosion by molten glass in a crucible test are temperature, system redox, molten salt phases, glass chemistry, and test duration.

The majority of data collected for Monofrax® K-3 (hereafter referred to as K-3) corrosion is from crucible tests, but a small amount comes directly from scaled and production melters. Crucible test data has been collected under varying conditions, whereas data collected from operational melters is relatively fewer and represents conditions specific to the melter campaign. The result is that the published data can be grouped and analyzed in multiple ways, not all of which are readily comparable.

The Standard Test Method for Isothermal Corrosion Resistance of Refractories to Molten Glass (ASTM C621)[2] outlines the general guidelines used across industry. That method describes a sealed, static test in which the surface area of the refractory coupon and the volume of glass are fixed. A significant portion of the crucible data pertaining to nuclear waste glasses has been collected in a modified configuration; the most notable differences being the surface area of the refractory coupon to volume of the glass and use of a method for bubbling the melt. To our knowledge, the influence of those parameters on the refractory corrosion has not been quantified.

In this work, it was determined that static tests and bubbled tests would be performed. Savannah River National Laboratory (SRNL) was tasked with setting up and performing static testing while PNNL was tasked with setting up and performing bubbled testing.[1] Initial activities were performed to establish laboratory methods that reproduce data comparable to existing data sets of K-3 refractory corrosion by low activity waste (LAW) and high-level waste (HLW) glass compositions. Later activities were focused on refining the test parameters to establish a standard test practice to be used between Laboratories and collecting additional data to be used in the enhanced waste glass model development.

[1] The purpose of bubbling melts in this work was to induce a fluid flow between the refractory coupon and the molten glass prototypic of that observed in the WTP melters. This flow rate and bubbler geometry was developed with the Idaho National Laboratory (INL). In addition to the static and bubbled tests, a dynamic test in which the refractory coupon is moved through the molten glass was conducted at University of Chemistry and Technology in Prague, Czech Republic. Those tests were intended to provide insight into the effects of erosion that contribute to the measured corrosion profile. These activities are reported elsewhere.

This document serves primarily to convey the refractory loss measurement results from corrosion testing of K-3 refractory with waste glass compositions developed for use in the WTP melters. The data will be used in the enhanced property/composition models being developed for waste glass vitrification and melter operations.

2.0 Experimental Procedure

2.1 Materials

K-3 test coupons and pre-melted glass were prepared at PNNL and provided to SRNL for use in testing. A set of thirty glass compositions were provided to SRNL, their identifiers are listed in Table 2-1 and compositions can be found in Appendix D.

Table 2-1. List of Glasses, Test Identifiers (IDs), and Test Parameters Used in Corrosion Testing.

	Corrosion Test Parameters (Temperature/Time)			
	1200 ºC 168 hours (7 days)	1150 ºC 168 hours (7 days)	1200 ºC 72 hours (3 days)	1150 ºC 72 hours (3 days)
Glass ID	**Test ID**	**Test ID**	**Test ID**	**Test ID**
ORPLE4	ORPLE4-1200-7	ORPLE4-1150-7	ORPLE4-1200-3	ORPLE4-1150-3
ISG-2	ISG-2-1200-7	ISG-2-1150-7	ISG-2-1200-3	ISG-2-1150-3
LORPM4R2	LORPM4R2-1200-7	LORPM4R2-1150-7	LORPM4R2-1200-3	LORPM4R2-1150-3
LAWA187	LAWA187-1200-7	LAWA187-1150-7	LAWA187-1200-3	LAWA187-1150-3
AY102D2-05	AY102D2-05-1200-7	AY102D2-05-1150-7	AY102D2-05-1200-3	AY102D2-05-1150-3
LAWA44PNCC	LAWA44PNCC-1200-7	LAWA44PNCC-1150-7	LAWA44PNCC-1200-3	LAWA44PNCC-1150-3
ORPLG27	ORPLG27-1200-7	ORPLG27-1150-7	ORPLG27-1200-3	ORPLG27-1150-3

2.2 Refractory Coupon Size and Preparation

These coupons were first measured for acceptable dimension and tolerances. Coupons that were not in the specification were prepared to be brought into tolerance or discarded. Coupon dimensions were maintained at approximately 10 mm (0.39 inch) square by approximately 60 mm (2.36 inch) in length. Width dimensions were generally controlled to ± 0.005 mm/mm along the length of the specimen. [2] Prior to use, prepared coupons were sonicated in deionized water for 5-10 minutes to remove loose material and surface contamination and subsequently dried in an oven at approximately 90 °C.

Orientation of coupons was maintained for initial and post-test coupon measurements via the use of a distinguishing feature on the coupon or a registration mark made above the expected glass line. Each test coupon was measured at a minimum of three (3) locations along the length of the coupon; one measurement at the anticipated melt line, one measurement below the expected melt line, approximately half-way between the expected melt line and the bottom of the coupon, and one measurement well above the expected melt line. Width measurements were made at each location using a caliper.

2.3 Crucible Test Configuration

Pt/Au alloy crucibles were used in this testing, all having equal dimension and a nominal working volume of 100 ml with an opening diameter approximately 57 mm and a height of 58 mm. Testing was conducted

[2] Due to programmatic constraints, some coupon dimensions were outside this tolerance. While the results are not expected to be influenced significantly, select coupons may be re-measured for confirmation.

by placing the refractory coupon directly on the bottom of the crucible. The melt line was estimated using a known volume of glass and was located approximately 20 mm from the bottom of the coupon. The coupon protruded beyond the top of the crucible and was held in place with either a Pt/Au alloy or Al_2O_3 lid with a pre-made hole to stabilize the coupon. In this manner, while the system was covered, it was not sealed to the atmosphere. A schematic of the setup is shown in Figure 2-1.

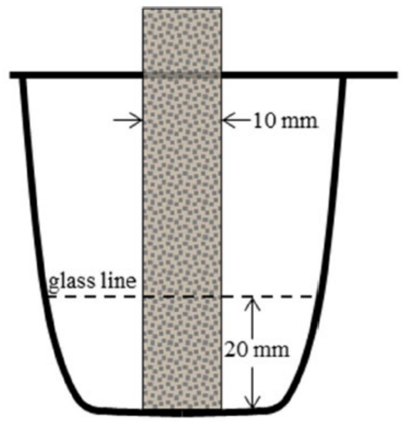

Figure 2-1. Schematic representation of the static crucible corrosion test configuration.

2.4 Corrosion Testing

For each glass, a prepared refractory coupon was placed in the center of a Pt/Au alloy crucible. An appropriate amount of glass was added to the crucible, surrounding the coupon, to reach the targeted melt line. The estimated initial ratio of refractory surface area to glass volume (SA/V) was 0.27.[1] A lid was fit to the crucible and coupon that was then loaded into a furnace at room temperature. The furnace was heated nominally at 10 °C/min to the desired hold temperature. Each glass experienced four time-temperature combinations of 1200 °C for 7 days, 1200 °C for 3 days, 1150 °C for 7 days, and 1150 °C for 3 days. When the test duration time elapsed, the coupons were removed from the glass at temperature and allowed to cool.

After testing, residual glass on the coupons was removed using a hydrofluoric (HF) acid treatment. Coupons were submerged in HF acid and then rinsed in water for 15 minutes. The total time in HF acid for each coupon varied between 6-30 hours to remove the residual glass and expose the refractory for measurement. The coupons were inspected periodically and considered sufficiently cleaned when the coupon edges at and below the corroded neck were exposed and free of glass, as determined visually.

2.5 Calculation of Refractory Loss

After removing the residual glass, the three positions on the coupon identified in Section 2.0 were established: the melt-line (g), the half-way line (h), and the top position above the melt-line (P1). The positions are shown schematically in Figure 2-2. All four faces at those locations were measured using a stereo optical microscope. The corrosion at a specific position was computed using the following equation:

$$P_c = \frac{[P - (p_1 + p_2 + p_3 + p_4)/4]}{2}, \text{ where}$$

P_c = corrosion at position P, in mm, P = average width of coupon at position P before test, in mm, and ($p_1 + p_2 + p_3 + p_4$) = width of the four faces of the cleaned coupon measured at position P after test, in mm.

To maintain a common nomenclature with the ASTM C621, neck-line (melt-line) corrosion is denoted with the letters G/g and half-way line corrosion is denoted with the letters H/h.

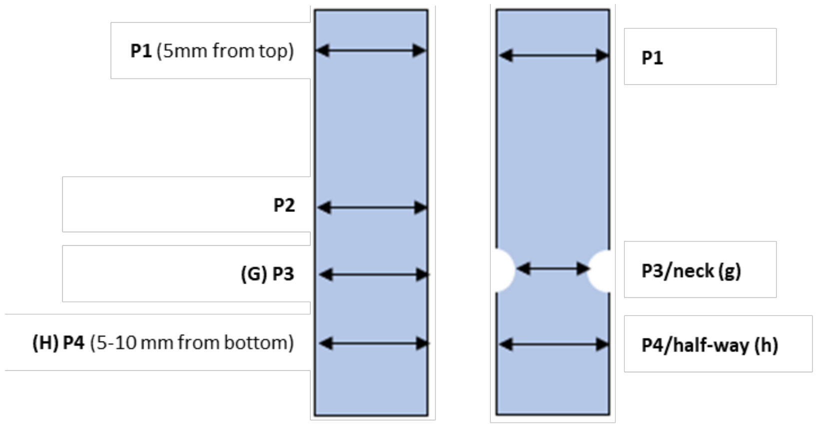

Figure 2-2. Schematic of refractory coupon position measurements before (left) and after (right) corrosion testing.

2.6 Quality Assurance

The task activities were controlled under the Task Technical and Quality Assurance Plan (TTQAP) for Hanford Waste Glass Development and Characterization.[3]

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2. Activities performed in this task are compliant to both American Society of Mechanical Engineers (ASME) NQA-1-2008 with NQA-1a-2009 addenda and NQA-1-2019.

3.0 Results and Discussion

3.1 Refractory Coupons

Images of the K-3 coupons after testing and cleaning in HF acid are provided in Appendix A . In general, the melt line corrosion is readily visible and all neck lines remained intact. Residual glass on the refractory coupon after testing can influence the refractory loss measurement. Nevertheless, the amount of exposed K-3 after HF acid cleaning was sufficient for measurements of the material loss at the melt-line and, in most cases, the half-way line for all samples.

A summary of the coupon dimensions and corrosion measurements (material loss) for three positions (including the melt-line and half-way positions) along the refractory coupons are provided in Appendix B and Appendix C, respectively.

4.0 References

1. Jin, T.; Hall, M. A.; Vienna, J. D.; Eaton, W. C.; Amoroso, J. W.; Wiersma, B. J.; Li, W.; Abboud, A. W.; Guillen, D. P.; Kruger, A. A., Glass-contact refractory of the nuclear waste vitrification melters in the United States: a review of corrosion data and melter life. *Int. Mater. Rev.* **2023**.
2. *Standard Test Method for Isothermal Corrosion Resistance of Refractories to Molten Glass*; 2018.
3. Amoroso, J. W. *Task Technical and Quality Assurance Plan for Hanford Waste Glass Development and Characterization*; SRNL-RP- 2013-00692, Revision 2; Savannah River National Laboratory: Aiken, SC, 2023.

Appendix A: Digital Images of Refractory Coupons After Glass Corrosion Testing Before and After HF Acid Cleaning.

Sequence #	Glass ID	Test ID	Post-corrosion test	HF cleaned post-corrosion test
1	ORPLE4	ORPLE4-1200-7		
2	ISG-2	ISG-2-1200-7		
3	LORPM4R2	LORPM4R2-1200-7		
4	LAWA187	LAWA187-1200-7		
5	AY102D2-05	AY102D2-05-1200-7		
6	LAWA44PNCC	LAWA44PNCC-1200-7		
7	ORPLG27	ORPLG27-1200-7		
8	ORPLE4	ORPLE4-1150-7		
9	ISG-2	ISG-2-1150-7		
10	LORPM4R2	LORPM4R2-1150-7		
11	LAWA187	LAWA187-1150-7		
12	AY102D2-05	AY102D2-05-1150-7		
13	LAWA44PNCC	LAWA44PNCC-1150-7		
14	ORPLG27	ORPLG27-1150-7		
15	ORPLE4	ORPLE4-1200-3		
16	ISG-2	ISG-2-1200-3		

Sequence #	Glass ID	Test ID	Post-corrosion test	HF cleaned post-corrosion test
17	LORPM4R2	LORPM4R2-1200-3		
18	LAWA187	LAWA187-1200-3		
19	AY102D2-05	AY102D2-05-1200-3		
20	LAWA44PNCC	LAWA44PNCC-1200-3		
21	ORPLG27	ORPLG27-1200-3		
22	ORPLE4	ORPLE4-1150-3		
23	ISG-2	ISG-2-1150-3		
24	LORPM4R2	LORPM4R2-1150-3		
25	LAWA187	LAWA187-1150-3		
26	AY102D2-05	AY102D2-05-1150-3		
27	LAWA44PNCC	LAWA44PNCC-1150-3		
28	ORPLG27	ORPLG27-1150-3		

Appendix B: Initial Refractory Coupon Data

Test ID	Temp	Time	SA/V	Corrosion Position (P)	Length (L) from bottom	Side 1 & 3	Side 2 & 4	Average (s)	Tolerance (mm/mm) = |((s_P1-s_P4) / (L_P1-L_P4))|
Unit	°C	Days	in^{-1}	-	mm	mm	mm	mm	-
ORPLE4-1200-7	1200	7	0.27	P1 (top)	55.98	9.96	10.07	10.02	0.0026
				P3 (**G**, neck)	20.00	9.90	9.96	9.93	
				P4 (**H**, bottom)	10.00	9.87	9.92	9.90	
ISG-2-1200-7	1200	7	0.27	P1 (top)	53.28	10.01	9.93	9.97	0.0003
				P3 (**G**, neck)	20.00	9.97	10.01	9.99	
				P4 (**H**, bottom)	10.00	9.97	10.01	9.99	
LORPM4R2-1200-7	1200	7	0.27	P1 (top)	54.78	10.07	9.80	9.94	0.0016
				P3 (**G**, neck)	20.00	10.06	9.95	10.00	
				P4 (**H**, bottom)	10.00	10.05	9.97	10.01	
LAWA187-1200-7	1200	7	0.27	P1 (top)	53.96	9.92	9.88	9.90	0.0019
				P3 (**G**, neck)	20.00	9.98	9.96	9.97	
				P4 (**H**, bottom)	10.00	9.98	9.99	9.98	
AY102D2-05-1200-7	1200	7	0.27	P1 (top)	56.15	10.08	10.02	10.05	0.0026
				P3 (**G**, neck)	20.00	10.01	9.94	9.97	
				P4 (**H**, bottom)	10.00	9.97	9.88	9.93	
LAWA44PNCC-1200-7	1200	7	0.27	P1 (top)	55.50	9.80	10.06	9.93	0.0006
				P3 (**G**, neck)	20.00	9.83	10.04	9.93	
				P4 (**H**, bottom)	10.00	9.82	9.99	9.90	
ORPLG27-1200-7	1200	7	0.27	P1 (top)	55.51	10.01	9.68	9.85	0.0024
				P3 (**G**, neck)	20.00	10.02	9.87	9.94	
				P4 (**H**, bottom)	10.00	10.02	9.89	9.95	
ORPLE4-1150-7	1150	7	0.27	P1 (top)	54.33	10.10	10.00	10.05	0.0005
				P3 (**G**, neck)	20.00	10.08	10.00	10.04	
				P4 (**H**, bottom)	10.00	10.05	10.00	10.03	
ISG-2-1150-7	1150	7	0.27	P1 (top)	54.96	9.97	10.03	10.00	0.0011
				P3 (**G**, neck)	20.00	10.00	10.09	10.05	
				P4 (**H**, bottom)	10.00	10.01	10.09	10.05	
LORPM4R2-1150-7	1150	7	0.27	P1 (top)	56.88	10.09	10.01	10.05	0.0003
				P3 (**G**, neck)	20.00	10.06	10.05	10.05	
				P4 (**H**, bottom)	10.00	10.04	10.03	10.03	
LAWA187-1150-7	1150	7	0.27	P1 (top)	55.90	9.89	10.00	9.95	0.0015
				P3 (**G**, neck)	20.00	9.95	10.07	10.01	
				P4 (**H**, bottom)	10.00	9.96	10.07	10.02	
AY102D2-05-1150-7	1150	7	0.27	P1 (top)	54.97	10.07	9.88	9.98	0.0007
				P3 (**G**, neck)	20.00	10.02	9.97	9.99	
				P4 (**H**, bottom)	10.00	10.03	9.99	10.01	
LAWA44PNCC-1150-7	1150	7	0.27	P1 (top)	54.88	10.15	10.02	10.09	0.0006
				P3 (**G**, neck)	20.00	10.11	10.02	10.06	
				P4 (**H**, bottom)	10.00	10.13	9.99	10.06	
ORPLG27-1150-7	1150	7	0.27	P1 (top)	53.53	10.09	9.97	10.03	0.0002
				P3 (**G**, neck)	20.00	10.06	9.99	10.02	
				P4 (**H**, bottom)	10.00	10.04	10.01	10.02	
ORPLE4-1200-3	1200	3	0.27	P1 (top)	56.07	10.04	9.94	9.99	0.0019
				P3 (**G**, neck)	20.00	10.10	10.04	10.07	
				P4 (**H**, bottom)	10.00	10.09	10.06	10.08	
ISG-2-1200-3	1200	3	0.27	P1 (top)	55.44	10.02	10.06	10.04	0.0001
				P3 (**G**, neck)	20.00	10.04	10.07	10.05	
				P4 (**H**, bottom)	10.00	10.04	10.05	10.04	
LORPM4R2-1200-3	1200	3	0.27	P1 (top)	55.72	10.05	10.05	10.05	0.0002
				P3 (**G**, neck)	20.00	10.00	10.05	10.02	
				P4 (**H**, bottom)	10.00	10.05	10.03	10.04	
LAWA187-1200-3	1200	3	0.27	P1 (top)	54.11	10.12	10.09	10.11	0.0002

Test ID / Unit	Temp (°C)	Time (Days)	SA/V (in^{-1})	Corrosion Position (P)	Length (L) from bottom (mm)	Side 1 & 3 (mm)	Side 2 & 4 (mm)	Average (s) (mm)	Tolerance (mm/mm) = $\lvert((s_{P1}-s_{P4}) / (L_{P1}-L_{P4}))\rvert$ (-)
				P3 (**G**, neck)	20.00	10.11	10.12	10.11	
				P4 (**H**, bottom)	10.00	10.09	10.11	10.10	
AY102D2-05-1200-3	1200	3	0.27	P1 (top)	54.71	9.94	9.87	9.90	0.0034
				P3 (**G**, neck)	20.00	10.13	9.96	10.04	
				P4 (**H**, bottom)	10.00	10.14	9.98	10.06	
LAWA44PNCC-1200-3	1200	3	0.27	P1 (top)	56.37	10.12	9.99	10.05	0.0005
				P3 (**G**, neck)	20.00	10.14	9.96	10.05	
				P4 (**H**, bottom)	10.00	10.15	9.92	10.03	
ORPLG27-1200-3	1200	3	0.27	P1 (top)	56.94	10.10	10.08	10.09	0.0007
				P3 (**G**, neck)	20.00	10.13	10.10	10.11	
				P4 (**H**, bottom)	10.00	10.13	10.11	10.12	
ORPLE4-1150-3	1150	3	0.27	P1 (top)	54.86	10.03	9.91	9.97	0.0049
				P3 (**G**, neck)	20.00	10.14	10.17	10.15	
				P4 (**H**, bottom)	10.00	10.17	10.20	10.19	
ISG-2-1150-3	1150	3	0.27	P1 (top)	55.09	10.24	10.12	10.18	0.0022
				P3 (**G**, neck)	20.00	10.14	10.15	10.14	
				P4 (**H**, bottom)	10.00	10.03	10.13	10.08	
LORPM4R2-1150-3	1150	3	0.27	P1 (top)	55.82	9.83	9.98	9.90	0.0064
				P3 (**G**, neck)	20.00	10.08	10.13	10.11	
				P4 (**H**, bottom)	10.00	10.22	10.18	10.20	
LAWA187-1150-3	1150	3	0.27	P1 (top)	53.78	10.11	9.99	10.05	0.0024
				P3 (**G**, neck)	20.00	10.13	10.15	10.14	
				P4 (**H**, bottom)	10.00	10.12	10.19	10.16	
AY102D2-05-1150-3	1150	3	0.27	P1 (top)	53.70	10.01	10.16	10.08	0.0022
				P3 (**G**, neck)	20.00	9.87	10.18	10.02	
				P4 (**H**, bottom)	10.00	9.83	10.15	9.99	
LAWA44PNCC-1150-3	1150	3	0.27	P1 (top)	55.08	10.16	10.03	10.09	0.0022
				P3 (**G**, neck)	20.00	10.15	9.87	10.01	
				P4 (**H**, bottom)	10.00	10.17	9.83	10.00	
ORPLG27-1150-3	1150	3	0.27	P1 (top)	55.02	10.07	10.22	10.14	0.0027
				P3 (**G**, neck)	20.00	10.02	10.12	10.07	
				P4 (**H**, bottom)	10.00	10.00	10.04	10.02	

Appendix C: Refractory Coupon Corrosion Data

↓Test ID	Temp	Time	SA/V	Corrosion Position (P)	Side 1 (p_1)	Side 2 (p_2)	Side 3 (p_3)	Side 4 (p_4)	$P_{avg.} = (p_1 + p_2 + p_3 + p_4)/4$	$P_c = (P-p_{avg})]/2$	$P_c = (P-p_{avg})]/2$
Unit→	°C	Days	in^{-1}	-	mm	mm	mm	mm	mm	mm	inch
ORPLE4-1200-7	1200	7	0.27	P1 (top)	10.25	10.39	10.21	10.32	10.29	-0.14	-0.0055
				P3 (**G**, neck)	5.50	4.99	5.16	5.38	5.26	2.34	0.0919
				P4 (**H**, bottom)	9.02	9.16	9.02	9.02	9.06	0.42	0.0165
ISG-2-1200-7	1200	7	0.27	P1 (top)	10.15	10.16	10.14	10.16	10.15	-0.09	-0.0036
				P3 (**G**, neck)	9.16	9.32	9.18	9.16	9.21	0.39	0.0154
				P4 (**H**, bottom)	9.79	9.92	9.65	9.71	9.77	0.11	0.0043
LORPM4R2-1200-7	1200	7	0.27	P1 (top)	10.18	10.02	10.21	9.97	10.10	-0.08	-0.0031
				P3 (**G**, neck)	9.38	9.24	9.30	9.09	9.25	0.37	0.0147
				P4 (**H**, bottom)	9.91	9.85	9.83	9.84	9.86	0.07	0.0029
LAWA187-1200-7	1200	7	0.27	P1 (top)	10.06	10.15	10.02	10.07	10.08	-0.09	-0.0035
				P3 (**G**, neck)	6.19	5.62	6.07	5.82	5.93	2.02	0.0795
				P4 (**H**, bottom)	9.38	9.24	9.18	8.79	9.15	0.42	0.0164
AY102D2-05-1200-7	1200	7	0.27	P1 (top)	10.15	10.12	10.17	10.09	10.13	-0.04	-0.0017
				P3 (**G**, neck)	7.58	7.57	8.29	7.72	7.79	1.09	0.0429
				P4 (**H**, bottom)	9.57	9.57	9.69	9.55	9.60	0.17	0.0065
LAWA44PNCC-1200-7	1200	7	0.27	P1 (top)	9.92	10.17	9.92	10.15	10.04	-0.06	-0.0022
				P3 (**G**, neck)	8.32	8.75	8.40	8.67	8.54	0.70	0.0275
				P4 (**H**, bottom)	9.56	9.68	9.49	9.64	9.59	0.15	0.0061
ORPLG27-1200-7	1200	7	0.27	P1 (top)	10.20	9.87	10.20	9.81	10.02	-0.09	-0.0034
				P3 (**G**, neck)	6.60	6.58	6.40	6.57	6.54	1.70	0.0670
				P4 (**H**, bottom)	9.86	9.63	9.89	9.76	9.79	0.08	0.0033
ORPLE4-1150-7	1150	7	0.27	P1 (top)	10.34	10.17	10.36	10.20	10.27	-0.11	-0.0043
				P3 (**G**, neck)	5.78	5.63	5.97	6.17	5.89	2.08	0.0817
				P4 (**H**, bottom)	9.66	9.63	9.60	9.58	9.62	0.20	0.0080
ISG-2-1150-7	1150	7	0.27	P1 (top)	10.16	10.18	10.13	10.14	10.15	-0.08	-0.0031
				P3 (**G**, neck)	9.61	9.64	9.68	9.59	9.63	0.21	0.0082
				P4 (**H**, bottom)	9.99	9.99	10.01	10.01	10.00	0.02	0.0009
LORPM4R2-1150-7	1150	7	0.27	P1 (top)	10.16	10.04	10.19	10.07	10.12	-0.03	-0.0013
				P3 (**G**, neck)	9.32	9.23	9.33	9.07	9.24	0.41	0.0160
				P4 (**H**, bottom)	10.11	9.91	9.99	9.89	9.98	0.03	0.0011
LAWA187-1150-7	1150	7	0.27	P1 (top)	10.84	10.83	10.75	10.78	10.80	-0.43	-0.0168
				P3 (**G**, neck)	6.42	5.97	5.97	6.48	6.21	1.90	0.0748
				P4 (**H**, bottom)	9.68	9.75	9.51	9.73	9.67	0.17	0.0068
AY102D2-05-1150-7	1150	7	0.27	P1 (top)	10.22	10.14	10.2	10.16	10.18	-0.10	-0.0040
				P3 (**G**, neck)	9.39	9.10	9.34	9.30	9.28	0.36	0.0140
				P4 (**H**, bottom)	9.91	9.92	9.92	9.86	9.90	0.05	0.0020
LAWA44PNCC-1150-7	1150	7	0.27	P1 (top)	10.24	10.13	10.2	10.17	10.19	-0.05	-0.0020
				P3 (**G**, neck)	9.11	9.03	8.88	8.91	8.98	0.54	0.0212
				P4 (**H**, bottom)	9.86	9.81	9.71	9.71	9.77	0.14	0.0057
ORPLG27-1150-7	1150	7	0.27	P1 (top)	10.21	10.10	10.25	10.07	10.16	-0.06	-0.0025
				P3 (**G**, neck)	6.48	6.76	6.90	6.75	6.72	1.65	0.0650
				P4 (**H**, bottom)	9.89	9.84	9.85	9.85	9.86	0.08	0.0032
ORPLE4-1200-3	1200	3	0.27	P1 (top)	10.26	10.12	10.29	10.15	10.21	-0.11	-0.0043
				P3 (**G**, neck)	6.93	6.92	6.75	6.82	6.86	1.61	0.0632
				P4 (**H**, bottom)	9.70	9.69	9.78	9.63	9.70	0.19	0.0074
ISG-2-1200-3	1200	3	0.27	P1 (top)	10.09	10.10	10.08	10.12	10.10	-0.03	-0.0012
				P3 (**G**, neck)	9.46	9.42	9.43	9.42	9.43	0.31	0.0122
				P4 (**H**, bottom)	9.87	9.80	9.76	9.82	9.81	0.12	0.0045
LORPM4R2-1200-3	1200	3	0.27	P1 (top)	10.11	10.11	10.11	10.08	10.10	-0.03	-0.0011
				P3 (**G**, neck)	9.48	9.52	9.58	9.37	9.49	0.27	0.0105
				P4 (**H**, bottom)	9.84	9.74	9.79	9.74	9.78	0.13	0.0051
				P1 (top)	10.33	10.29	10.38	10.22	10.31	-0.10	-0.0039

↓Test ID	Temp	Time	SA/V	Corrosion Position (P)	Side 1 (p_1)	Side 2 (p_2)	Side 3 (p_3)	Side 4 (p_4)	$P_{avg.} = (p_1 + p_2 + p_3 + p_4)/4$	$P_c = (P - p_{avg})]/2$	$P_c = (P - p_{avg})]/2$
Unit→	**°C**	**Days**	**in^{-1}**	**-**	**mm**	**mm**	**mm**	**mm**	**mm**	**mm**	**inch**
LAWA187-1200-3	1200	3	0.27	P3 (**G**, neck)	6.84	7.01	6.93	6.95	6.93	1.59	0.0625
				P4 (**H**, bottom)	9.03	8.97	9.03	9.08	9.03	0.54	0.0211
				P1 (top)	10.01	9.95	10.03	9.94	9.98	-0.04	-0.0016
AY102D2-05-1200-3	1200	3	0.27	P3 (**G**, neck)	8.13	8.25	8.25	8.13	8.19	0.93	0.0365
				P4 (**H**, bottom)	9.50	9.61	9.77	9.66	9.64	0.21	0.0083
				P1 (top)	10.16	10.07	10.15	10.03	10.10	-0.03	-0.0010
LAWA44PNCC-1200-3	1200	3	0.27	P3 (**G**, neck)	9.25	9.07	9.13	9.11	9.14	0.45	0.0179
				P4 (**H**, bottom)	9.97	9.65	9.79	9.63	9.76	0.14	0.0053
				P1 (top)	10.37	10.36	10.33	10.32	10.35	-0.13	-0.0051
ORPLG27-1200-3	1200	3	0.27	P3 (**G**, neck)	7.48	7.24	7.46	7.50	7.42	1.35	0.0530
				P4 (**H**, bottom)	10.01	9.91	9.94	9.84	9.93	0.10	0.0038
				P1 (top)	10.14	9.99	10.12	9.99	10.06	-0.05	-0.0019
ORPLE4-1150-3	1150	3	0.27	P3 (**G**, neck)	7.22	7.7	7.59	7.54	7.51	1.32	0.0520
				P4 (**H**, bottom)	9.74	10.01	9.91	9.81	9.87	0.16	0.0062
				P1 (top)	10.32	10.19	10.34	10.22	10.27	-0.05	-0.0018
ISG-2-1150-3	1150	3	0.27	P3 (**G**, neck)	9.80	9.55	9.90	9.98	9.81	0.17	0.0066
				P4 (**H**, bottom)	9.78	9.55	9.80	9.83	9.74	0.17	0.0066
				P1 (top)	9.95	10.05	9.96	10.03	10.00	-0.05	-0.0019
LORPM4R2-1150-3	1150	3	0.27	P3 (**G**, neck)	9.56	9.74	9.76	9.42	9.62	0.24	0.0095
				P4 (**H**, bottom)	9.86	9.89	10.06	9.81	9.91	0.15	0.0058
				P1 (top)	10.32	10.17	10.3	10.15	10.24	-0.09	-0.0036
LAWA187-1150-3	1150	3	0.27	P3 (**G**, neck)	7.99	7.52	7.91	7.91	7.83	1.15	0.0454
				P4 (**H**, bottom)	9.91	10.01	9.89	9.9	9.93	0.11	0.0045
				P1 (top)	10.11	10.25	10.10	10.23	10.17	-0.04	-0.0018
AY102D2-05-1150-3	1150	3	0.27	P3 (**G**, neck)	9.33	9.73	9.21	9.60	9.47	0.28	0.0109
				P4 (**H**, bottom)	9.65	9.91	9.67	9.94	9.79	0.10	0.0038
				P1 (top)	10.27	10.17	10.3	10.12	10.22	-0.06	-0.0024
LAWA44PNCC-1150-3	1150	3	0.27	P3 (**G**, neck)	9.74	9.32	9.60	9.08	9.44	0.29	0.0113
				P4 (**H**, bottom)	9.94	9.69	9.94	9.60	9.79	0.10	0.0040
				P1 (top)	10.23	10.40	10.22	10.42	10.32	-0.09	-0.0035
ORPLG27-1150-3	1150	3	0.27	P3 (**G**, neck)	7.37	7.60	7.42	7.57	7.49	1.29	0.0508
				P4 (**H**, bottom)	9.64	9.76	9.84	9.76	9.75	0.13	0.0053

Appendix D: VSL Touchpoint Target Glass Compositions (wt%)

Oxide	ORPLE4	ISG-2	LORPM4R2	LAWA187	AY102D2-05	LAWA44PNCC	ORPLG27
Al_2O_3	7.65	6.14	9.45	10.70	12.20	6.20	6.00
BaO	0.00	0.00	0.01	0.00	0.07	0.00	0.00
B_2O_3	9.83	17.40	12.39	12.80	7.30	8.90	7.90
CaO	10.45	2.52	5.06	6.50	0.50	2.00	2.70
CdO	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Cl	0.03	0.00	0.75	0.65	0.13	0.65	0.23
Cr_2O_3	0.11	0.00	0.29	0.50	0.30	0.00	0.60
Cs2O	0.15	0.00	0.00	0.00	0.00	0.00	0.00
F	0.23	0.00	0.28	0.00	0.15	0.00	0.09
Fe_2O_3	0.23	0.00	0.30	0.90	13.60	7.00	0.30
K_2O	0.61	0.00	5.89	0.50	3.30	0.50	5.80
Li_2O	2.10	0.00	0.00	0.00	0.90	0.00	0.00
MgO	1.05	1.80	4.93	0.90	0.10	2.00	0.40
MnO	0.00	0.00	0.00	0.00	2.03	0.00	0.00
Na_2O	18.03	12.27	13.97	23.00	20.30	20.00	21.01
Nd_2O_3	0.00	0.00	0.00	0.00	0.15	0.00	0.00
NiO	0.00	0.00	0.03	0.00	0.33	0.00	0.01
P_2O_5	0.14	0.00	0.47	0.00	0.60	0.03	0.14
PbO	0.00	0.00	0.03	0.00	0.52	0.00	0.01
SnO_2	0.00	0.00	0.00	1.00	0.00	0.00	3.20
SO_3	1.08	0.00	0.64	0.62	0.50	0.10	0.35
SiO_2	40.41	56.54	36.00	34.91	31.30	44.61	42.13
TiO_2	0.00	0.00	1.08	0.00	0.00	2.00	0.00
V_2O_5	1.21	0.00	4.00	1.00	0.00	0.00	0.00
ZnO	3.14	0.00	4.42	3.00	2.10	3.00	2.70
ZrO_2	3.54	3.32	0.00	3.00	3.40	3.00	6.40
others	0.01	0.12	0.00	0.02	0.22	0.01	0.03
Total	100.00	100.11	100.00	100.00	100.00	100.00	100.00

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