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Composition Measurements of the LAW ML1 Glasses

M. C. Hsieh

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REVIEWS AND APPROVALS

AUTHORS:

_____
M. C. Hsieh, Applied Materials Research

TECHNICAL REVIEW:

_____
A. N. Stanfield, Applied Materials Research, Reviewed per E7 2.60

APPROVAL:

_____
J. Manna, Division Director, Environmental and Legacy Management

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EXECUTIVE SUMMARY

This report provides the results from the chemical analyses of the glass compositions of the quenched Low-Activity Waste Machine Learning study glasses, a series of simulated nuclear waste glasses designed and fabricated at Pacific Northwest National Laboratory. These data will be used in the development, validation, and implementation of enhanced property/composition models for waste glass vitrification at Hanford.

Chemical analyses were performed on a representative sample of each of the quenched glasses to allow for comparisons with target compositions. The relative differences between the target and measured concentrations of F^- for one glass, P_2O_5 for two glasses, SO_3 for three glasses, and ZrO_2 for two of the glasses were greater than 10%. These results can be used in further characterization of this series of glasses, including the normalization of Product Consistency Test results.

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LIST OF ABBREVIATIONS

BDL	below detection limit
DOE	U. S. Department of Energy
IC	ion chromatography
ICP-OES	inductively coupled plasma – optical emission spectroscopy
ID	identifier
KH	potassium hydroxide fusion
LAW	low-activity waste
LM	lithium metaborate fusion
LRM	low-activity test reference material
ML1	Machine Learning
ORP	Office of River Protection
PCT	Product Consistency Test
PF	sodium peroxide fusion
PNNL	Pacific Northwest National Laboratory
Q	quenched
seq.	sequence
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
TTQAP	Task Technical and Quality Assurance Plan
wt.%	weight percent
WTP	Waste Treatment and Immobilization Plant
SRNL	Savannah River National Laboratory

1.0 Introduction

The U.S. Department of Energy (DOE) is responsible for building the Waste Treatment and Immobilization Plant (WTP) at the Hanford site in Washington state to remediate 56 million gallons of radioactive waste historically stored in 177 underground tanks. The Office of River Protection (ORP) has requested that the Savannah River National Laboratory (SRNL) contribute in areas of recognized capabilities and expertise for glass waste form development to support successful startup of the WTP.

Successful efforts have allowed for demonstration of greatly enhanced treatment efficiencies of those projected from the minimum requirements set forth in the WTP Contract[a]. Additional flexibility and expansion of the qualified glass forming region are the current focus.[1] SRNL support of this work is defined in the Task Technical and Quality Assurance Plan (TTQAP).[2]

This report provides results from the chemical analyses of the baseline (quenched) version of a series of simulated nuclear waste glasses designed and fabricated at Pacific Northwest National Laboratory (PNNL). The glasses were selected as part of a broader study of the influence of glass composition on chemical durability, sulfur retention, and other properties.[3] The glasses were designated the Low-Activity Waste Machine Learning (LAW ML1) study glasses. The resulting data will be used in the development, validation, and implementation of enhanced property/composition models for nuclear waste glasses.[1]

2.0 Experimental Procedure

2.1 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in Savannah River Site (SRS) Manual E7, Procedure 2.60.[4] SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011.[5] Laboratory data for this study were recorded in the SRNL Electronic Laboratory Notebook system, experiment L6390-00441-07. The glasses provided by PNNL were designed and fabricated following a Task Plan.[1]

2.2 Glasses Selected for Study

The baseline (quenched) glass compositions in this study were selected and fabricated by PNNL. Samples of the quenched (Q) baseline glasses were received at SRNL for chemical composition analysis. PNNL identifiers (IDs) for the glass samples and the associated SRNL sample IDs are listed in Table 2-1.

Table 2-1. Identifiers for the LAW ML1 Study Glasses

PNNL ID	Lab ID
LAWML1-00	S-14876
LAWML1-05	S-14877
LAWML1-09	S-14878
LAWML1-10	S-14879
LAWML1-11	S-14880
LAWML1-12	S-14881
LAWML1-13	S-14882
LAWML1-17	S-14883

2.3 Glass Composition Analysis

Chemical analyses were performed under the direction of an analytical plan[6] on a representative sample of each of the glasses listed in Table 2-1 to allow for comparisons with the target compositions. Three

[a] Contract DE-AC27-01RV14136, as amended, U. S. Department of Energy, Richland, WA (2000).

dissolution techniques were used for preparing each of the glass samples, in duplicate, for analysis (potassium hydroxide fusion (KH), lithium metaborate fusion (LM), and sodium peroxide fusion (PF)).[7-9] Note that for some analytes, the analytical plan specified more than one preparation method for analysis. The results were reviewed and, in general, the method that provided the better recovery of the analyte was selected for reporting.

Each of the duplicate samples was analyzed twice for each element of interest by inductively coupled plasma – optical emission spectroscopy (ICP-OES)[10] or ion chromatography (IC),[11] for a total of four measurements per element per glass. Glass standards were also intermittently measured to assess the performance of the ICP-OES and IC measurements over the course of these analyses. Specifically, several samples of the low-activity test reference material (LRM) were included as part of the analytical plan. The LRM composition reported as the "Consensus Average" is used as the reference composition of this glass.[12] The preparation and measurement methods used for each of the reported glass components are listed in Table 2-2.

Table 2-2. Preparation and Measurement Methods Used in Reporting the Analyte Concentrations of the Study Glasses

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

3.0 Results and Discussion

JMP® Version 16.0.0 (SAS Institute, Inc.)[13] was used to support these analyses.

3.1 Review and Evaluation of the Quenched Glass Composition Measurements

Table A-1, Table A-2, and Table A-3 in Appendix A provide the elemental concentration measurements in weight percent (wt.%) from glasses prepared using KH, LM, and PF methods, respectively. Elemental measurements for samples of the LRM glass are also included in these tables of Appendix A.

3.1.1 Treatment of Detection Limits

The elemental concentrations in Table A-1, Table A-2, and Table A-3 in Appendix A were converted to oxide concentrations by multiplying the values of each element by the gravimetric factor for the corresponding oxide. A concentration measurement that was reported to be below the detection limit (BDL) was set to the detection limit for the purposes of data review and calculation of the sum of oxides for each glass in Table A-4 in Appendix A. Concentration measurements that were BDL are denoted with a less than symbol (<).

3.1.2 Composition Measurements by Glass Identifier

Exhibit A-1 in Appendix A provides plots of the oxide concentration measurements by the PNNL Glass ID (including the LRM glasses) by Lab ID grouped by target concentration. Different colors are used to represent the different glasses. These plots show the individual measurements across the duplicates of each preparation method and the two instrument calibrations for each glass. 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 presented in these exhibits reveals the repeatability of the four individual values for each oxide for each glass. There were no indications of errors in preparation or measurement that had to be addressed in the treatment of the data.

3.1.3 Results for the LRM Standard Glass

Exhibit A-2 in Appendix A provides a comparison of the LRM results to their acceptability limits utilized by SRNL.[10] The review is in the form of plots of the measurements arranged by element, framed by upper and lower acceptability limits for the concentration of each element of interest. The results show that all measurements of the LRM elements of interest were within the acceptability limits during the execution of the analyses.

3.1.4 Measured versus Target Compositions

All measurements for each element for each glass (Table A-1, Table A-2, and Table A-3 in Appendix A) were used in the calculations of oxide values, which were then averaged to determine a representative chemical composition for each glass. A sum of oxides was also computed for each glass based upon the averaged oxide values. Exhibit A-3 in Appendix A provides plots showing the result for each glass for each oxide to allow PNNL to draw comparisons between the measured and target values.

Table A-4 in Appendix A provides a summary of the average compositions, target compositions, and some associated differences and relative differences. The measured sum of oxides for all glasses falls within the interval of 98.6 wt.% and 100 wt.%, indicating acceptable recovery of the glass components.[14] Entries in Table A-4 show the relative differences between the measured and target values for the analytes with measured and target values above 1 wt.%. The relative differences were shaded if they are 10% or more and are summarized below.

- F^- relative difference was -16% for LAWML1-12.
- SO_3 relative differences were 10% or greater for LAWML1-05, LAWML1-12, and LAWML1-13.
- P_2O_5 relative differences were 10% or greater for LAWML1-09 and LAWML1-12.
- ZrO_2 relative differences were 10% or greater for LAWML1-09 and LAWML1-12.

4.0 Summary

Chemical analyses were performed on a representative sample of each of the quenched glasses to allow for comparisons with target compositions. The relative differences between the target and measured concentrations of F^- for one glass, P_2O_5 for two glasses, SO_3 for three glasses, and ZrO_2 for two of the glasses were greater than 10%. These results can be used in further characterization of this series of glasses, including the normalization of Product Consistency Test (PCT) results.

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Appendix A. Tables and Exhibits Supporting the LAW ML1 Glass Composition Measurements

Table A-1. KH Measurements (wt.%) of the Study Glasses

PNNL ID	Lab ID	Block	Sub – Block	Seq.	Cl-	F-
LRM	1	1	1	LRMKH111	<0.0250	0.897
LAWML1-13	1	1	2	S-14882KH21	0.0922	0.369
LAWML1-00	1	1	3	S-14876KH11	<0.0250	0.892
LAWML1-05	1	1	4	S-14877KH21	0.111	0.704
LAWML1-17	1	1	5	S-14883KH21	0.659	0.288
LAWML1-10	1	1	6	S-14879KH11	0.0827	0.0546
LAWML1-12	1	1	7	S-14881KH21	0.0744	1.27
LAWML1-13	1	1	8	S-14882KH11	0.0842	0.377
LAWML1-10	1	1	9	S-14879KH21	0.0858	0.0584
LRM	1	1	10	LRMKH112	<0.0250	0.912
LAWML1-11	1	1	11	S-14880KH11	0.241	0.0965
LAWML1-17	1	1	12	S-14883KH11	0.653	0.290
LAWML1-05	1	1	13	S-14877KH11	0.114	0.693
LAWML1-12	1	1	14	S-14881KH11	0.0733	1.28
LAWML1-00	1	1	15	S-14876KH21	<0.0250	0.883
LAWML1-09	1	1	16	S-14878KH11	0.0843	0.336
LAWML1-11	1	1	17	S-14880KH21	0.240	0.0950
LAWML1-09	1	1	18	S-14878KH21	0.0873	0.351
LRM	1	1	19	LRMKH113	<0.0250	0.898
LRM	1	2	1	LRMKH121	<0.0250	0.936
LAWML1-13	1	2	2	S-14882KH12	0.086	0.389
LAWML1-11	1	2	3	S-14880KH22	0.250	0.0995
LAWML1-13	1	2	4	S-14882KH22	0.0912	0.389
LAWML1-09	1	2	5	S-14878KH12	0.0869	0.352
LAWML1-12	1	2	6	S-14881KH12	0.0759	1.34
LAWML1-05	1	2	7	S-14877KH12	0.118	0.728
LAWML1-12	1	2	8	S-14881KH22	0.0733	1.30
LAWML1-11	1	2	9	S-14880KH12	0.239	0.0954
LRM	1	2	10	LRMKH122	<0.0250	0.894
LAWML1-17	1	2	11	S-14883KH22	0.653	0.288
LAWML1-05	1	2	12	S-14877KH22	0.107	0.706
LAWML1-10	1	2	13	S-14879KH12	0.0797	0.0538
LAWML1-09	1	2	14	S-14878KH22	0.0863	0.353
LAWML1-10	1	2	15	S-14879KH22	0.0836	0.0572
LAWML1-00	1	2	16	S-14876KH22	<0.0250	0.893
LAWML1-17	1	2	17	S-14883KH12	0.653	0.291
LAWML1-00	1	2	18	S-14876KH12	<0.0250	0.897
LRM	1	2	19	LRMKH123	<0.0250	0.897

Table A-2. LM Measurements (wt.%) of the Study Glasses

PNNL ID	Block	Sub – Block	Seq.	Lab ID	Cr	Fe	K	Mg	Mn	Na	S	Ti	V
LRM	1	1	1	LRMLM111	0.126	0.953	1.31	0.0665	0.0574	15.6	0.0937	0.0593	<0.0500
LAWML1-00	1	1	2	S-14876LM21	0.125	0.920	1.37	0.0673	0.0583	16.0	0.0962	0.0609	<0.0500
LAWML1-00	1	1	3	S-14876LM11	0.127	0.933	1.35	0.0681	0.0581	16.1	0.0877	0.0602	<0.0500
LAWML1-11	1	1	4	S-14880LM11	0.0305	<0.0500	2.94	0.0215	<0.0100	17.6	0.235	<0.0500	<0.0500
LAWML1-05	1	1	5	S-14877LM11	0.0349	0.0899	0.140	0.131	<0.0100	8.53	0.654	<0.0500	2.46
LAWML1-09	1	1	6	S-14878LM11	0.143	<0.0500	0.171	0.0135	<0.0100	18.9	0.109	<0.0500	<0.0500
LAWML1-12	1	1	7	S-14881LM11	0.0392	0.0754	0.0696	0.105	<0.0100	15.5	0.667	<0.0500	2.01
LAWML1-13	1	1	8	S-14882LM21	<0.0250	0.0770	<0.0500	0.118	<0.0100	10.6	0.645	<0.0500	2.14
LAWML1-10	1	1	9	S-14879LM21	0.115	<0.0500	0.0573	0.0134	<0.0100	18.2	0.0853	<0.0500	<0.0500
LRM	1	1	10	LRMLM112	0.127	0.959	1.29	0.0677	0.0577	16.1	0.100	0.0606	<0.0500
LAWML1-11	1	1	11	S-14880LM21	0.0314	<0.0500	2.86	0.0220	<0.0100	17.5	0.223	<0.0500	<0.0500
LAWML1-09	1	1	12	S-14878LM21	0.143	<0.0500	0.173	0.0128	<0.0100	18.6	0.112	<0.0500	<0.0500
LAWML1-17	1	1	13	S-14883LM21	0.059	<0.0500	0.530	0.0379	<0.0100	18.2	0.307	<0.0500	<0.0500
LAWML1-05	1	1	14	S-14877LM21	0.0363	0.0897	0.128	0.131	<0.0100	8.14	0.657	<0.0500	2.43
LAWML1-10	1	1	15	S-14879LM11	0.113	<0.0500	0.0576	0.0144	<0.0100	18.6	0.0810	<0.0500	<0.0500
LAWML1-12	1	1	16	S-14881LM21	0.0392	0.0725	0.0681	0.103	<0.0100	15.1	0.686	<0.0500	2.01
LAWML1-17	1	1	17	S-14883LM11	0.0585	<0.0500	0.519	0.0369	<0.0100	18.1	0.306	<0.0500	<0.0500
LAWML1-13	1	1	18	S-14882LM11	0.0256	0.0810	<0.0500	0.126	<0.0100	11.1	0.677	<0.0500	2.25
LRM	1	1	19	LRMLM113	0.128	0.955	1.27	0.0680	0.0581	15.6	0.0959	0.0609	<0.0500
LRM	1	2	1	LRMLM121	0.122	0.935	1.21	0.0655	0.0565	15.2	0.0948	0.0583	<0.0500
LAWML1-09	1	2	2	S-14878LM22	0.138	<0.0500	0.154	0.0121	<0.0100	18.2	0.112	<0.0500	<0.0500
LAWML1-10	1	2	3	S-14879LM22	0.110	<0.0500	0.0500	0.0129	<0.0100	18.2	0.0769	<0.0500	<0.0500
LAWML1-12	1	2	4	S-14881LM22	0.0376	0.0716	0.0601	0.101	<0.0100	14.8	0.673	<0.0500	1.85
LAWML1-10	1	2	5	S-14879LM12	0.110	<0.0500	0.0503	0.0140	<0.0100	18.1	0.0854	<0.0500	<0.0500
LAWML1-05	1	2	6	S-14877LM22	0.0348	0.0885	0.118	0.129	<0.0100	7.74	0.630	<0.0500	2.24
LAWML1-17	1	2	7	S-14883LM12	0.0562	<0.0500	0.486	0.0360	<0.0100	17.9	0.298	<0.0500	<0.0500
LAWML1-09	1	2	8	S-14878LM12	0.139	<0.0500	0.155	0.0128	<0.0100	17.8	0.114	<0.0500	<0.0500
LAWML1-13	1	2	9	S-14882LM12	<0.0250	0.0812	<0.0500	0.125	<0.0100	11.1	0.682	<0.0500	2.12
LRM	1	2	10	LRMLM122	0.126	0.961	1.23	0.0680	0.0582	15.6	0.0956	0.0605	<0.0500
LAWML1-00	1	2	11	S-14876LM12	0.127	0.948	1.26	0.0687	0.0587	15.5	0.0918	0.0608	<0.0500
LAWML1-12	1	2	12	S-14881LM12	0.0382	0.0752	0.0678	0.103	<0.0100	14.5	0.665	<0.0500	1.84
LAWML1-11	1	2	13	S-14880LM22	0.0304	<0.0500	2.71	0.0229	<0.0100	16.7	0.230	<0.0500	<0.0500
LAWML1-00	1	2	14	S-14876LM22	0.126	0.942	1.28	0.0694	0.0595	15.5	0.0973	0.0625	<0.0500

Table A-2. LM Measurements (wt.%) of the Study Glasses (continued)

PNNL ID	Block	Sub – Block	Seq.	Lab ID	Cr	Fe	K	Mg	Mn	Na	S	Ti	V
LAWML1-11	1	2	15	S-14880LM12	0.0301	<0.0500	2.77	0.0215	<0.0100	17.3	0.239	<0.0500	<0.0500
LAWML1-17	1	2	16	S-14883LM22	0.0578	<0.0500	0.521	0.038	<0.0100	18.0	0.296	<0.0500	<0.0500
LAWML1-05	1	2	17	S-14877LM12	0.0347	0.0908	0.136	0.132	<0.0100	7.80	0.650	<0.0500	2.24
LAWML1-13	1	2	18	S-14882LM22	<0.0250	0.0779	<0.0500	0.120	<0.0100	10.2	0.653	<0.0500	1.96
LRM	1	2	19	LRMLM123	0.127	0.970	1.25	0.0688	0.0586	15.5	0.0978	0.0613	<0.0500

Table A-3. PF Measurements (wt.%) of the Study Glasses

PNNL ID	Block	Sub – Block	Seq.	Lab ID	Al	B	Ca	Li	P	Si	Sn	Zn	Zr
LRM	1	1	1	LRMPF111	5.07	2.37	0.378	<0.0500	0.216	24.8	<0.100	<0.100	0.681
LAWML1-09	1	1	2	S-14878PF21	2.12	3.15	<0.100	0.0557	1.40	19.6	3.50	1.83	4.33
LAWML1-17	1	1	3	S-14883PF21	1.82	3.19	2.13	<0.0500	<0.100	21.9	2.52	1.83	1.82
LAWML1-00	1	1	4	S-14876PF11	5.19	2.41	0.416	<0.0500	0.213	25.2	<0.100	<0.100	0.744
LAWML1-10	1	1	5	S-14879PF11	1.79	3.21	<0.100	0.0573	0.141	22.6	3.45	1.79	2.82
LAWML1-09	1	1	6	S-14878PF11	2.17	3.24	<0.100	0.0569	1.37	20.0	3.61	1.90	4.35
LAWML1-13	1	1	7	S-14882PF11	2.38	2.73	8.99	1.34	0.440	20.8	<0.100	<0.100	3.06
LAWML1-12	1	1	8	S-14881PF11	1.97	2.99	7.56	<0.0500	0.894	19.5	1.61	0.277	1.18
LAWML1-17	1	1	9	S-14883PF11	1.81	3.19	2.16	0.0533	<0.100	22.0	2.53	1.83	1.83
LRM	1	1	10	LRMPF112	5.13	2.41	0.384	<0.0500	0.215	25.0	<0.100	<0.100	0.727
LAWML1-10	1	1	11	S-14879PF21	1.82	3.27	<0.100	0.0575	0.142	22.8	3.55	1.82	2.82
LAWML1-05	1	1	12	S-14877PF21	2.00	3.15	9.13	1.50	0.131	22.0	<0.100	<0.100	2.97
LAWML1-13	1	1	13	S-14882PF21	2.32	2.67	8.83	1.30	0.422	20.4	<0.100	<0.100	2.99
LAWML1-05	1	1	14	S-14877PF11	2.03	3.17	9.15	1.50	0.135	21.9	<0.100	<0.100	2.99
LAWML1-11	1	1	15	S-14880PF11	1.82	2.85	0.509	0.0600	<0.100	22.3	3.47	1.60	2.64
LAWML1-00	1	1	16	S-14876PF21	5.07	2.40	0.402	<0.0500	0.210	24.8	<0.100	<0.100	0.753
LAWML1-11	1	1	17	S-14880PF21	1.79	2.81	0.482	0.0569	<0.100	22.1	3.45	1.58	2.58
LAWML1-12	1	1	18	S-14881PF21	1.95	2.96	7.47	<0.0500	1.04	19.3	1.74	0.291	1.46
LRM	1	1	19	LRMPF113	5.05	2.35	0.374	<0.0500	0.220	24.4	<0.100	<0.100	0.698
LRM	1	2	1	LRMPF121	5.04	2.37	0.374	<0.0500	0.209	25.7	<0.100	<0.100	0.669
LAWML1-13	1	2	2	S-14882PF12	2.30	2.64	8.63	1.27	0.413	21.0	<0.100	<0.100	2.91
LAWML1-00	1	2	3	S-14876PF22	5.06	2.35	0.397	<0.0500	0.209	25.5	<0.100	<0.100	0.695
LAWML1-05	1	2	4	S-14877PF12	1.99	3.09	8.98	1.50	0.126	22.6	<0.100	<0.100	2.89
LAWML1-17	1	2	5	S-14883PF12	1.77	3.21	2.12	<0.0500	<0.100	22.7	2.46	1.80	1.80
LAWML1-09	1	2	6	S-14878PF22	2.08	3.12	<0.100	<0.0500	1.28	20.0	3.38	1.79	4.04
LAWML1-12	1	2	7	S-14881PF12	1.91	2.92	7.32	<0.0500	0.845	19.9	1.51	0.262	1.11
LAWML1-09	1	2	8	S-14878PF12	2.09	3.11	<0.100	0.0551	1.28	20.1	3.46	1.81	4.06
LAWML1-13	1	2	9	S-14882PF22	2.27	2.63	8.60	1.28	0.411	20.9	<0.100	<0.100	2.90
LRM	1	2	10	LRMPF122	5.01	2.34	0.369	<0.0500	0.213	25.4	<0.100	<0.100	0.704
LAWML1-10	1	2	11	S-14879PF22	1.75	3.18	<0.100	0.0772	0.150	22.9	3.44	1.76	2.71
LAWML1-00	1	2	12	S-14876PF12	5.00	2.34	0.392	<0.0500	0.200	25.4	<0.100	<0.100	0.689
LAWML1-11	1	2	13	S-14880PF12	1.76	2.77	0.484	0.0583	<0.100	22.6	3.37	1.54	2.52

Table A-3. PF Measurements (wt.%) of the Study Glasses (continued)

PNNL ID	Block	Sub – Block	Seq.	Lab ID	Al	B	Ca	Li	P	Si	Sn	Zn	Zr
LAWML1-10	1	2	14	S-14879PF12	1.73	3.12	<0.100	0.0514	0.133	23.1	3.36	1.72	2.73
LAWML1-05	1	2	15	S-14877PF22	1.99	3.14	8.97	1.50	0.125	22.7	<0.100	<0.100	2.94
LAWML1-12	1	2	16	S-14881PF22	1.88	2.87	7.14	<0.0500	0.995	19.5	1.68	0.273	1.39
LAWML1-11	1	2	17	S-14880PF22	1.75	2.75	0.455	0.0610	<0.100	22.4	3.35	1.54	2.48
LAWML1-17	1	2	18	S-14883PF22	1.77	3.12	2.04	<0.0500	<0.100	22.3	2.45	1.77	1.78
LRM	1	2	19	LRMPF123	4.95	2.31	0.357	<0.0500	0.200	25.0	<0.100	<0.100	0.700

Table A-4. Comparison of Measured versus Target Compositions

PNNL ID	Oxide	Measured (wt.%)	Target (wt.%)	Difference of Measured vs Target	% Difference Measured vs Target
LAWML1-00	Al_2O_3	9.60	9.51	0.099	1%
LAWML1-00	B_2O_3	7.65	7.85	-0.213	-3%
LAWML1-00	CaO	0.562	0.540	0.022	
LAWML1-00	Cl	<0.025	0	0.025	
LAWML1-00	Cr_2O_3	0.185	0.190	-0.005	
LAWML1-00	F	0.892	0.860	0.032	
LAWML1-00	Fe_2O_3	1.34	1.38	-0.042	-3%
LAWML1-00	K_2O	1.58	1.48	0.104	7%
LAWML1-00	Li_2O	<0.108	0.110	-0.002	
LAWML1-00	MgO	0.113	0.100	0.013	
LAWML1-00	MnO	0.0757	0.08	-0.004	
LAWML1-00	Na_2O	21.3	20.0	1.165	6%
LAWML1-00	P_2O_5	0.477	0.54	-0.064	
LAWML1-00	SiO_2	54.0	54.2	-0.136	0%
LAWML1-00	SnO_2	<0.127	0	0.127	
LAWML1-00	SO_3	0.233	0.3	-0.067	
LAWML1-00	TiO_2	0.102	0.1	0.002	
LAWML1-00	V_2O_5	<0.0893	0	0.089	
LAWML1-00	ZnO	<0.124	0	0.124	
LAWML1-00	ZrO_2	0.973	0.93	0.044	
LAWML1-00	**Sum of Oxides**	**99.5**	**98.2**	**1.312**	**1%**
LAWML1-05	Al_2O_3	3.78	3.82	-0.036	-1%
LAWML1-05	B_2O_3	10.1	10.3	-0.198	-2%
LAWML1-05	CaO	12.7	12.7	-0.027	0%
LAWML1-05	Cl	0.112	0.126	-0.014	
LAWML1-05	Cr_2O_3	0.0514	0.0555	-0.004	
LAWML1-05	F	0.713	0.864	-0.151	
LAWML1-05	Fe_2O_3	0.128	0.133	-0.005	
LAWML1-05	K_2O	0.157	0.166	-0.009	
LAWML1-05	Li_2O	3.23	3.16	0.069	2%
LAWML1-05	MgO	0.217	0.186	0.031	
LAWML1-05	MnO	<0.0129	0.0136	-0.001	
LAWML1-05	Na_2O	10.9	10.4	0.455	4%
LAWML1-05	P_2O_5	0.296	0.296	0	
LAWML1-05	SiO_2	47.7	47.5	0.206	0%
LAWML1-05	SnO_2	<0.127	0	0.127	
LAWML1-05	SO_3	1.62	1.92	-0.303	-16%
LAWML1-05	TiO_2	<0.0834	0.0899	-0.006	
LAWML1-05	V_2O_5	4.18	4.07	0.112	3%
LAWML1-05	ZnO	<0.124	0	0.124	
LAWML1-05	ZrO_2	3.98	4.16	-0.179	-4%
LAWML1-05	**Sum of Oxides**	**100**	**100**	**0.193**	**0%**
LAWML1-09	Al_2O_3	4.00	4.01	-0.014	0%
LAWML1-09	B_2O_3	10.2	10.3	-0.141	-1%
LAWML1-09	CaO	<0.14	0.006	0.134	
LAWML1-09	Cl	0.0869	0.0918	-0.005	
LAWML1-09	Cr_2O_3	0.206	0.209	-0.003	

Table A-4. Comparison of Measured versus Target Compositions (continued)

PNNL ID	Oxide	Measured (wt.%)	Target (wt.%)	Difference of Measured vs Target	% Difference Measured vs Target
LAWML1-09	F	0.352	0.434	-0.082	
LAWML1-09	Fe_2O_3	<0.0715	0.0317	0.04	
LAWML1-09	K_2O	0.197	0.193	0.004	
LAWML1-09	Li_2O	<0.117	0.114	0.003	
LAWML1-09	MgO	0.0212	0.00429	0.017	
LAWML1-09	MnO	<0.0129	0	0.013	
LAWML1-09	Na_2O	24.8	24.3	0.47	2%
LAWML1-09	P_2O_5	3.05	3.76	-0.707	-19%
LAWML1-09	SiO_2	42.6	42.8	-0.174	0%
LAWML1-09	SnO_2	4.43	4.48	-0.052	-1%
LAWML1-09	SO_3	0.279	0.367	-0.088	
LAWML1-09	TiO_2	<0.0834	0.0472	0.036	
LAWML1-09	V_2O_5	<0.0893	0	0.089	
LAWML1-09	ZnO	2.28	2.28	0.001	0%
LAWML1-09	ZrO_2	5.67	6.71	-1.043	-16%
LAWML1-09	**Sum of Oxides**	**98.6**	**100**	**-1.504**	**-2%**
LAWML1-10	Al_2O_3	3.35	3.5	-0.151	-4%
LAWML1-10	B_2O_3	10.3	10.6	-0.312	-3%
LAWML1-10	CaO	<0.140	0.00639	0.134	
LAWML1-10	Cl	0.083	0.0808	0.002	
LAWML1-10	Cr_2O_3	0.164	0.175	-0.011	
LAWML1-10	F	0.0565	0.0702	-0.014	
LAWML1-10	Fe_2O_3	<0.0715	0.0164	0.055	
LAWML1-10	K_2O	0.0648	0.0395	0.025	
LAWML1-10	Li_2O	0.131	0.123	0.008	
LAWML1-10	MgO	0.0227	0.00429	0.018	
LAWML1-10	MnO	<0.0129	0	0.013	
LAWML1-10	Na_2O	24.6	24.4	0.235	1%
LAWML1-10	P_2O_5	0.324	0.323	0.001	
LAWML1-10	SiO_2	48.9	49.8	-0.917	-2%
LAWML1-10	SnO_2	4.38	4.43	-0.05	-1%
LAWML1-10	SO_3	0.205	0.2	0.005	
LAWML1-10	TiO_2	<0.0834	0.016	0.067	
LAWML1-10	V_2O_5	<0.0893	0	0.089	
LAWML1-10	ZnO	2.21	2.2	0.006	0%
LAWML1-10	ZrO_2	3.74	4.01	-0.268	-7%
LAWML1-10	**Sum of Oxides**	**98.9**	**100**	**-1.064**	**-1%**
LAWML1-11	Al_2O_3	3.36	3.48	-0.117	-3%
LAWML1-11	B_2O_3	9.00	9.31	-0.31	-3%
LAWML1-11	CaO	0.675	0.631	0.044	
LAWML1-11	Cl	0.243	0.287	-0.044	
LAWML1-11	Cr_2O_3	0.0447	0.0474	-0.003	
LAWML1-11	F	0.0966	0.111	-0.014	
LAWML1-11	Fe_2O_3	<0.0715	0.0409	0.031	
LAWML1-11	K_2O	3.40	3.29	0.107	3%
LAWML1-11	Li_2O	0.127	0.132	-0.005	
LAWML1-11	MgO	0.0364	0.0142	0.022	

Table A-4. Comparison of Measured versus Target Compositions (continued)

PNNL ID	Oxide	Measured (wt.%)	Target (wt.%)	Difference of Measured vs Target	% Difference Measured vs Target
LAWML1-11	MnO	<0.0129	0.000646	0.012	
LAWML1-11	Na_2O	23.3	23.2	0.087	0%
LAWML1-11	P_2O_5	<0.229	0.135	0.094	
LAWML1-11	SiO_2	47.8	48.6	-0.787	-2%
LAWML1-11	SnO_2	4.33	4.48	-0.151	-3%
LAWML1-11	SO_3	0.579	0.602	-0.023	
LAWML1-11	TiO_2	<0.0834	0.0574	0.026	
LAWML1-11	V_2O_5	<0.0893	0	0.089	
LAWML1-11	ZnO	1.95	1.97	-0.022	-1%
LAWML1-11	ZrO_2	3.45	3.69	-0.239	-6%
LAWML1-11	**Sum of Oxides**	**98.9**	**100**	**-1.202**	**-1%**
LAWML1-12	Al_2O_3	3.64	3.74	-0.098	-3%
LAWML1-12	B_2O_3	9.45	9.69	-0.24	-2%
LAWML1-12	CaO	10.3	10.3	0.016	0%
LAWML1-12	Cl	0.0745	0.069	0.006	
LAWML1-12	Cr_2O_3	0.0563	0.0592	-0.003	
LAWML1-12	F	1.30	1.55	-0.247	-16%
LAWML1-12	Fe_2O_3	0.105	0.112	-0.007	
LAWML1-12	K_2O	0.0800	0.0828	-0.003	
LAWML1-12	Li_2O	<0.108	0.0181	0.09	
LAWML1-12	MgO	0.171	0.152	0.019	
LAWML1-12	MnO	<0.0129	0.0111	0.002	
LAWML1-12	Na_2O	20.2	19.7	0.486	2%
LAWML1-12	P_2O_5	2.16	2.47	-0.308	-12%
LAWML1-12	SiO_2	41.8	42.4	-0.577	-1%
LAWML1-12	SnO_2	2.08	2.2	-0.124	-6%
LAWML1-12	SO_3	1.68	1.86	-0.18	-10%
LAWML1-12	TiO_2	<0.0834	0.0798	0.004	
LAWML1-12	V_2O_5	3.44	3.32	0.121	4%
LAWML1-12	ZnO	0.343	0.335	0.008	
LAWML1-12	ZrO_2	1.74	1.97	-0.234	-12%
LAWML1-12	**Sum of Oxides**	**98.8**	**100**	**-1.27**	**-1%**
LAWML1-13	Al_2O_3	4.38	4.48	-0.101	-2%
LAWML1-13	B_2O_3	8.59	8.79	-0.201	-2%
LAWML1-13	CaO	12.3	12.3	-0.04	0%
LAWML1-13	Cl	0.0898	0.0867	0.003	
LAWML1-13	Cr_2O_3	<0.0368	0.0383	-0.002	
LAWML1-13	F	0.383	0.443	-0.06	
LAWML1-13	Fe_2O_3	0.113	0.125	-0.012	
LAWML1-13	K_2O	<0.0602	0.0746	-0.014	
LAWML1-13	Li_2O	2.79	2.73	0.063	2%
LAWML1-13	MgO	0.203	0.181	0.022	
LAWML1-13	MnO	<0.0129	0.0132	0	
LAWML1-13	Na_2O	14.5	14.8	-0.309	-2%
LAWML1-13	P_2O_5	0.966	1.02	-0.054	-5%
LAWML1-13	SiO_2	44.4	44.9	-0.456	-1%

Table A-4. Comparison of Measured versus Target Compositions (continued)

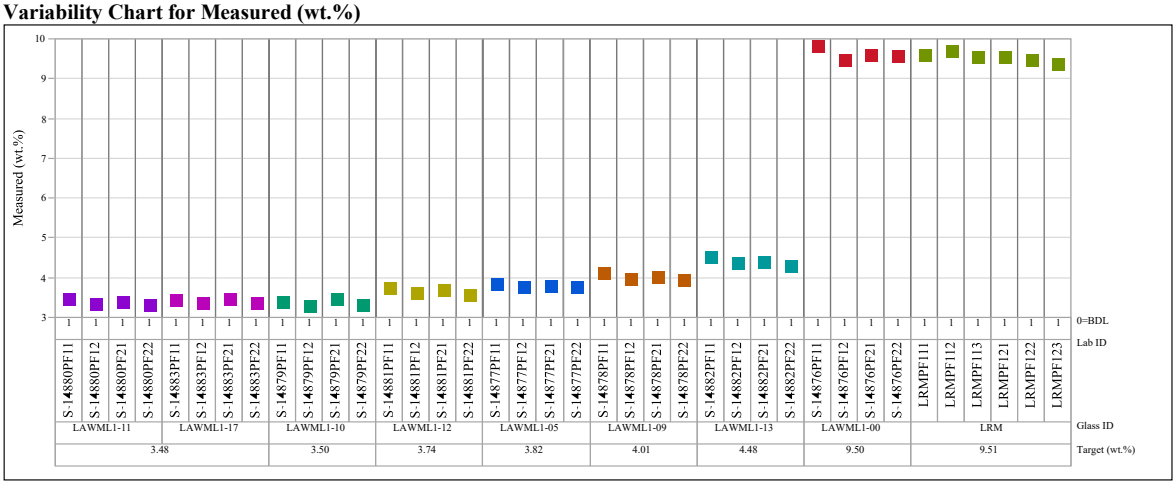
PNNL ID	Oxide	Measured (wt.%)	Target (wt.%)	Difference of Measured vs Target	% Difference Measured vs Target
LAWML1-13	SnO_2	<0.127	0	0.127	
LAWML1-13	SO_3	1.66	1.89	-0.231	-12%
LAWML1-13	TiO_2	<0.0834	0.0799	0.004	
LAWML1-13	V_2O_5	3.78	3.82	-0.04	-1%
LAWML1-13	ZnO	<0.124	0	0.124	
LAWML1-13	ZrO_2	4.01	4.21	-0.205	-5%
LAWML1-13	**Sum of Oxides**	**98.6**	**100**	**-1.382**	**-1%**
LAWML1-17	Al_2O_3	3.39	3.48	-0.093	-3%
LAWML1-17	B_2O_3	10.2	10.4	-0.169	-2%
LAWML1-17	CaO	2.96	2.8	0.156	6%
LAWML1-17	Cl	0.655	0.831	-0.176	
LAWML1-17	Cr_2O_3	0.0846	0.0918	-0.007	
LAWML1-17	F	0.289	0.334	-0.045	
LAWML1-17	Fe_2O_3	<0.0715	0.0573	0.014	
LAWML1-17	K_2O	0.619	0.587	0.032	
LAWML1-17	Li_2O	<0.109	0.109	0	
LAWML1-17	MgO	0.0617	0.0453	0.016	
LAWML1-17	MnO	<0.0129	0.00297	0.01	
LAWML1-17	Na_2O	24.3	24	0.331	1%
LAWML1-17	P_2O_5	<0.229	0.163	0.066	
LAWML1-17	SiO_2	47.5	48.1	-0.554	-1%
LAWML1-17	SnO_2	3.16	3.19	-0.029	-1%
LAWML1-17	SO_3	0.753	0.804	-0.051	
LAWML1-17	TiO_2	<0.0834	0.0647	0.019	
LAWML1-17	V_2O_5	<0.0893	0	0.089	
LAWML1-17	ZnO	2.25	2.25	0	0%
LAWML1-17	ZrO_2	2.44	2.59	-0.148	-6%
LAWML1-17	**Sum of Oxides**	**99.4**	**99.9**	**-0.537**	**-1%**
LRM	Al_2O_3	9.53	9.51	0.016	0%
LRM	B_2O_3	7.59	7.85	-0.256	-3%
LRM	CaO	0.521	0.54	-0.019	
LRM	Cl	<0.025	0	0.025	
LRM	Cr_2O_3	0.184	0.19	-0.006	
LRM	F	0.907	0.86	0.047	
LRM	Fe_2O_3	1.37	1.38	-0.014	-1%
LRM	K_2O	1.52	1.48	0.038	3%
LRM	Li_2O	<0.108	0.11	-0.002	
LRM	MgO	0.112	0.1	0.012	
LRM	MnO	0.0746	0.08	-0.005	
LRM	Na_2O	21.0	20	0.999	5%
LRM	P_2O_5	0.486	0.54	-0.054	
LRM	SiO_2	53.6	54.2	-0.611	-1%
LRM	SnO_2	<0.127	0	0.127	
LRM	SO_3	0.240	0.3	-0.06	
LRM	TiO_2	0.100	0.1	0	
LRM	V_2O_5	<0.0893	0	0.089	

Table A-4. Comparison of Measured versus Target Compositions (continued)

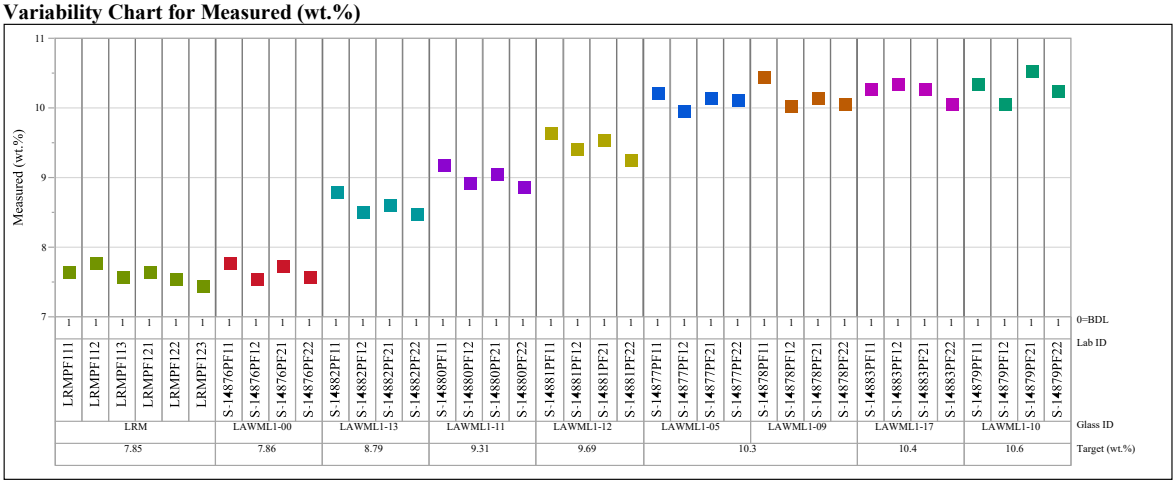
PNNL ID	Oxide	Measured (wt.%)	Target (wt.%)	Difference of Measured vs Target	% Difference Measured vs Target
LRM	ZnO	<0.124	0	0.124	
LRM	ZrO_2	0.941	0.93	0.011	
LRM	**Sum of Oxides**	**98.7**	**98.2**	**0.463**	**0%**

Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations

Oxide=Al_2O_3
Variability Chart for Measured (wt.%)



Oxide=B_2O_3, Prep Method=PF
Variability Chart for Measured (wt.%)



Oxide=CaO, Prep Method=PF
Variability Chart for Measured (wt.%)

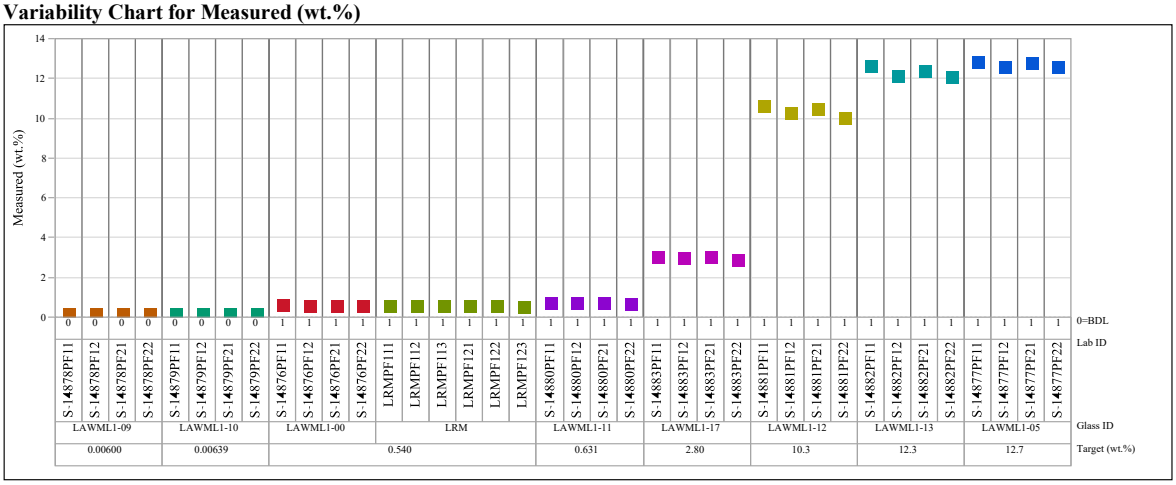
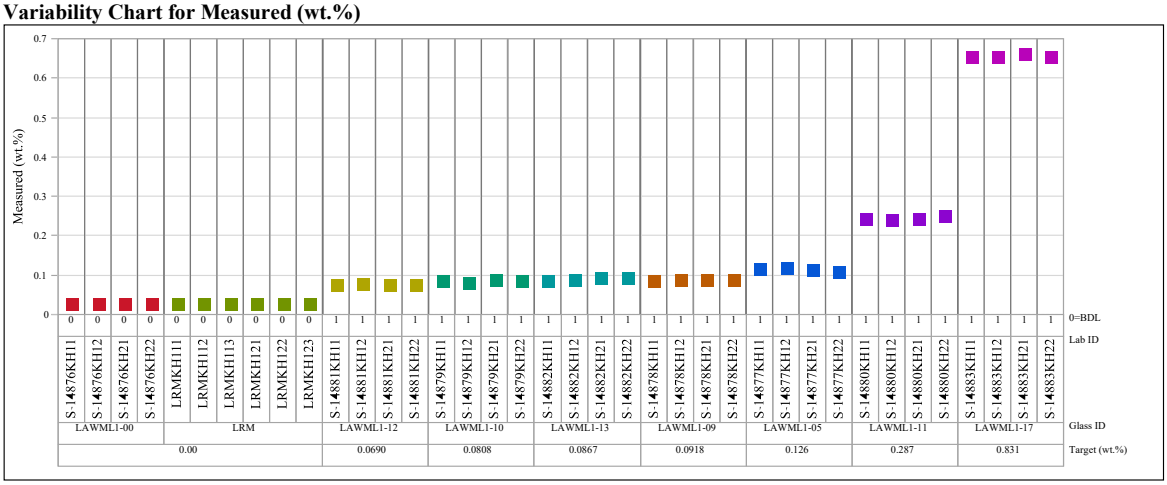
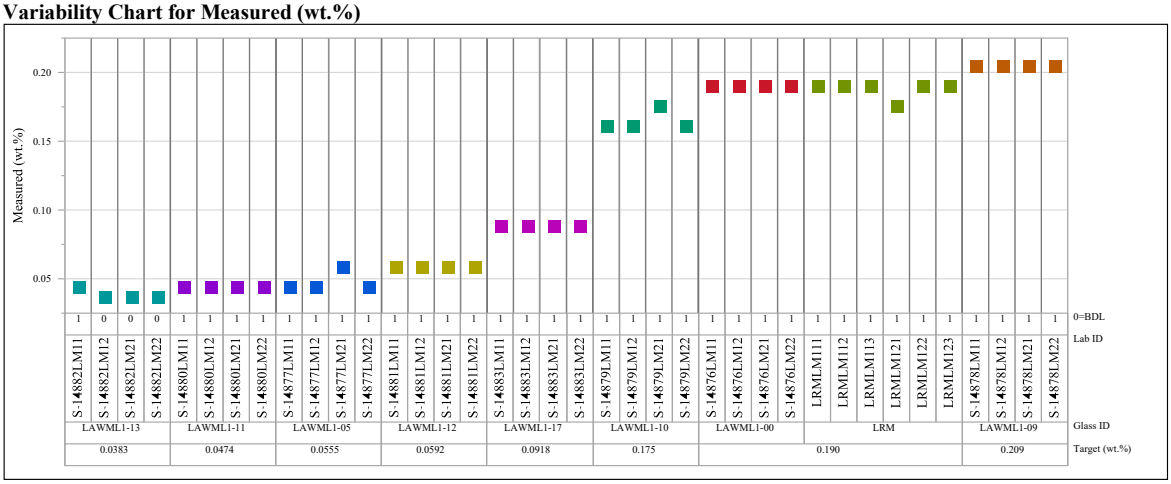


Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations (continued)

Oxide=Cl
Variability Chart for Measured (wt.%)



Oxide=Cr_2O_3
Variability Chart for Measured (wt.%)



Oxide=F
Variability Chart for Measured (wt.%)

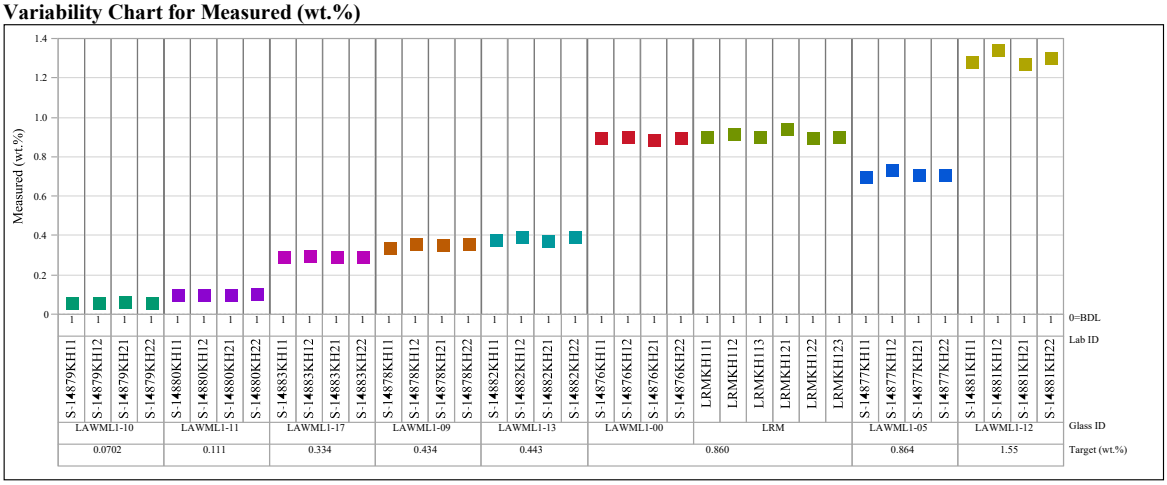
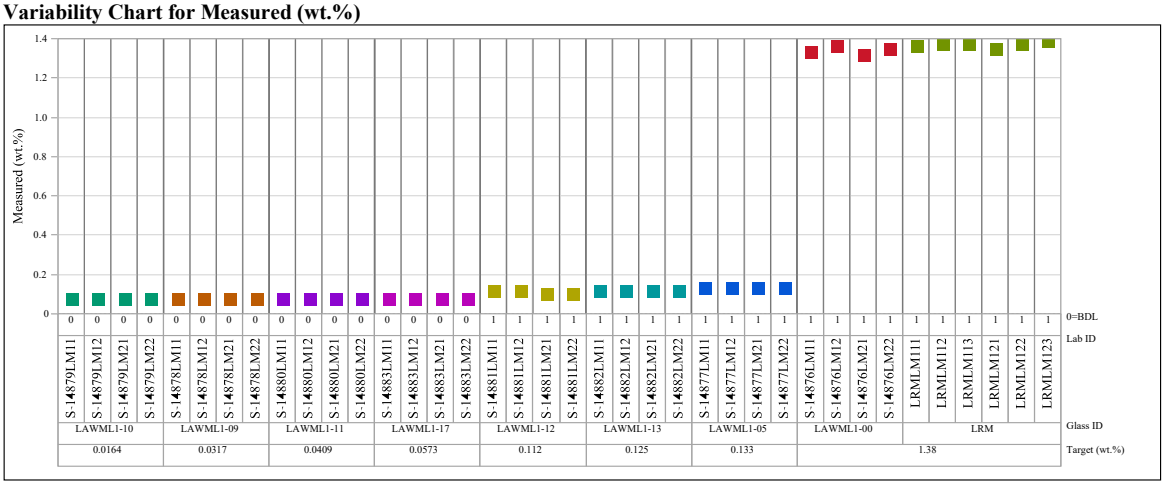
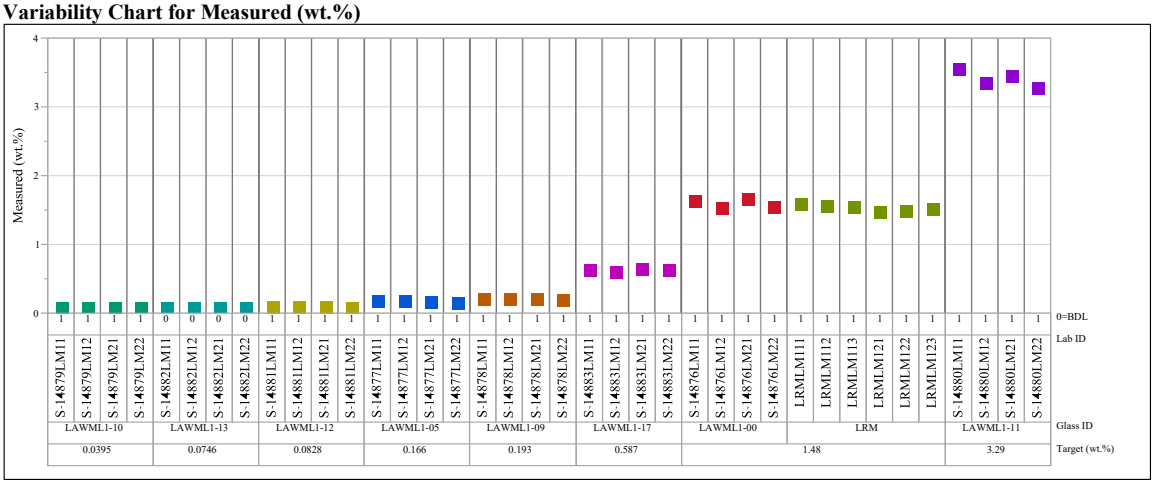


Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations (continued)

Oxide=Fe_2O_3
Variability Chart for Measured (wt.%)



Oxide=K_2O
Variability Chart for Measured (wt.%)



Oxide=Li_2O
Variability Chart for Measured (wt.%)

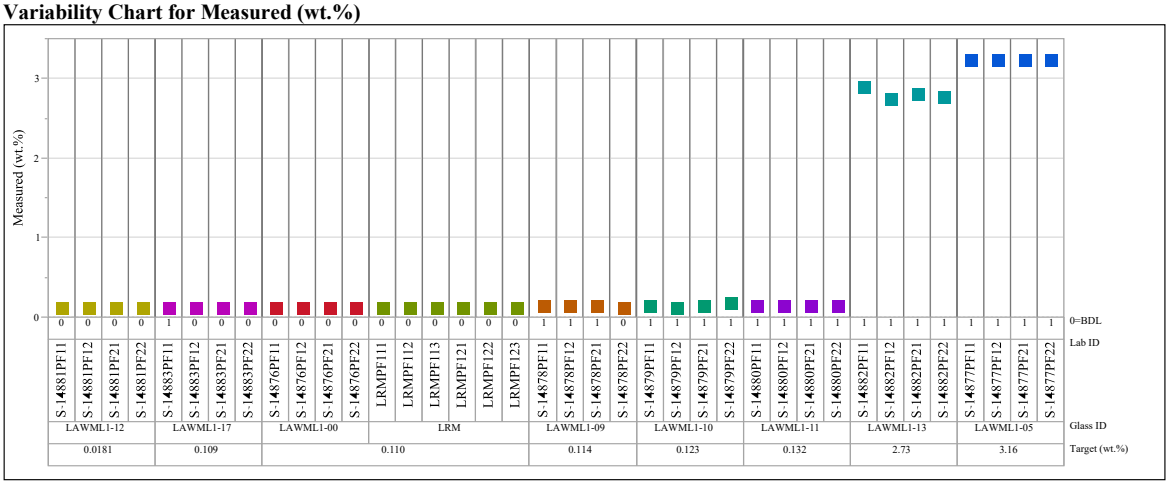
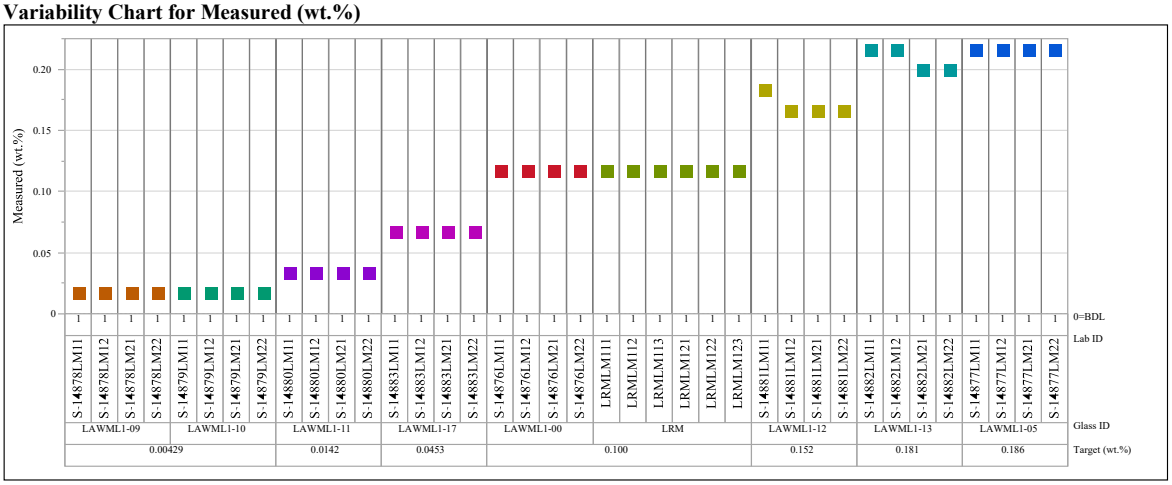
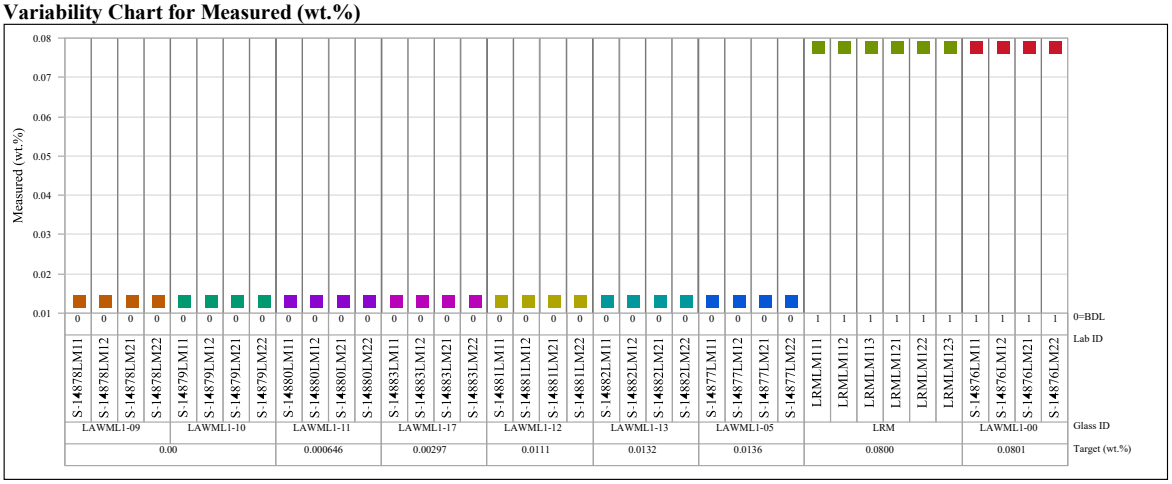


Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations (continued)

Oxide=MgO
Variability Chart for Measured (wt.%)



Oxide=MnO
Variability Chart for Measured (wt.%)



Oxide=Na_2O
Variability Chart for Measured (wt.%)

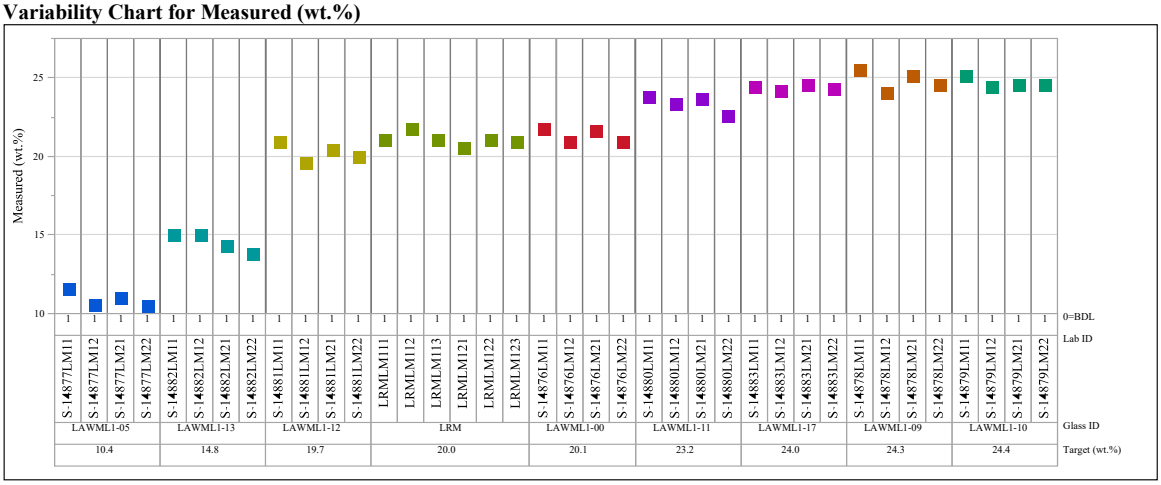
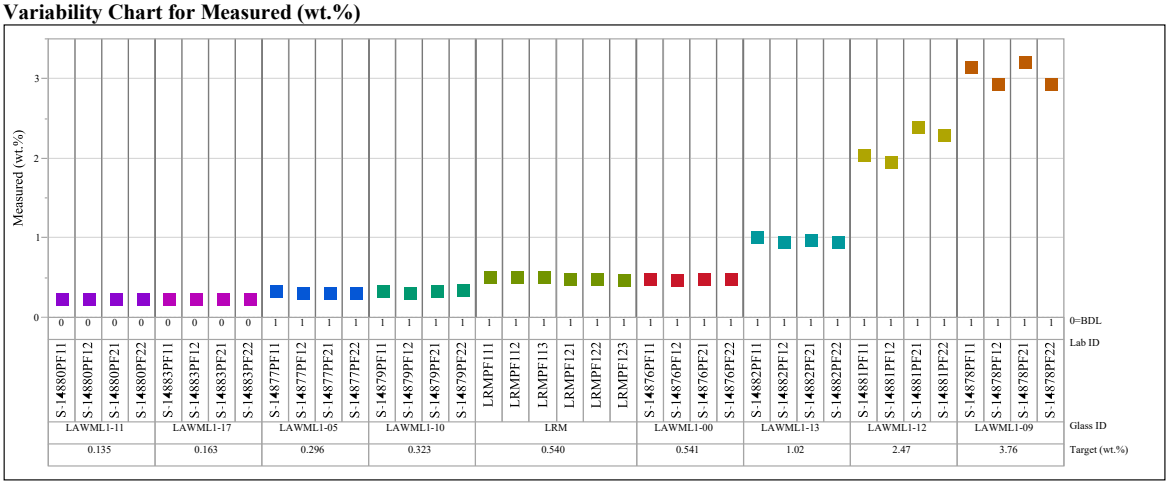
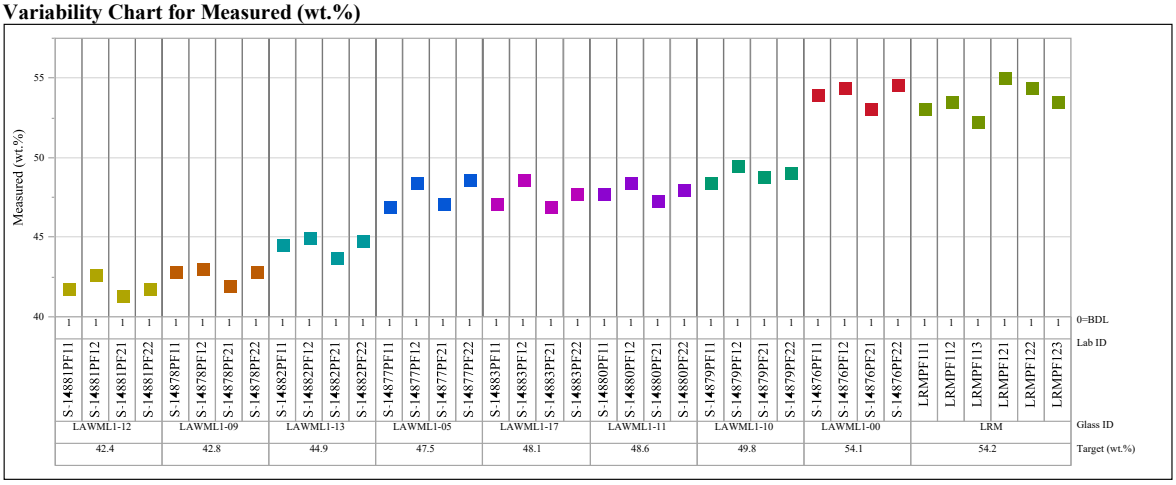


Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations (continued)

Oxide=P_2O_5
Variability Chart for Measured (wt.%)



Oxide=SiO_2
Variability Chart for Measured (wt.%)



Oxide=SnO_2
Variability Chart for Measured (wt.%)

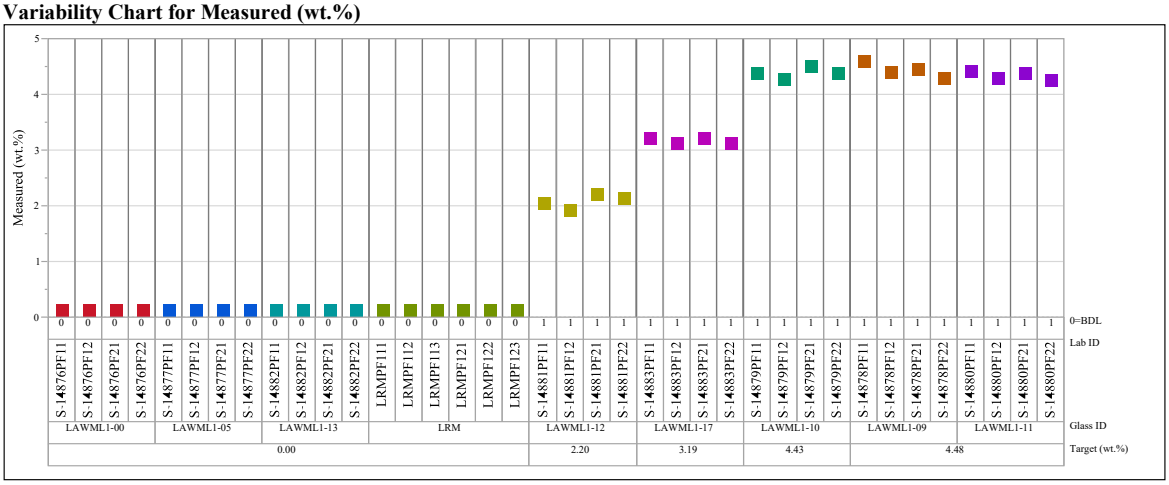
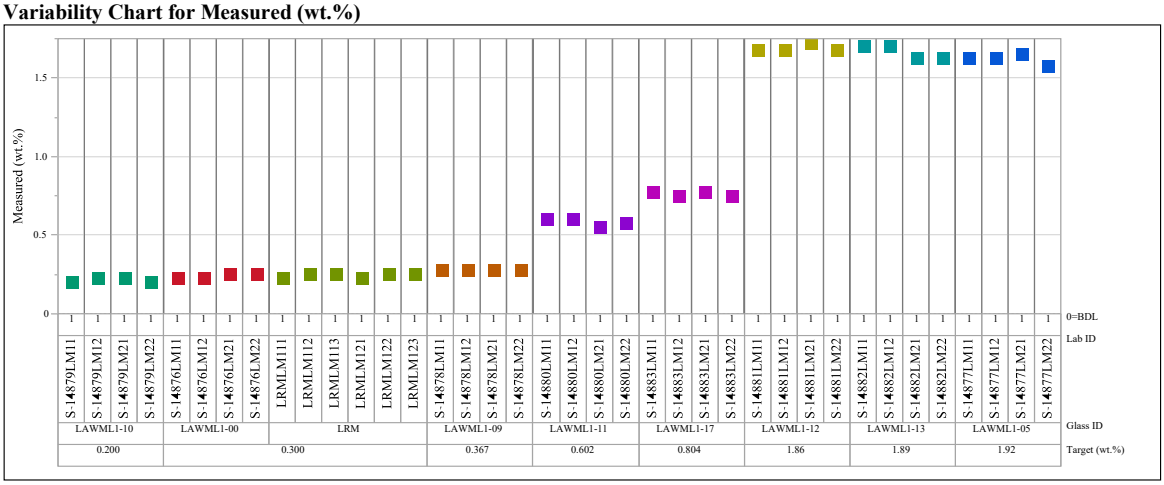
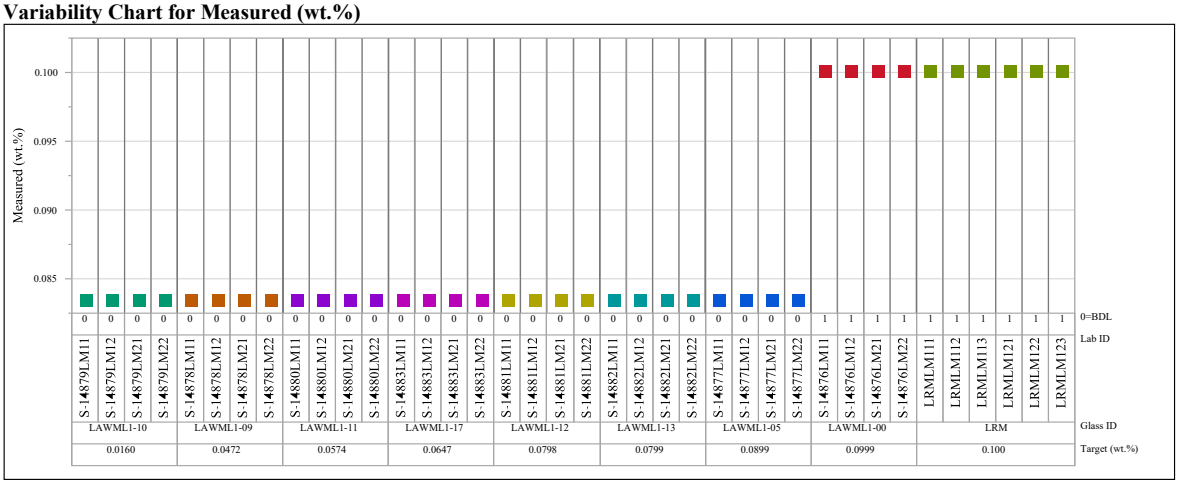


Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations (continued)

Oxide=SO_3
Variability Chart for Measured (wt.%)



Oxide=TiO_2
Variability Chart for Measured (wt.%)



Oxide=V_2O_5
Variability Chart for Measured (wt.%)

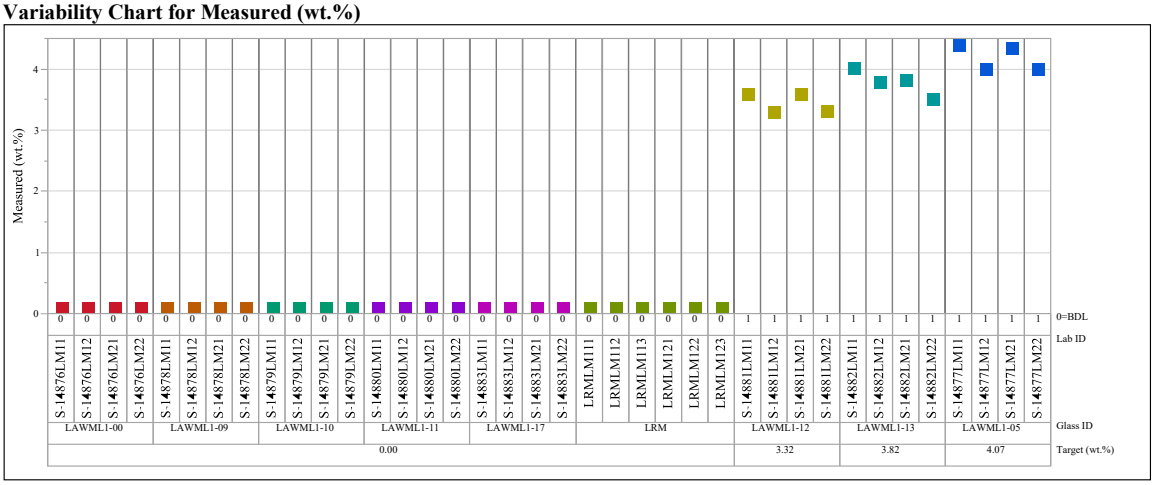
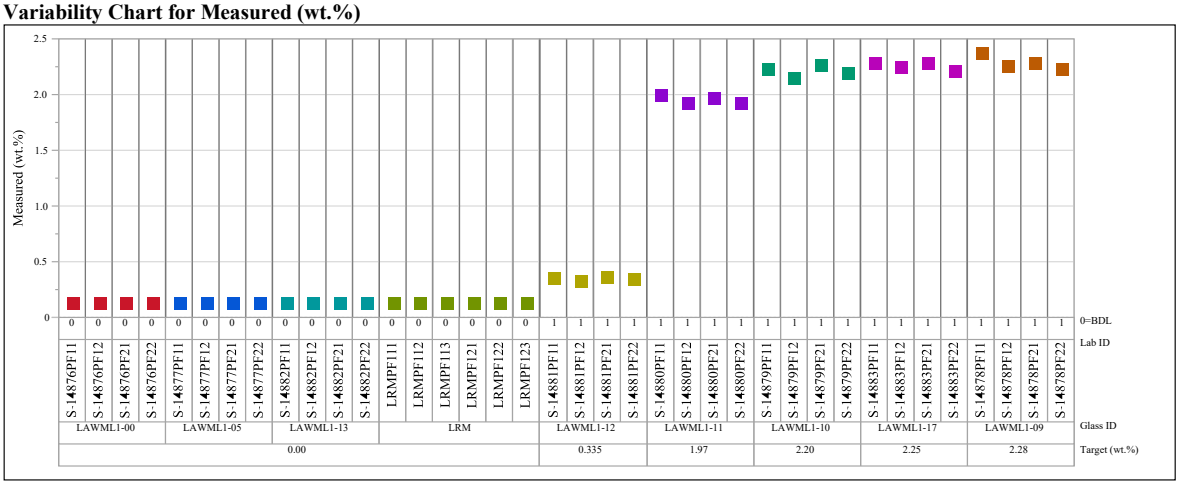


Exhibit A-1. Plots of Oxides by Glass Identifier by Target Concentrations (continued)

Oxide=ZnO
Variability Chart for Measured (wt.%)



Oxide=ZrO_2
Variability Chart for Measured (wt.%)

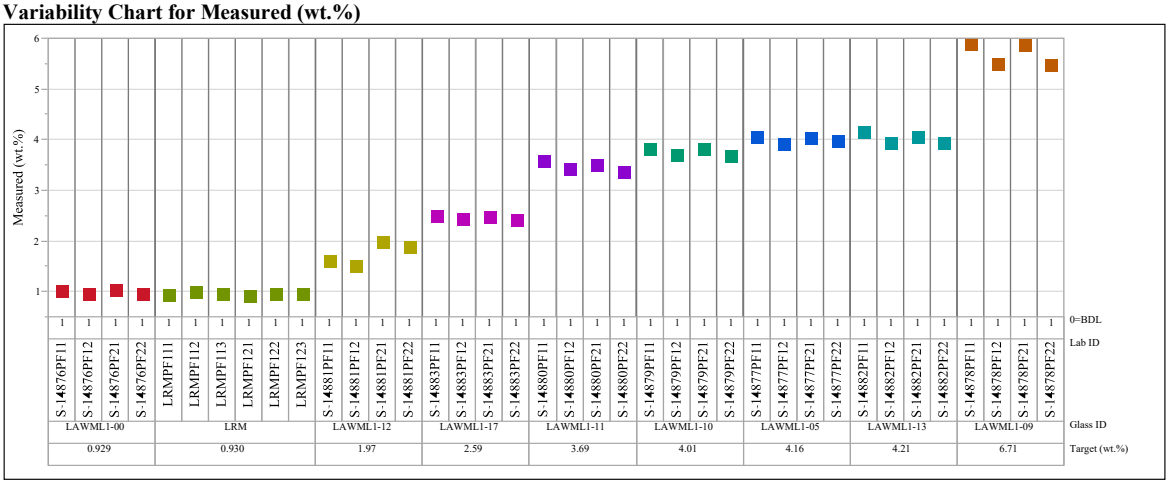
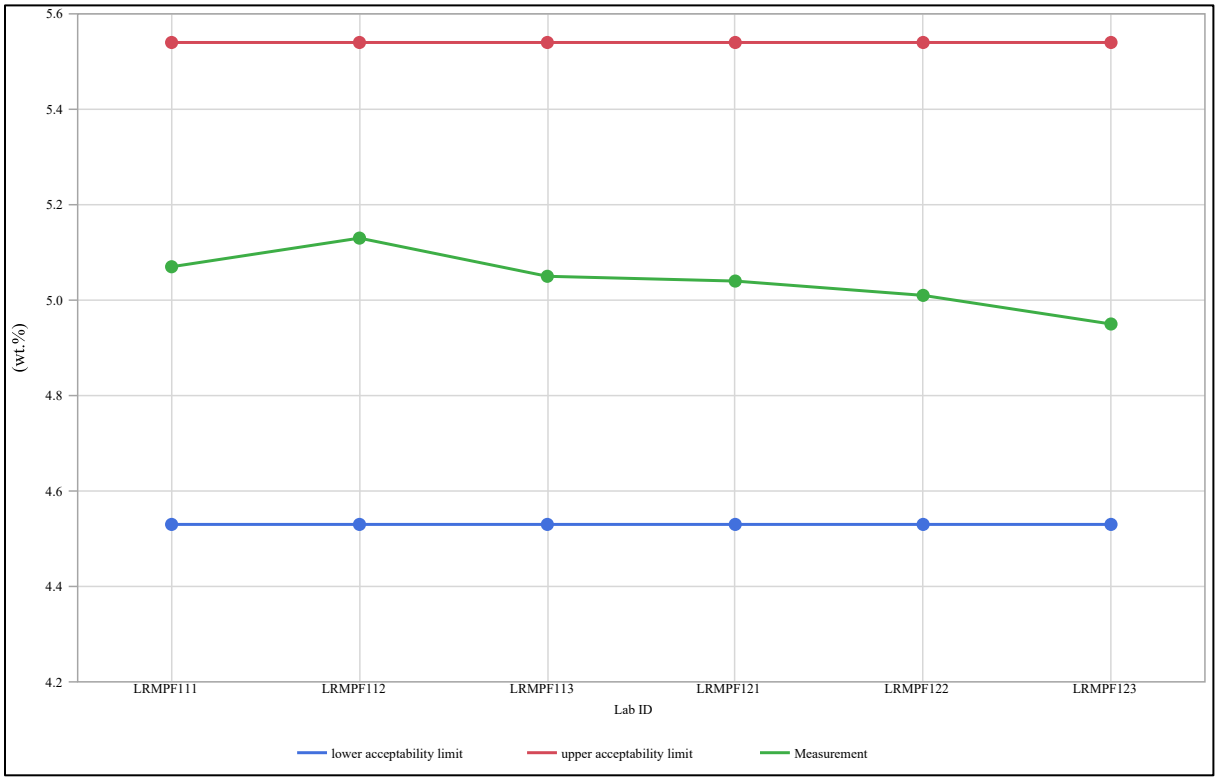


Exhibit A-2. Acceptability Evaluation for Measurements of the LRM Glass

Element=Al



Element=B

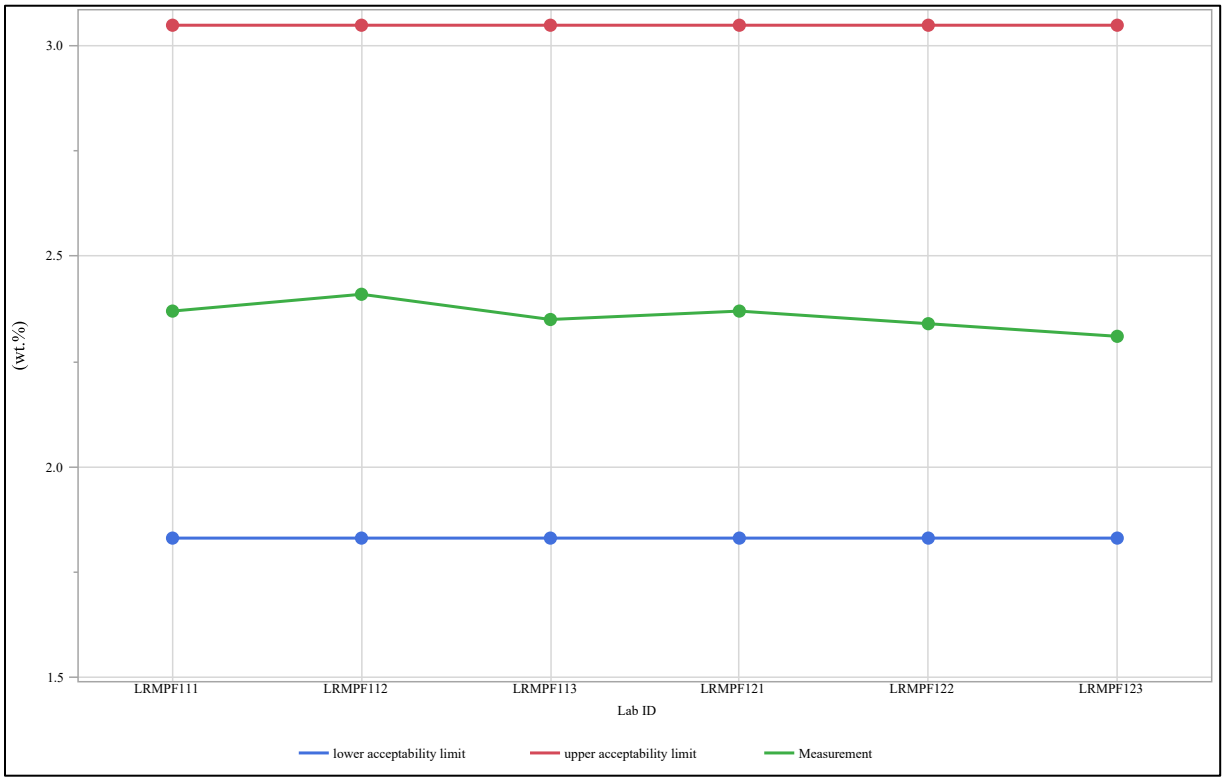
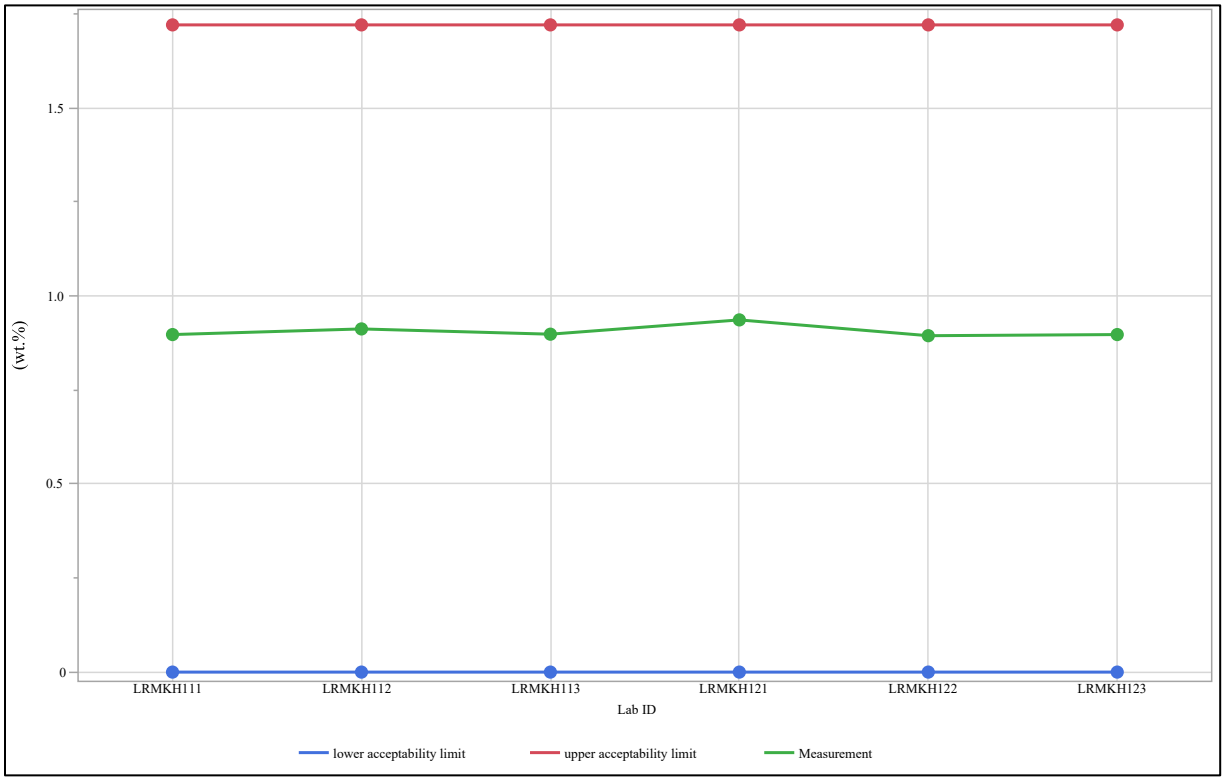


Exhibit A-2. Acceptability Evaluation for Measurements of the LRM Glass (continued)

Element=F



Element=Fe

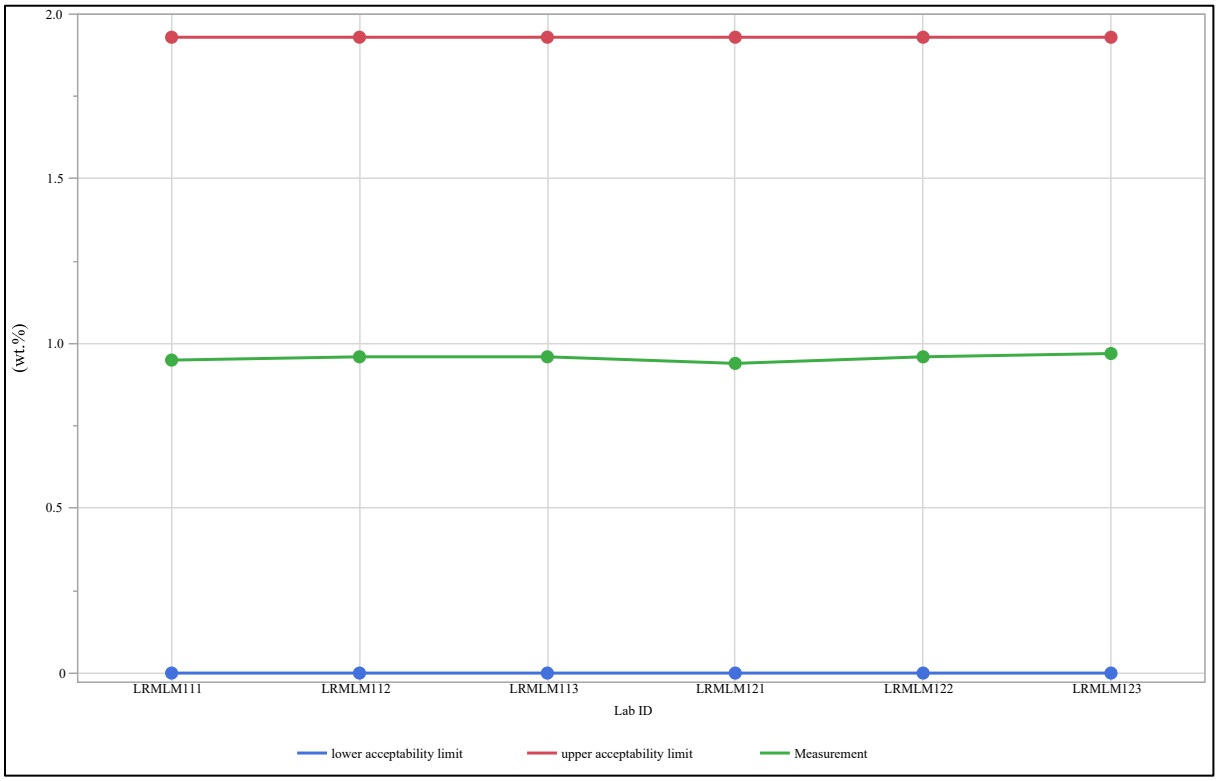
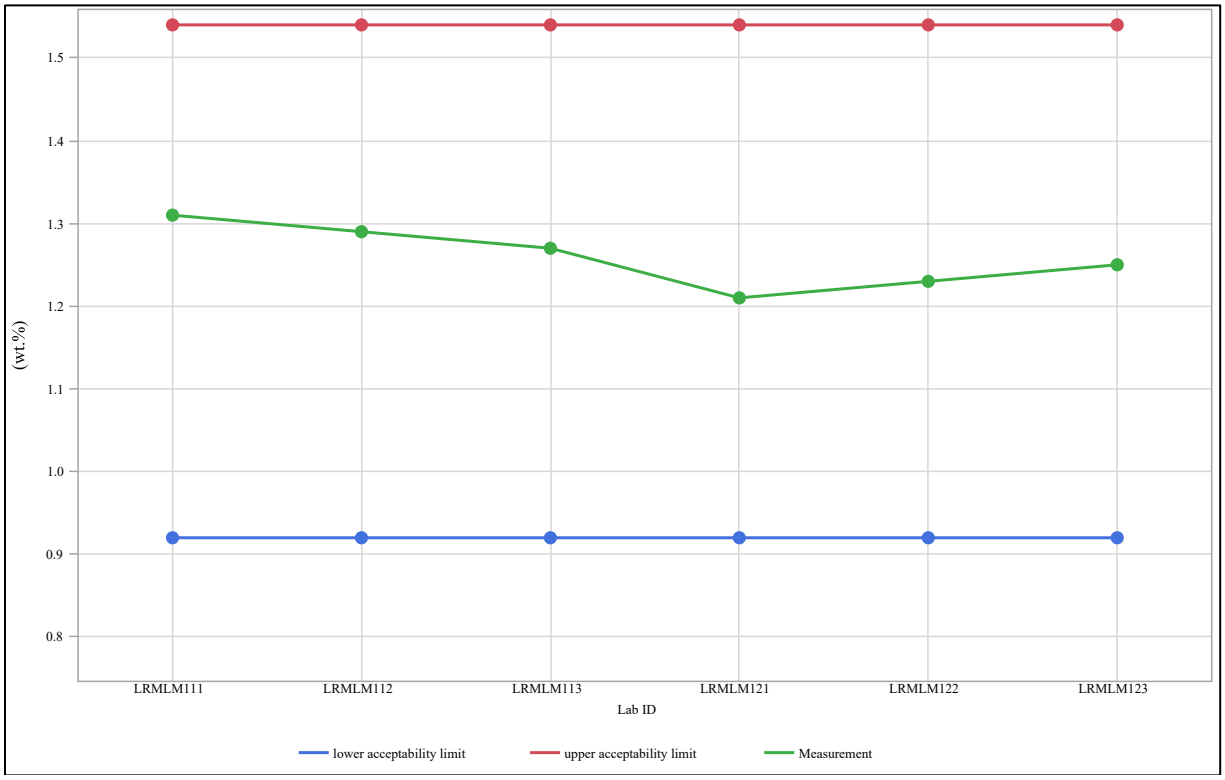


Exhibit A-2. Acceptability Evaluation for Measurements of the LRM Glass (continued)

Element=K



Element=Na

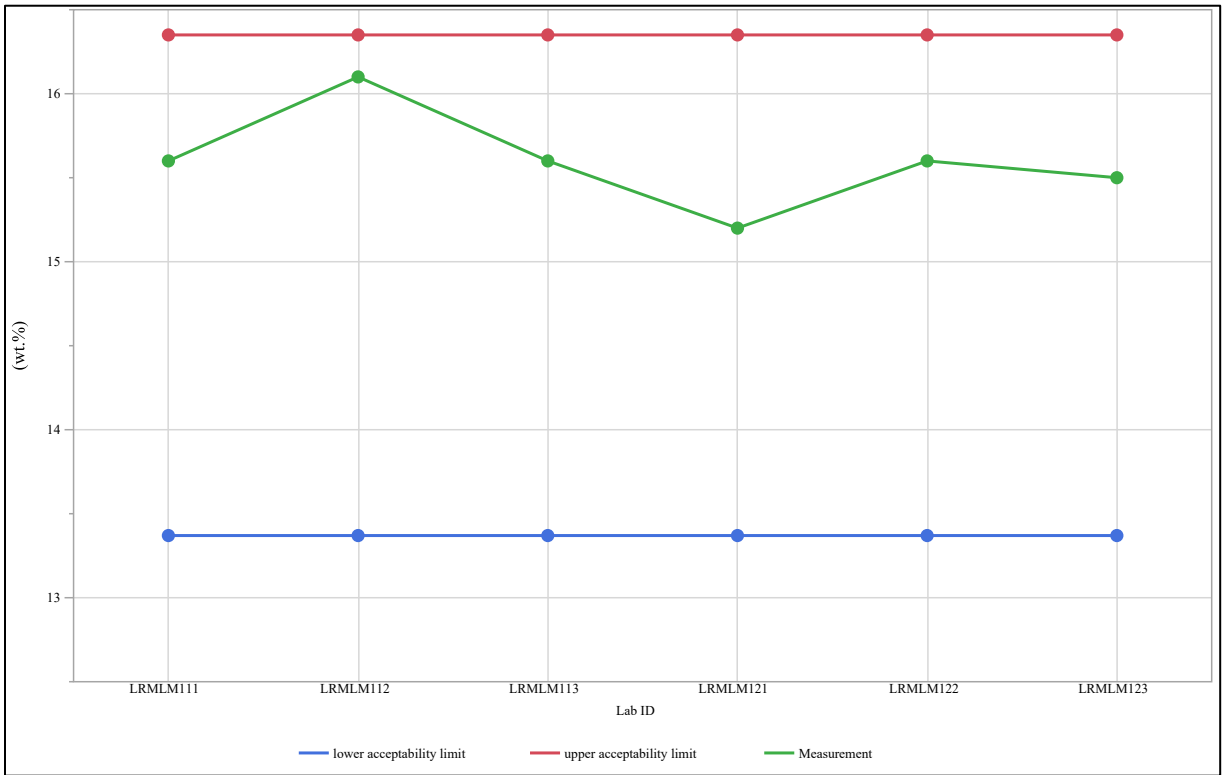
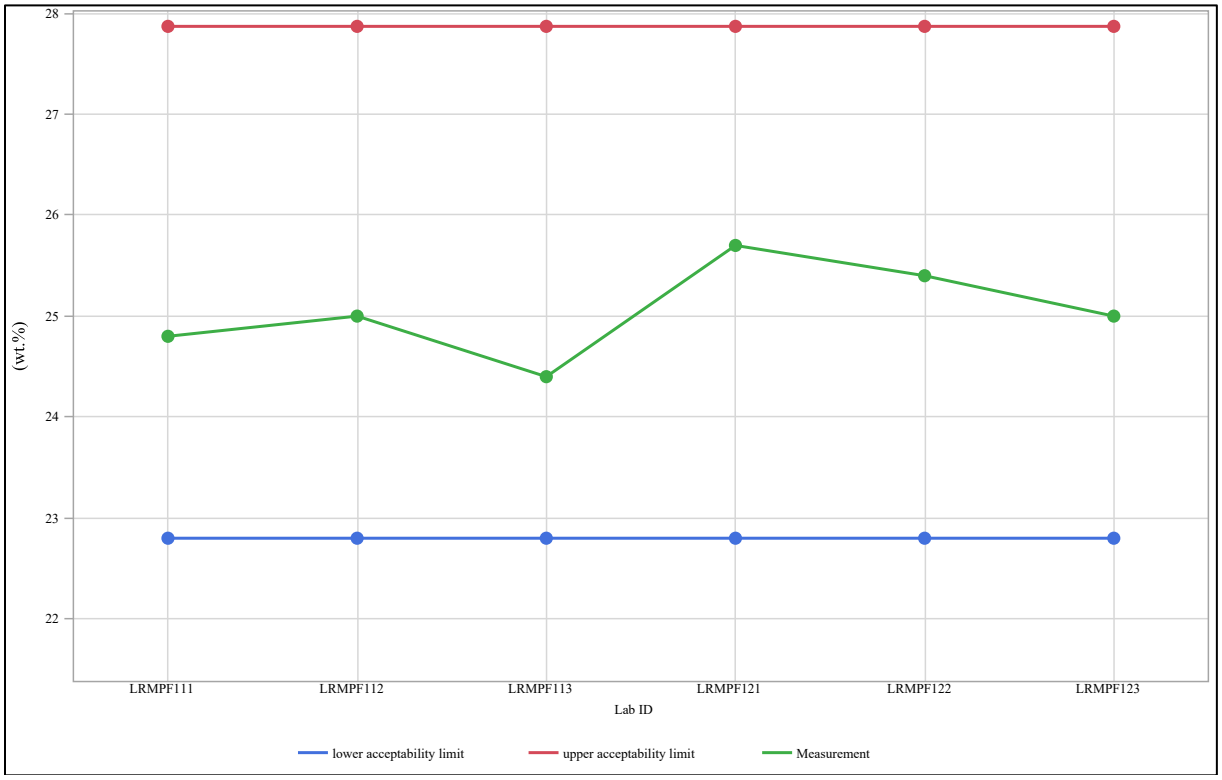


Exhibit A-2. Acceptability Evaluation for Measurements of the LRM Glass (continued)

Element=Si



Element=Zr

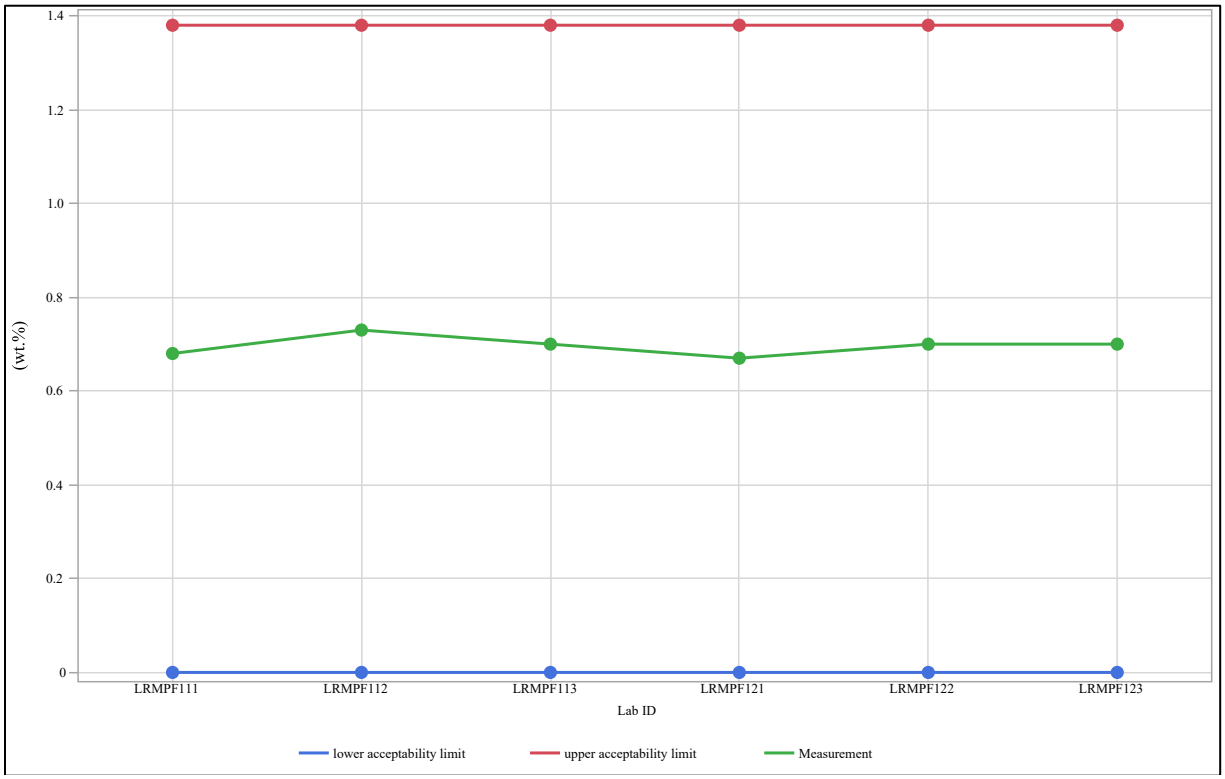
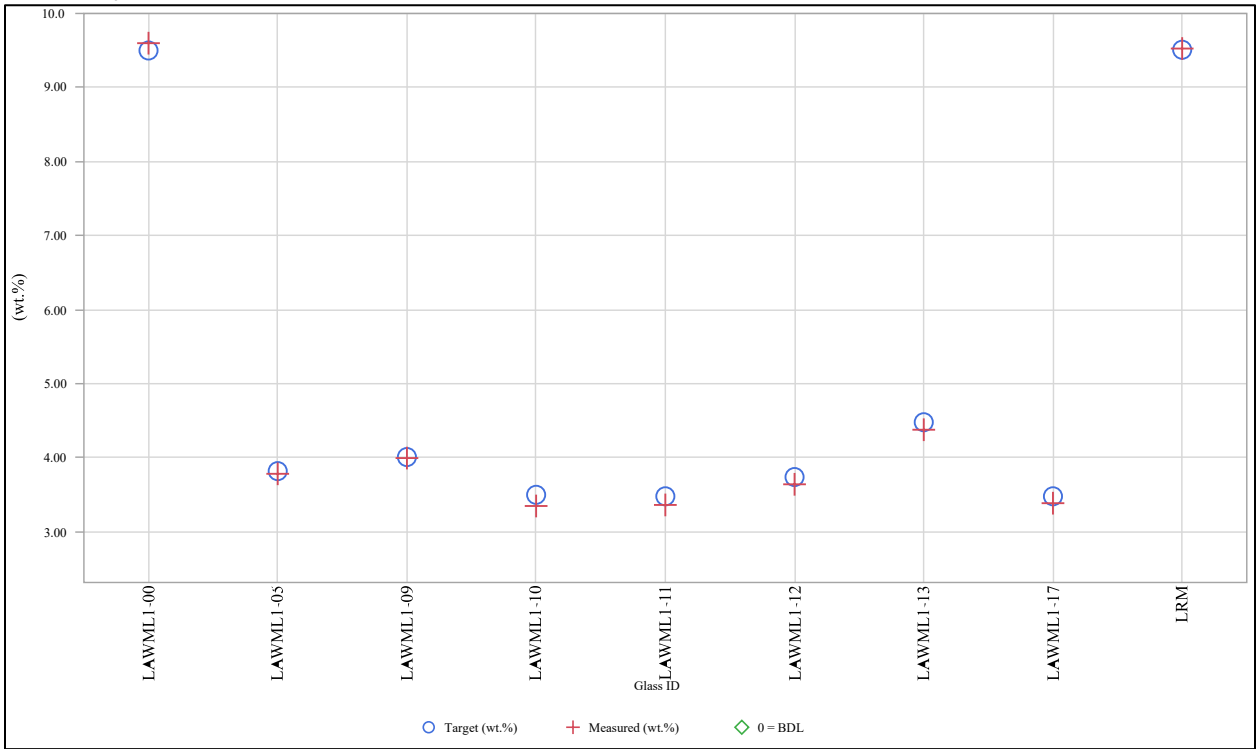


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide

Oxide=Al_2O_3



Oxide=B_2O_3

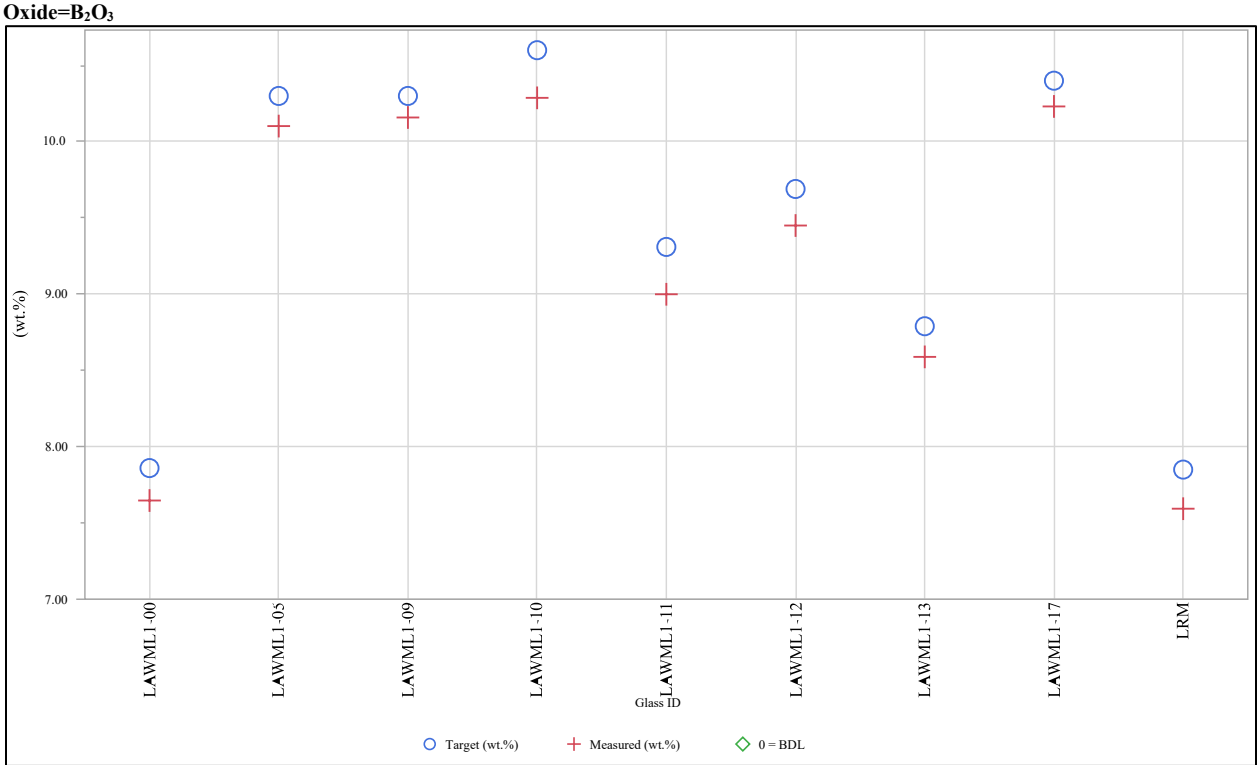
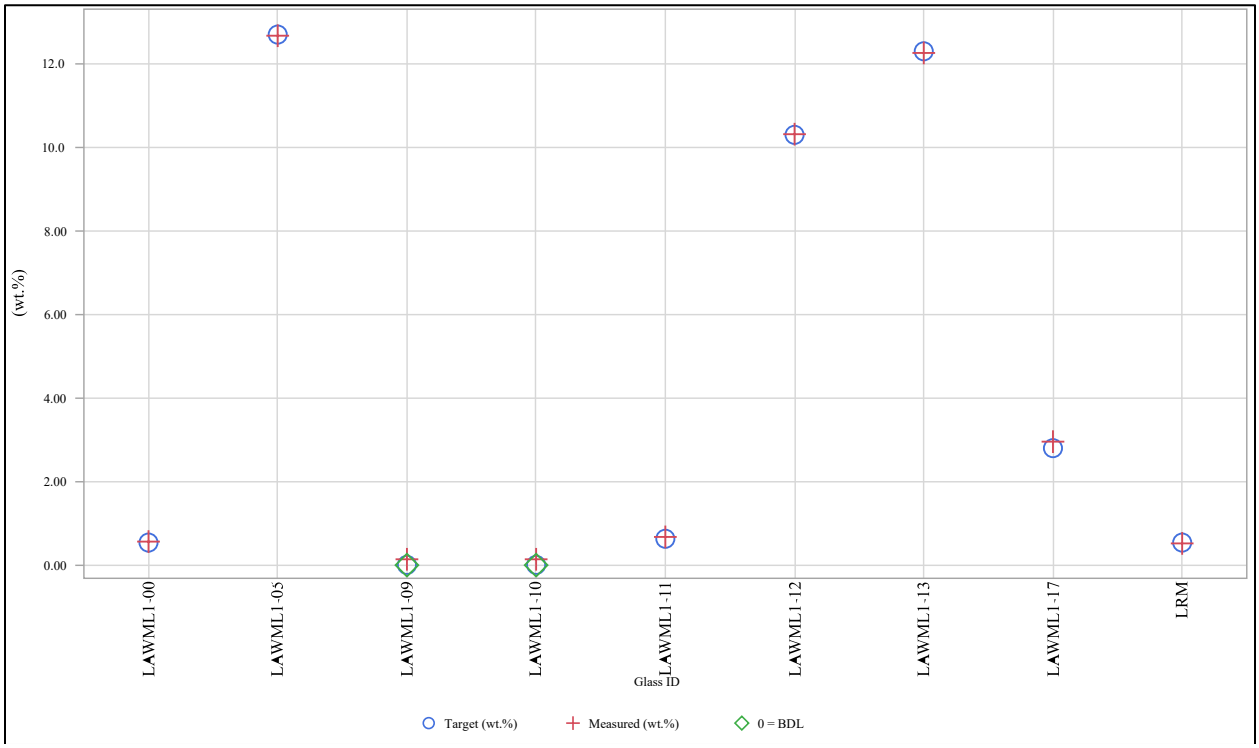


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=CaO



Oxide=Cl

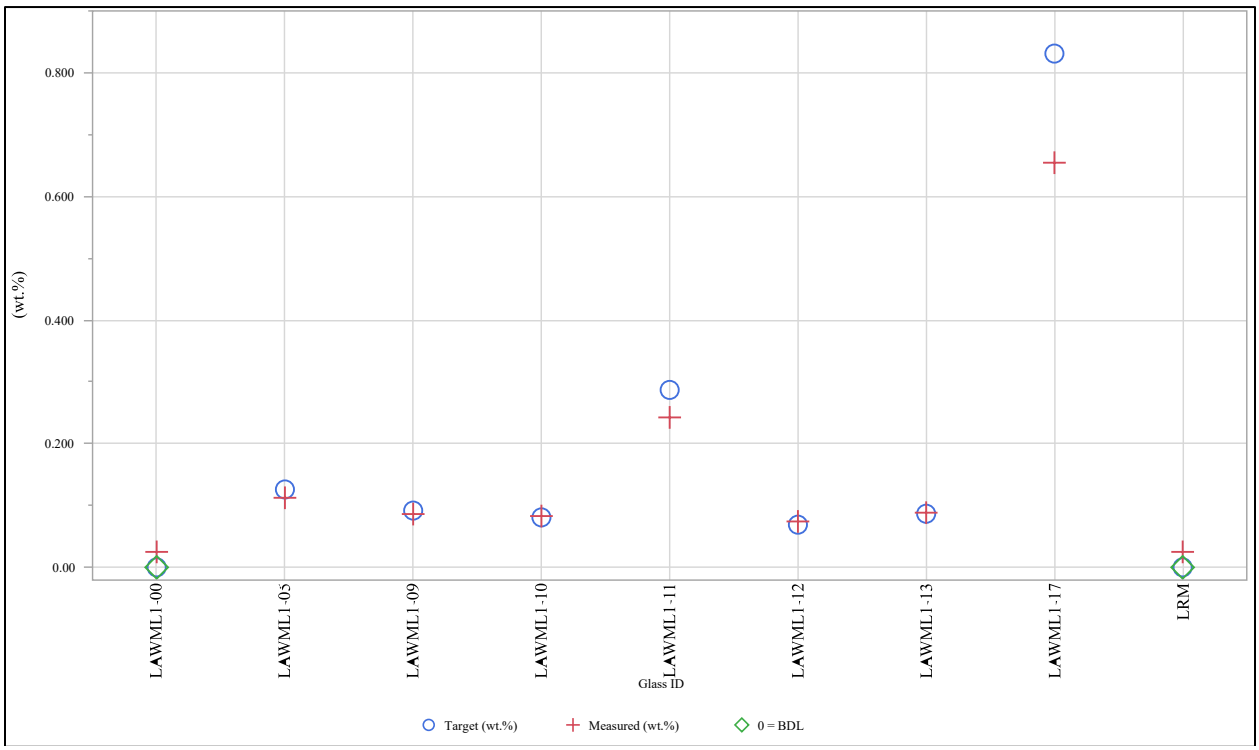
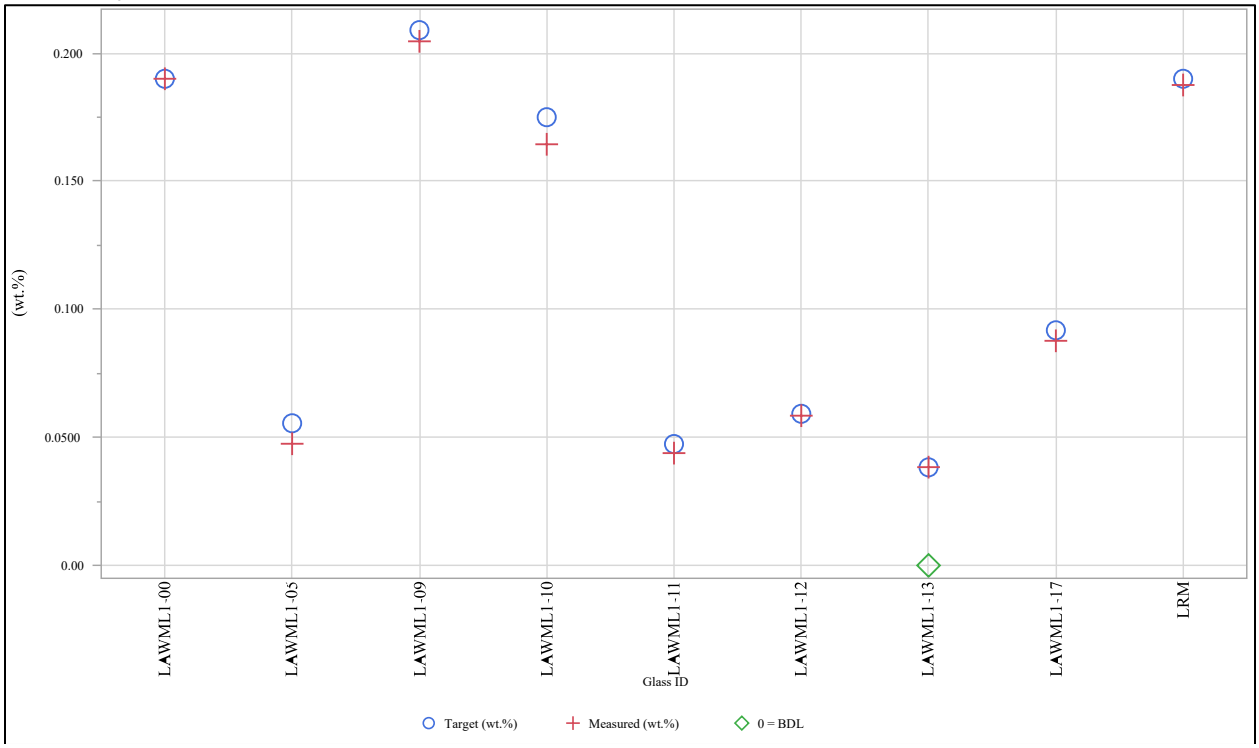


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=Cr_2O_3



Oxide=F

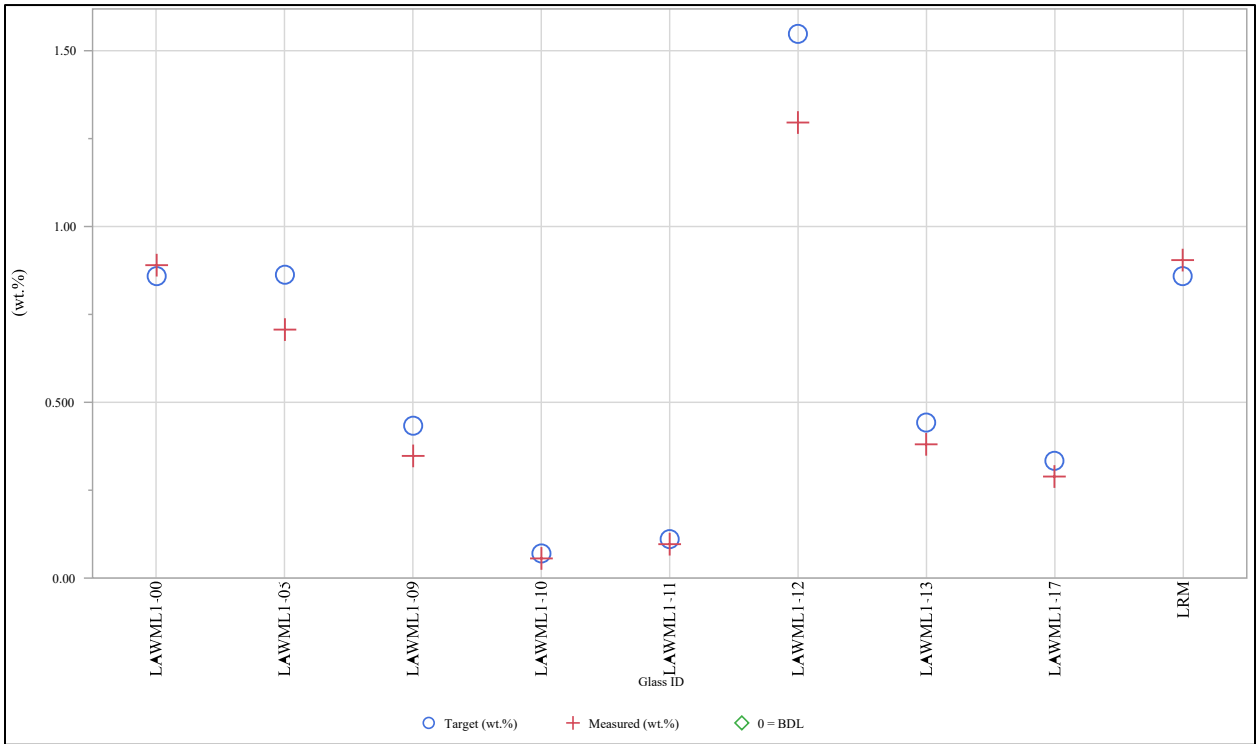
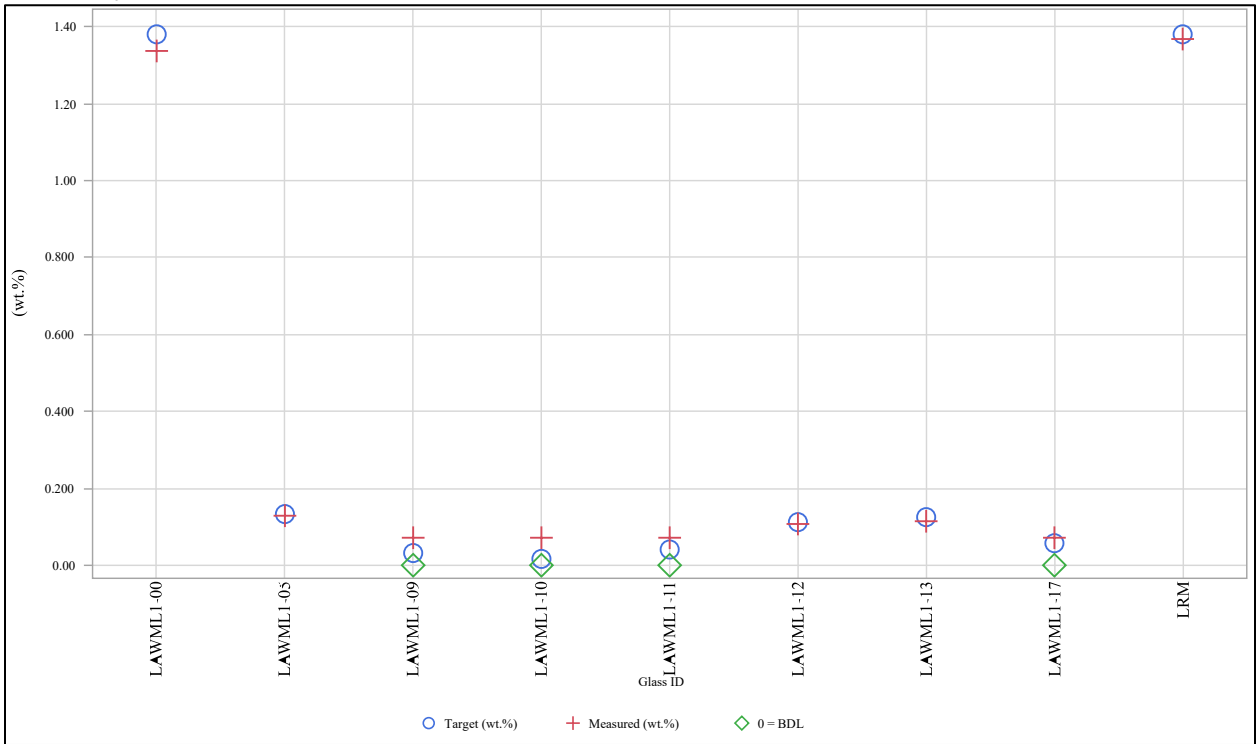


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=Fe_2O_3



Oxide=K_2O

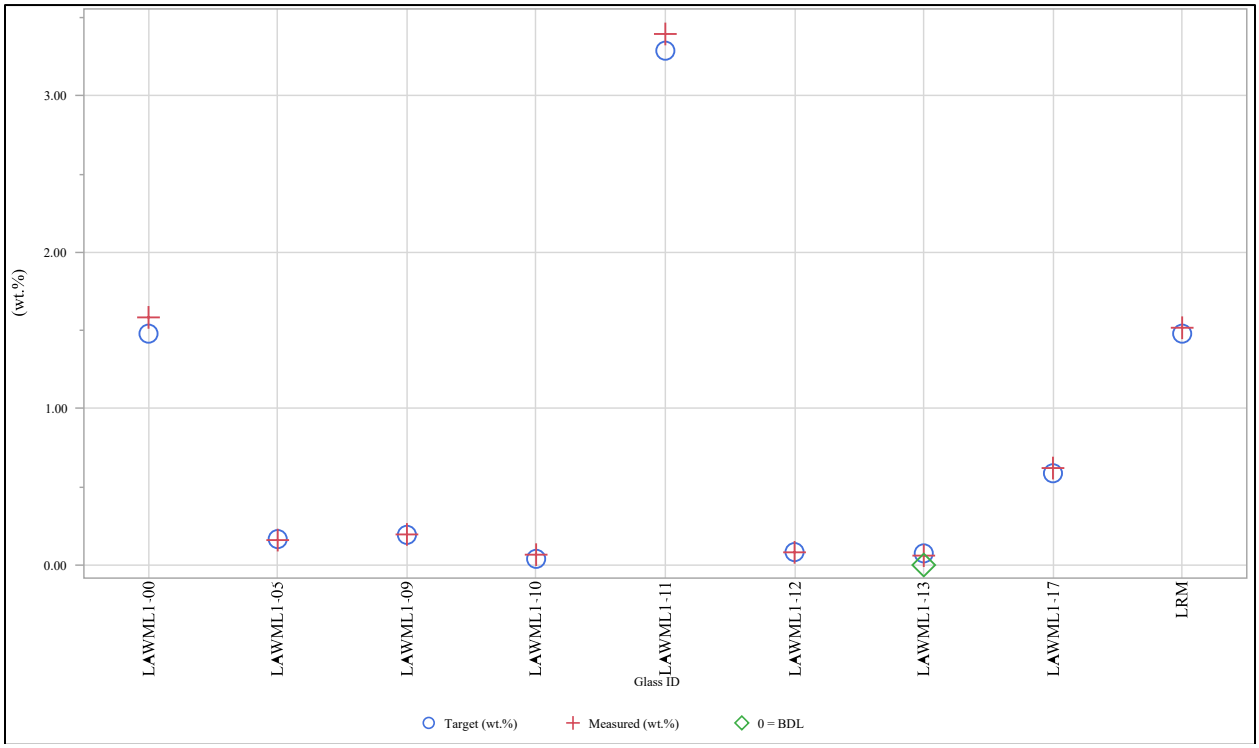
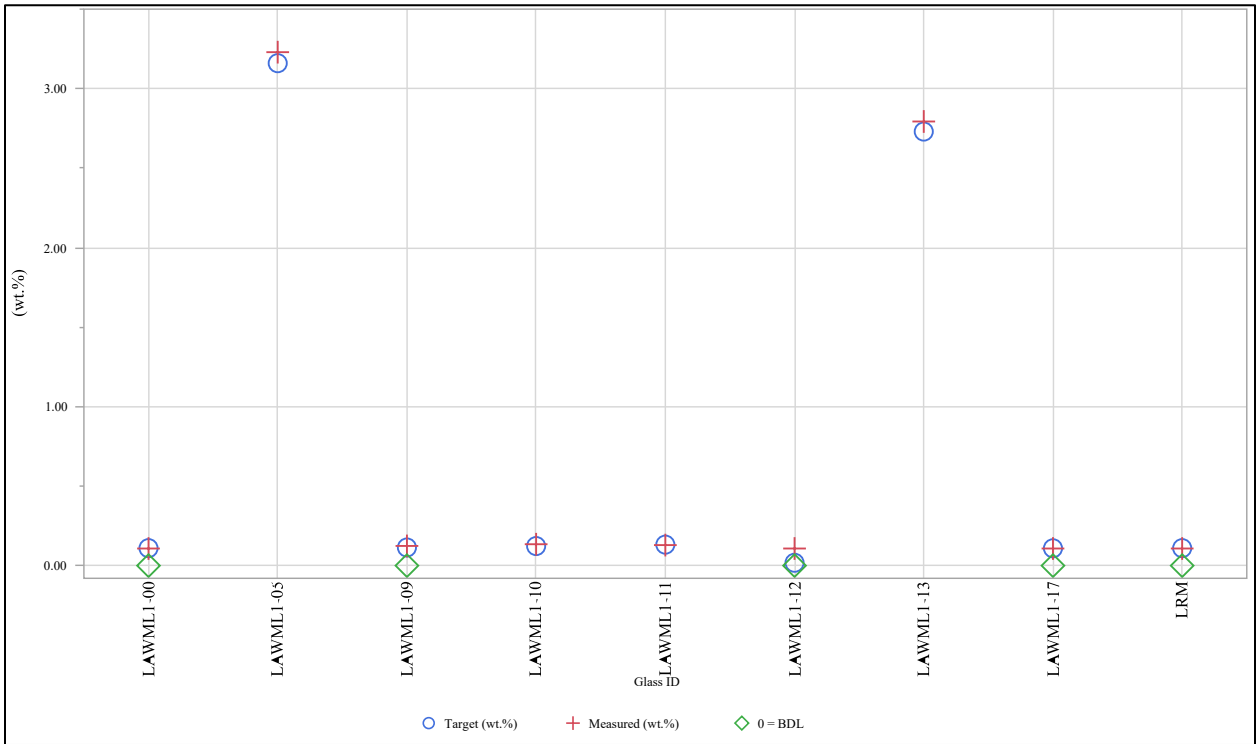


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=Li_2O



Oxide=MgO

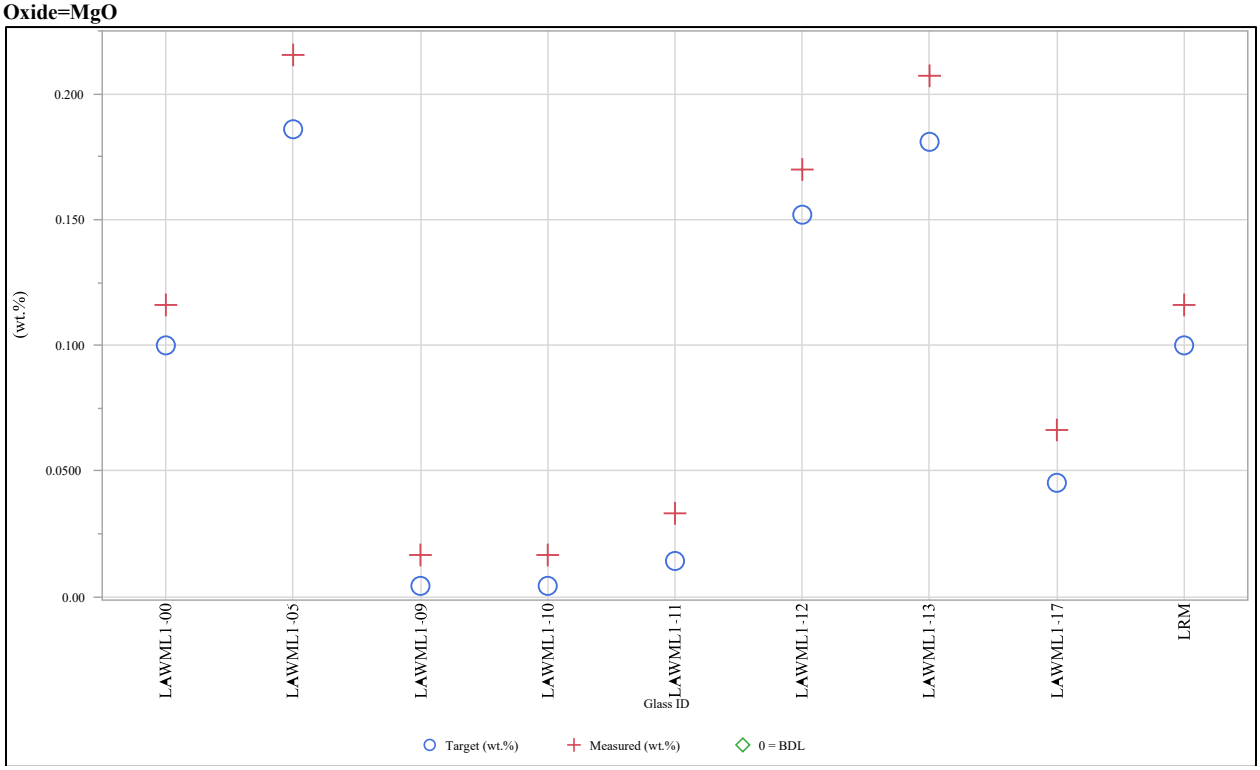
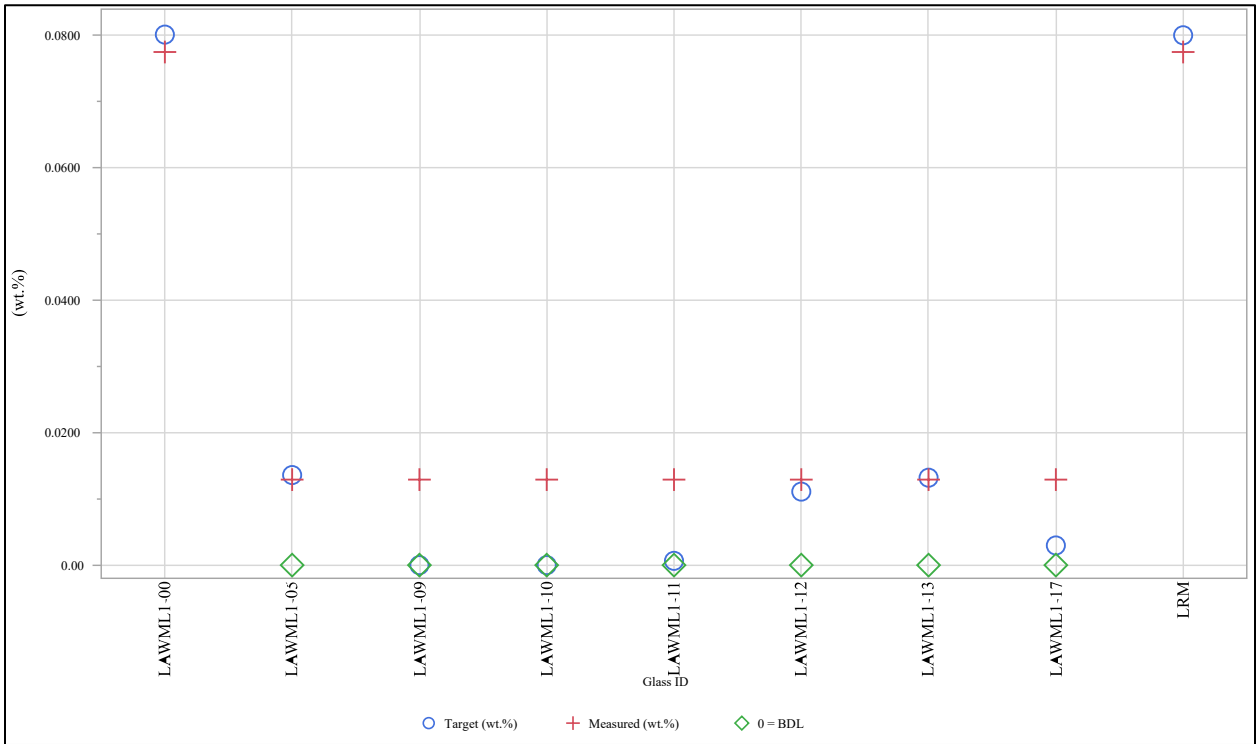


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=MnO



Oxide=Na_2O

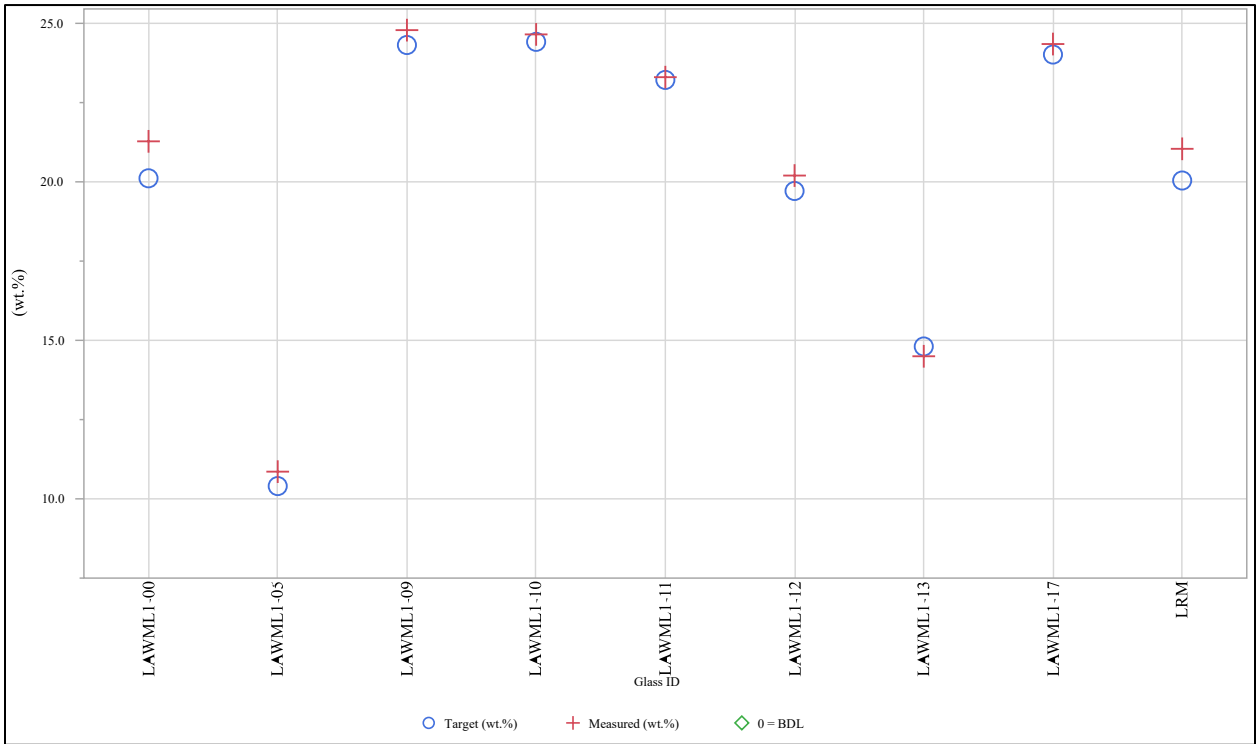
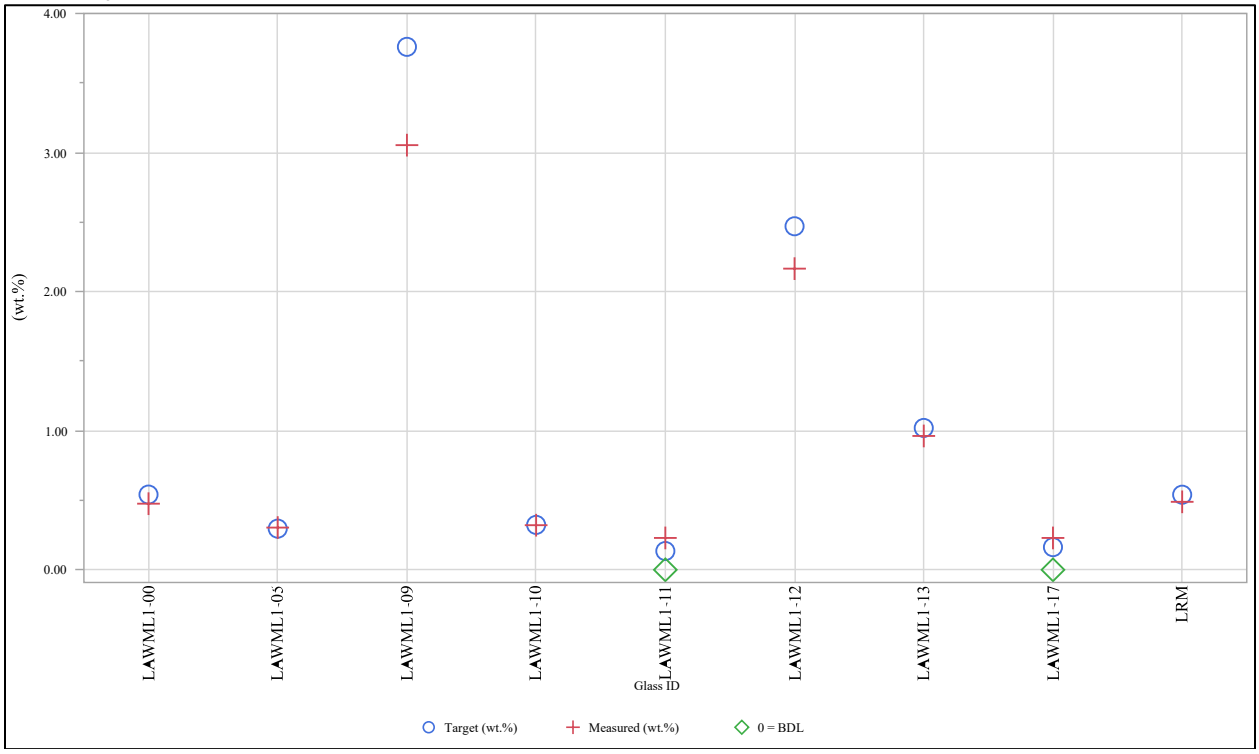


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=P_2O_5



Oxide=SiO_2

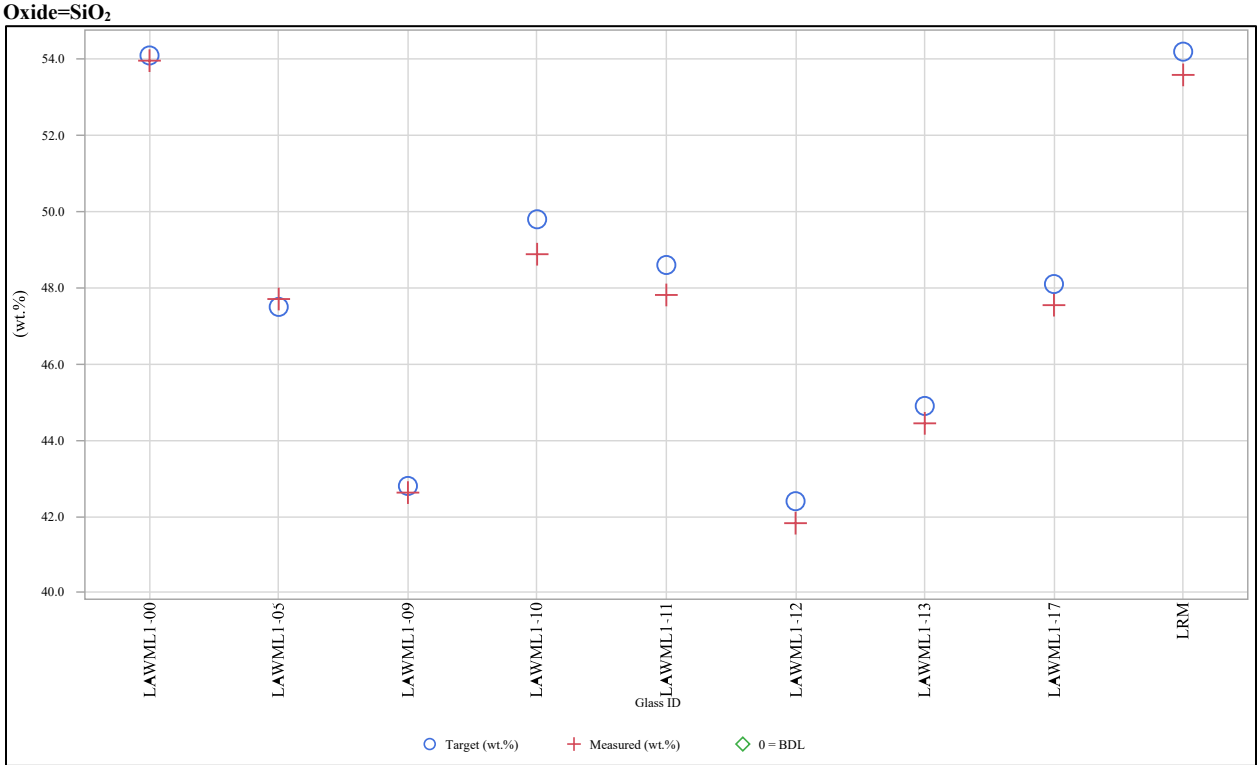
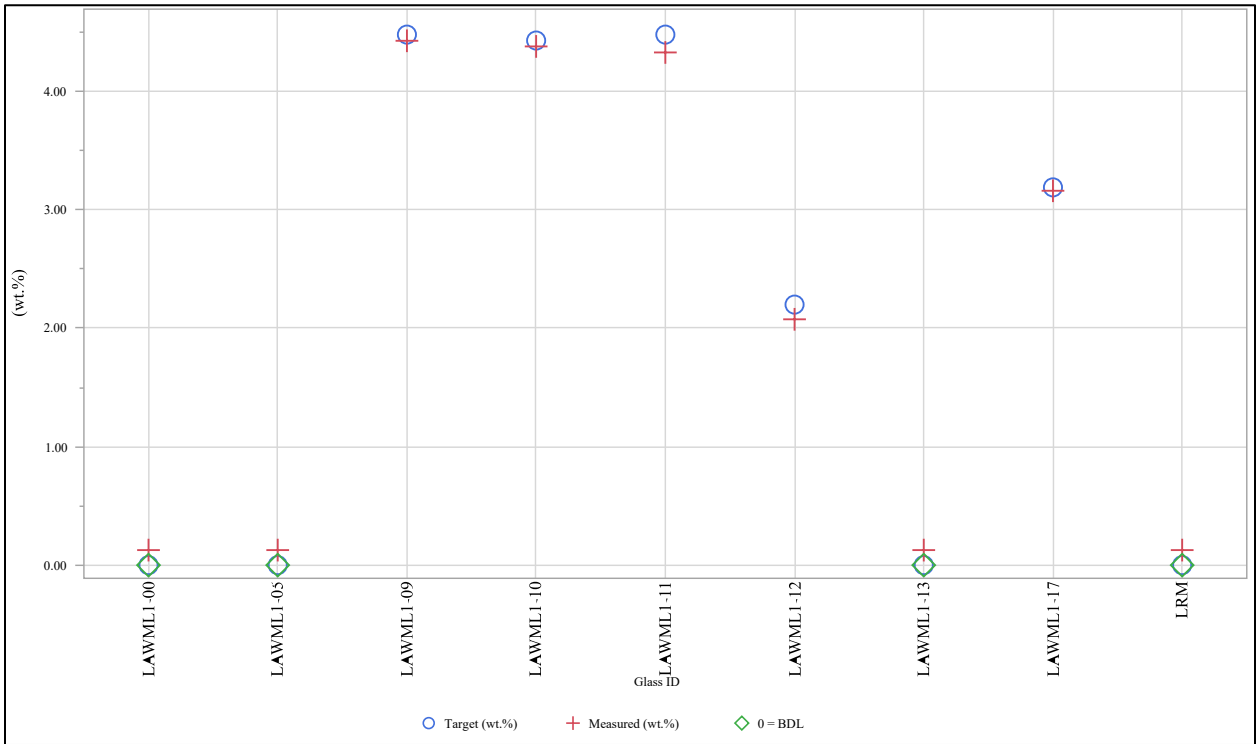


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=SnO_2



Oxide=SO_3

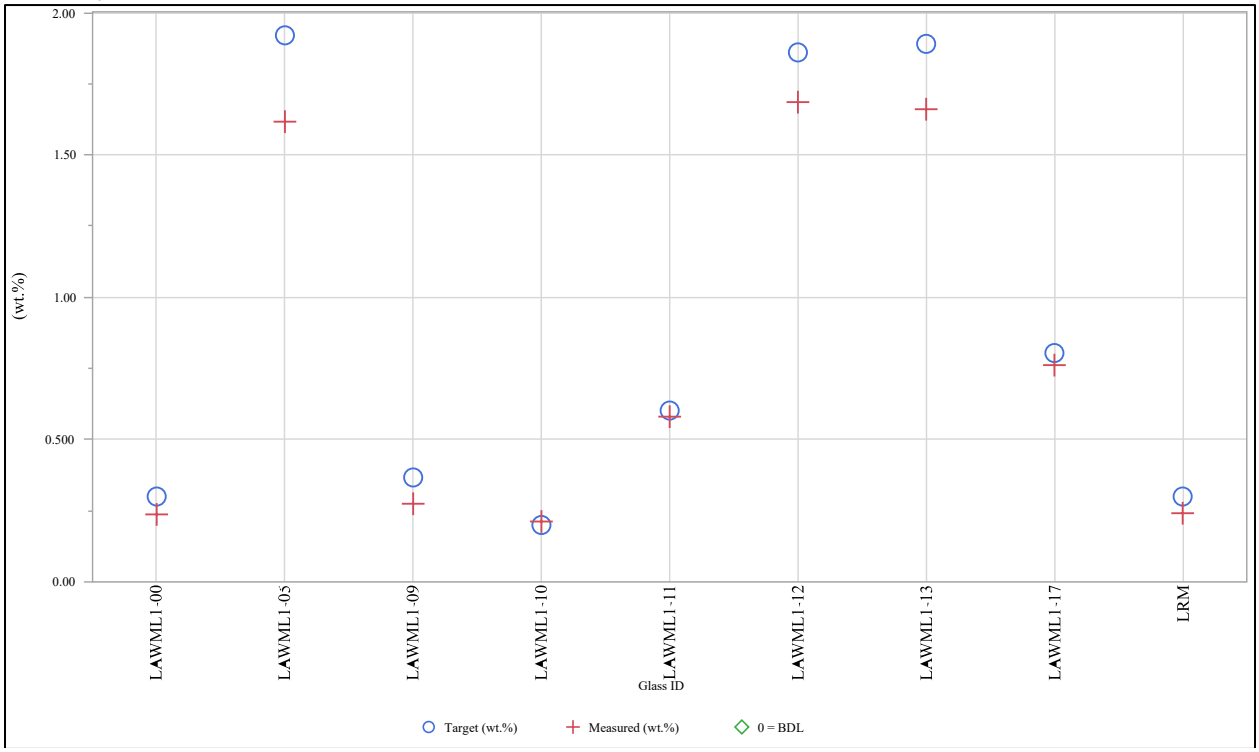
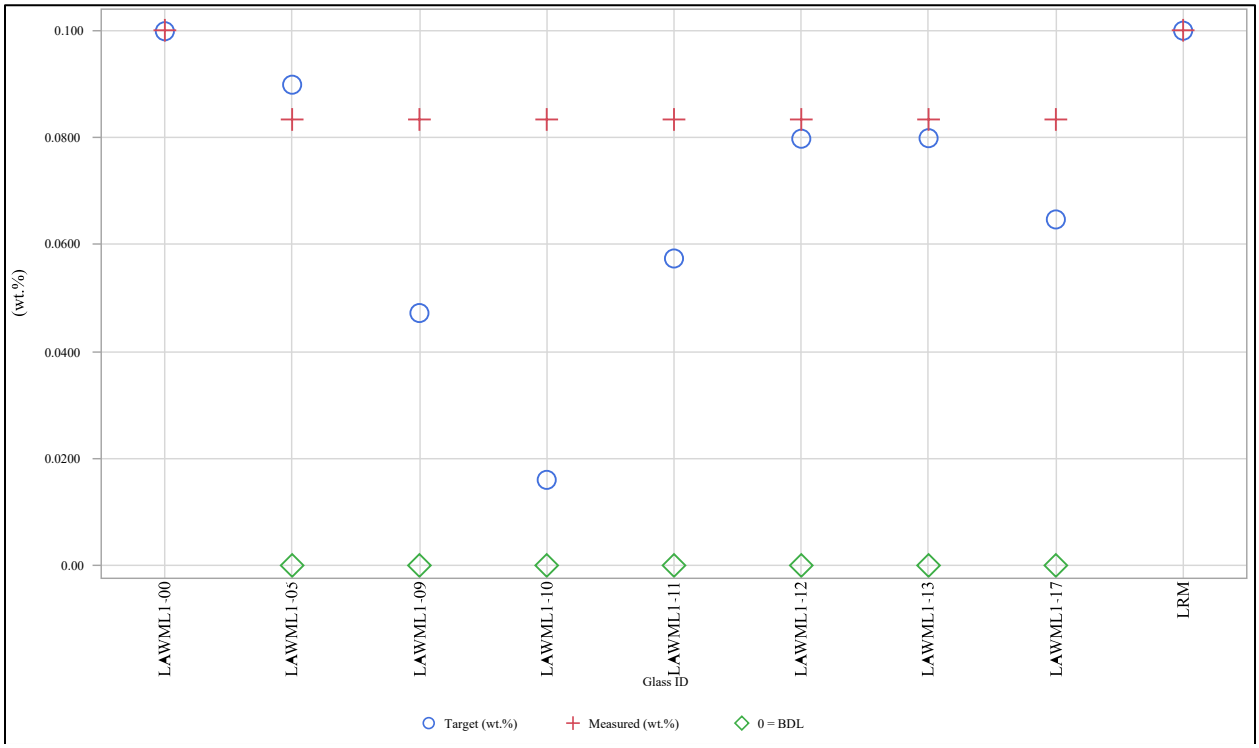


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=TiO_2



Oxide=V_2O_5

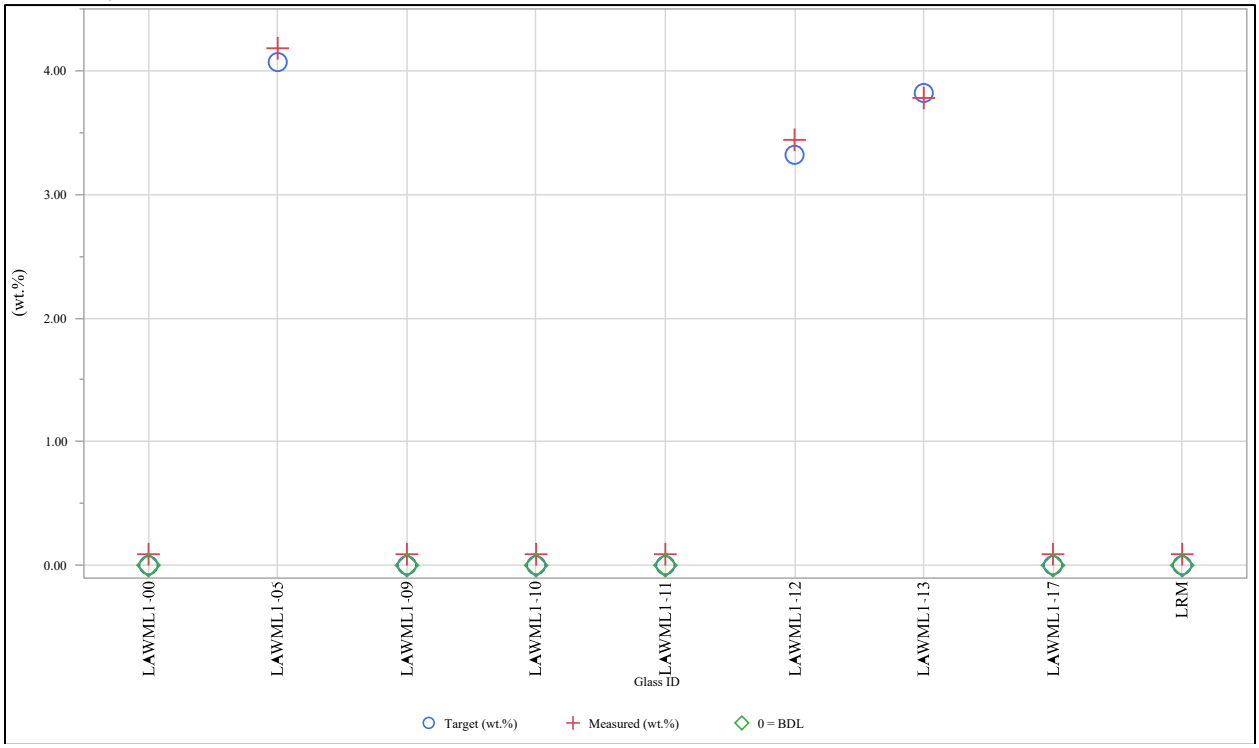
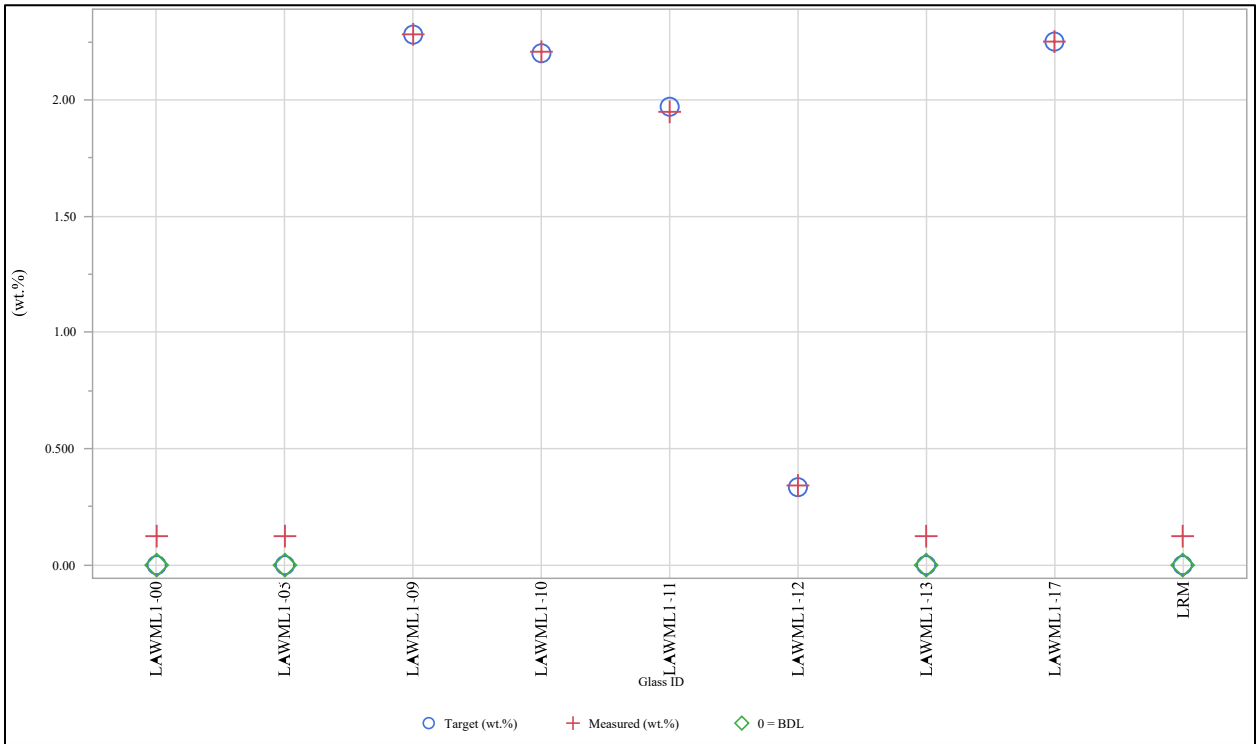


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=ZnO



Oxide=ZrO_2

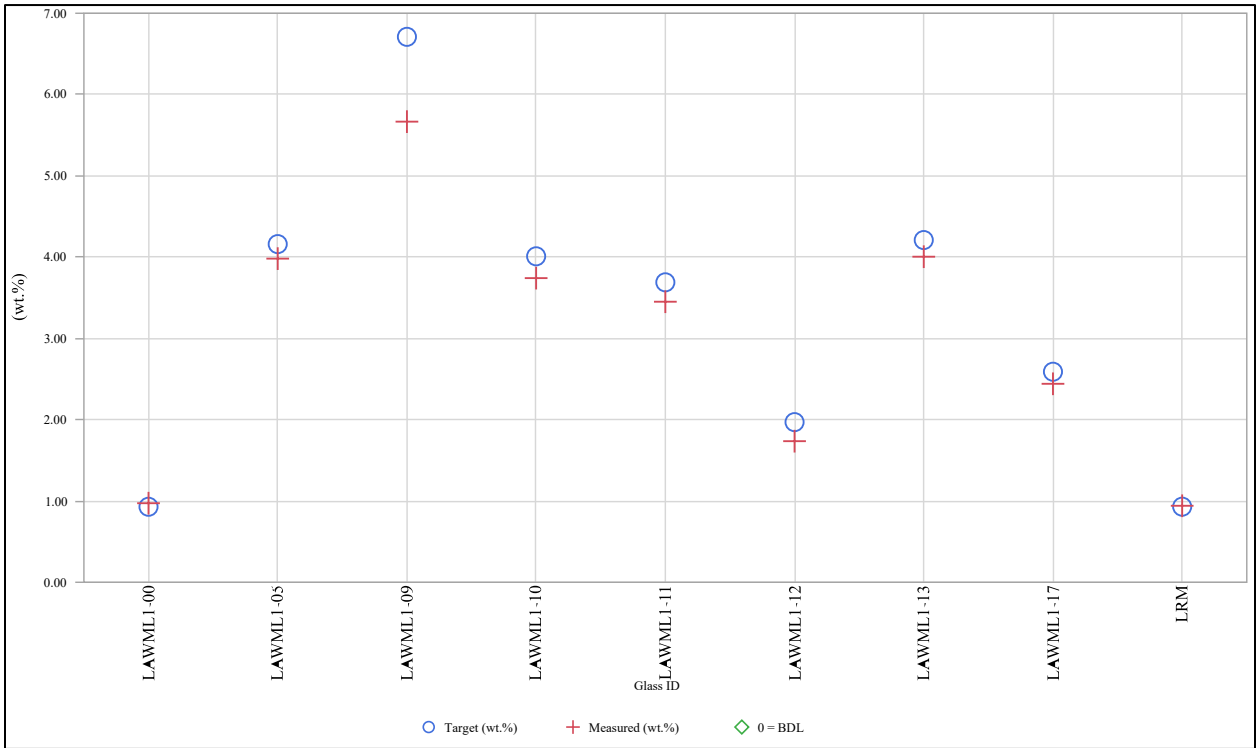
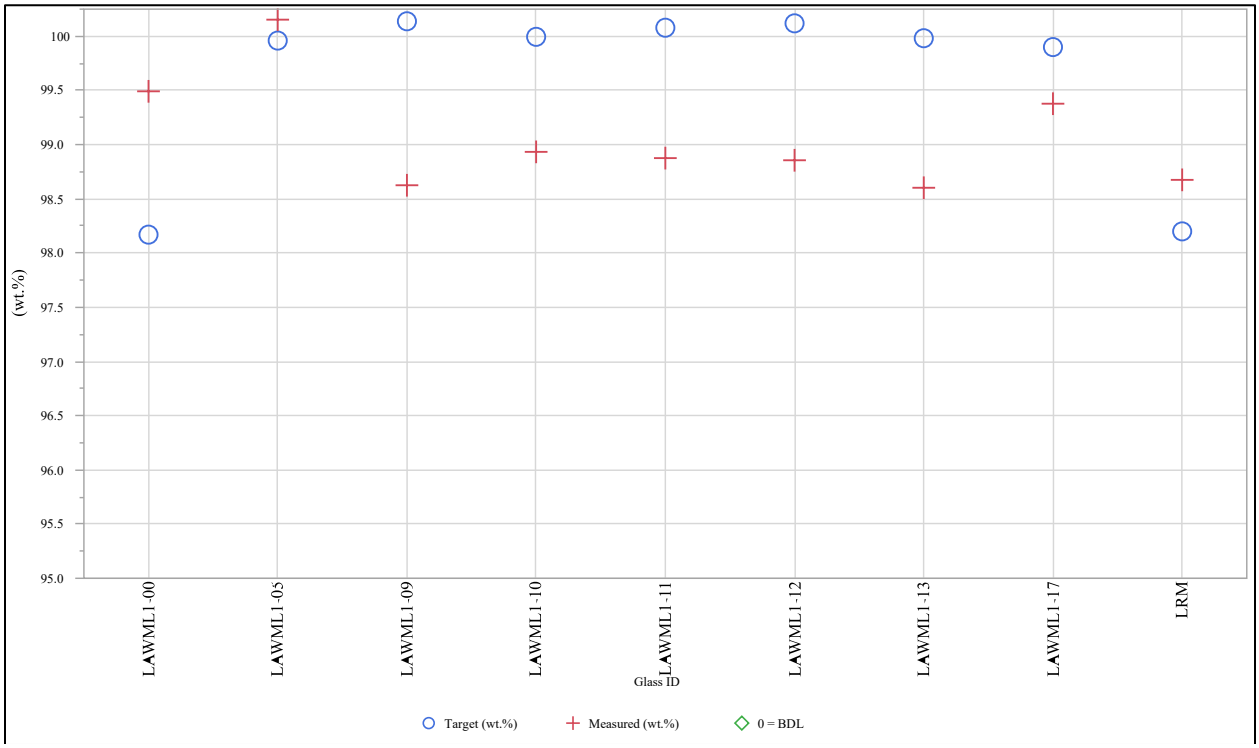


Exhibit A-3. Average Measured versus Target Concentrations by Glass ID by Oxide (continued)

Oxide=Sum of Oxides



Distribution:

Jake.Amoroso@srnl.doe.gov
CJ.Bannochie@srnl.doe.gov
Alex.Cozzi@srnl.doe.gov
Charles.Crawford@srnl.doe.gov
Elaine_N_Diaz@orp.doe.gov
William.C.Eaton@pnnl.gov
Vivianaluxa.Gervasio@pnnl.gov
Holly.Hall@srnl.doe.gov
Erich.Hansen@srnl.doe.gov
Connie.Herman@srnl.doe.gov
Anthony.Howe@srnl.doe.gov
Madison.Hsieh@srnl.doe.gov
Fabienne.Johnson@srnl.doe.gov
Albert_A_Kruger@orp.doe.gov
Christine.Langton@srnl.doe.gov
Brady.Lee@srnl.doe.gov
Xiaonan.Lu@pnnl.gov
Joseph.Manna@srnl.doe.gov
Daniel.McCabe@srnl.doe.gov
Gregg.Morgan@srnl.doe.gov
James.Neeway@pnnl.gov
Frank.Pennebaker@srnl.doe.gov
William.Ramsey@srnl.doe.gov
Whitney.Riley@srnl.doe.gov
Renee.Russell@pnnl.gov
Eric.Skidmore@srnl.doe.gov
Anna.Stanfield@srnl.doe.gov
Michael.Stone@srnl.doe.gov
John.Vienna@pnnl.gov
Boyd.Wiedenman@srnl.doe.gov
Richard.Wyrwas@srnl.doe.gov
Records Administration (EDWS)