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VSL-07S1220-1, Rev. 0, 7/25/07

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Office of River Protection

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Data Summary Report

Small Scale Melter Testing of HLW Algorithm Glasses: Matrix 1 Tests

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Data Summary Report

Small Scale Melter Testing of HLW Algorithm Glasses: Matrix 1 Tests

1.0 Introduction and Test Overview

Eight tests using different HLW feeds were conducted on the DM100-BL to determine the effect of variations in glass properties and feed composition on processing rates and melter conditions (off-gas characteristics, glass processing, foaming, cold cap, etc.) at constant bubbling rate. In over seven hundred hours of testing, the property extremes of glass viscosity, electrical conductivity, and $T_{1\%}$, as well as minimum and maximum concentrations of several major and minor glass components were evaluated using glass compositions that have been tested previously at the crucible scale. Other parameters evaluated with respect to glass processing properties were +/-15% batching errors in the addition of glass forming chemicals (GFCs) to the feed, and variation in the sources of boron and sodium used in the GFCs. Tests evaluating batching errors and GFC source employed variations on the HLW98-86 formulation (a glass composition formulated for HLW C-106/AY-102 waste and processed in several previous melter tests [1, 2]) in order to best isolate the effect of each test variable. These tests are outlined in a Test Plan [3] that was prepared in response to the Test Specification [4] for this work. The present report provides summary level data for all of the tests in the first test matrix (Matrix 1) in the Test Plan [3]. Summary results from the remaining tests, investigating minimum and maximum concentrations of major and minor glass components employing variations on the HLW98-86 formulation and glasses generated by the HLW glass formulation algorithm, will be reported separately after those tests are completed.

The test data summarized herein include glass production rates, the type and amount of feed used, a variety of measured melter parameters including temperatures and electrode power, feed sample analysis, measured glass properties, and gaseous emissions rates. More detailed information and analysis from the melter tests with complete emission chemistry, glass durability, and melter operating details will be provided in the final report.

A summary of the tests that were conducted is provided in Table 1. Each of the seven tests was of nominally one hundred hours in duration. Test B was conducted in two equal segments: the first with nominal additives, and the second with the replacement of borax with a mixture of boric acid and soda ash to determine the effect of alternative GFC sources on production rates and processing characteristics. Interestingly, sugar additions were required near mid points of Tests W and Z to reduce excessive foaming that severely limited feed processing rates. The sugar additions were very effective in recovering manageable processing conditions, albeit over the relatively short remainder of the test duration. Tests W and Z employed the highest melt viscosities but not by a particularly wide margin. Other tests, which did not exhibit such foaming issues, employed higher concentrations of manganese or iron or both. These results highlight the need for the development of protocols for the *a priori* determination of which HLW feeds will require sugar additions and the appropriate amounts of sugar to be added in order to control foaming (and maintain throughput) without over-reduction of the melt (which could lead to molten metal formation).

In total, over 8,800 kg of feed was processed to produce over 3200 kg of glass. Steady-state processing rates were achieved, and no secondary sulfate phases were observed during any of the tests. Analysis was performed on samples of the glass product taken throughout the tests to verify composition and properties. Sampling and analysis was also performed on melter exhaust to determine the effect of the feed and glass changes on melter emissions.

2.0 Operating Data

Production rates, run conditions, and the amount of feed used and glass poured for each of the seven tests are summarized in Table 1. Production rates are depicted over the course of each of the tests in Figures 1 – 7. The steady-state production rates ranged between 900 to 1600 $kg/m^2/day$ (with sugar additions to Tests W and Z) and bracketed the range of steady-state production rates (1100 to 1400 $kg/m^2/day$) measured on other WTP HLW waste streams processed on the DM100 under similar conditions [5-7]. Comparison of results from Tests W through Z shows that the melts with lower viscosity (and higher conductivity) processed faster. The less viscous and more conductive glasses generally have higher concentrations of alkali and lower concentrations of aluminum; however, the glass composition with the highest aluminum concentration, HLW-ALG-16, processed at a rate a third higher than the more viscous and less conductive formulations. Sugar additions during Tests W and Z allowed a near doubling of production rates from about 500 to 900 $kg/m^2/day$. The foaming during the first half of these tests was partially mitigated by the addition of 10 grams of sucrose per liter of feed. As noted above, the glass processing difficulties from the foaming occurred with the more viscous melts, presumably due to the inability of gas to readily escape from the melt. Foaming did not increase with glass manganese content and, in fact, the glass with the highest manganese concentration, HLW-ALG-17, processed at the highest rate of any the compositions tested, with no foaming problems. Tests processing the HLW98-86 formulation with fifteen percent GFC batching errors and with boric acid and soda ash replacing borax all resulted in steady-state production rates between 1000 and 1050 $kg/m^2/day$, indicating that these changes do not have a substantial effect on processing rates. These measured production rates are consistent with the rate of about 1150 $kg/m^2/day$ measured previously for this feed on the DM100 while bubbling at the higher rate of 17.2 lpm [8] as opposed to the 9 lpm used throughout the present tests. The decrease in production rate during Test B1 between 13 and 46 hours run time is attributable to a loose connection between the bubbler and air supply that was not apparent in the electronic readout. After the problem was identified and corrected, additional run time was added to the test in order to verify the steady-state rate of 1000 $kg/m^2/day$ that was obtained at the beginning of the test.

Melter operating conditions were held constant throughout the tests to facilitate comparison of results with previous tests [5-7]. Electronically recorded measured melter parameters are provided in Table 2. Measured test average glass temperatures in the bulk glass (5" and 10" from the bottom) were within 9°C of the target glass temperature of 1150°C during the tests. Glass temperatures at higher locations in the glass pool were lower than the target due to the intentional varying of the glass pool level at the beginning and end of each test as well as the expected temperature gradients near the cold cap. Plenum temperatures typically ranged from 350 to 500°C, indicating that the target of a complete cold cap was obtained throughout the tests. Higher plenum temperatures occurred during Test X at the highest production rate. Plenum temperatures monitored by the exposed thermocouple were about 25°C higher than the plenum temperature monitored in the thermowell due in part to shelves forming across the walls of the melter shielding the thermowell. The target bubbling rate of 9 lpm was maintained throughout the tests except during a portion of Test B1.

Differences in measured melter parameters between the tests were observed in electrode power and glass pool resistance in response to changes in the glass composition. Examples of these changes for select tests are shown in Figures 8 and 9. Test average glass resistance in Tests W and Z targeting high viscosity and low conductivity glasses were about 30 percent higher than in Tests X and Y targeting low viscosity and high conductivity glasses. The addition of sugar to the feed in Test W also resulted in a drop in glass resistance of about 30%, whereas the same sugar addition to the feed in Test Z appeared to have little effect on glass resistance. Power utilization was higher in Tests X and Y than other tests due to the higher production rates; power normalized to glass production rate shows the opposite trend.

3.0 Feed and Glass Analysis

Samples of melter feed and product glass were collected and analyzed throughout each test. Measured concentrations of glass from the end of each test and the respective melter feed are compared to the target compositions in Tables 3 – 9. The product glass compositions over the course of testing are illustrated in Figures 10.a – 13.b. Most of the oxides approximate their respective target values in the feed and glass samples; however, the magnitude and number of deviations was greater than observed in past studies with simulated HLW feeds prepared by the same vendor [9]. These deviations are currently being investigated with the vendor to determine the source of the deficiencies and surpluses. Surpluses of alumina at target concentrations less than 6 percent suggest a contamination.

The glass composition used in Tests W, X, Y, and Z are significantly different and therefore changes in oxide concentrations were observed throughout the tests, as shown in Figures 10.a, 11.a, 12.a and 13.a. Conversely, differences in glass compositions in Tests A, B, and C were not as large and correspondingly smaller changes in oxide concentrations were observed, as shown in Figures 10.b, 11.b, 12.b and 13.b. The most noticeable changes observed in Tests A, B and C was the expected increases of waste components such as iron and antimony.

Glasses from the end of feeding periods from Tests W, X, Y and Z were also analyzed for viscosity and conductivity to compare to target values obtained previously from the analysis of crucible glasses. Data displayed in Table 10 show that the measured glass properties from the discharged glasses approximate the target values for most of the properties. The viscosity was 10 poise above the target for Test X, due perhaps to the aluminum surplus and the lack of complete turnover due to the slow production rate. The test data from these four tests suggest the production rate would have been even lower in Test X at the target viscosity. The $T_{1\%}$ value for the final glass sample and other glasses from Test Z are currently being measured. Subsequent to Test Z, the melter was idled for about five weeks during which time several samples were taken from the melt pool to determine the extent of crystal formation and settling at the minimum idling temperatures. Analysis of crystal content for all these samples will be included in the final report.

The sugar additions to Tests W and Z resulted in somewhat different impacts on glass redox: divalent iron as a percent of total iron measured by Mossbauer spectroscopy in glass samples from Tests W and Z were 13.6 and 5.4 percent, respectively.

4.0 Emissions Monitored by FTIR

Average concentrations of select gaseous constituents measured by FTIR are given in Table 11. As expected, concentrations were low for most monitored species due to the low concentrations of nitrogen and organic compounds in the feed. Nitrogen oxide was the most abundant monitored nitrogen species emitted, as has been observed in previous melter tests [1, 2, 5-8, 10-13]. The concentrations of carbon dioxide and incomplete combustion byproducts, such as carbon monoxide and ammonia, predictably increased when sugar was added to the feed in Tests W and Z.

5.0 References

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Table 1. Summary of Results from HLW Algorithm DM100 Matrix 1 Tests.

		W	X	Y	Z
Test		High Viscosity	Low Viscosity Low Al_2O_3 Maximum NiO High MnO	High Conductivity Low Fe_2O_3	$T_{1\%}$ criterion (& Low Conductivity)
Target Test Condition		112 P @ 1150°C MnO = 5% SrO = 5%	19 P @ 1150°C Al_2O_3 = 1.93% NiO = 1.00% MnO = 6.91%	0.68 S/cm @ 1200°C Fe_2O_3 = 4.4 %	T1% = 963°C (0.23 S/cm @ 1150°C)
Time	Feed Start	3/5/07 8:00	3/12/07 8:00	3/19/07 8:00	3/26/07 13:05
Time	Feed End	3/9/07 17:30	3/16/07 5:50	3/23/07 13:00	3/30/07 20:30
Time	Interval	105.5 hr	93.8 hr	101.0 hr	103.4 hr
Water Feeding for Cold Cap		1.0 hr	1.0 hr	1.0 hr	1.4 hr
Slurry Feeding		104.5 hr	92.8 hr	100.0 hr	102.0 hr
Feeding Interruptions		275 min	152 min	34 min	237 min
Cold cap burn		0.9 hr	2.0 hr	0.8 hr	0.8 hr
Feed	Glass	HLW02-24	HLW-ALG-17	HLW-ALG-16	HLW02-46
Feed	Used	1218 kg	1400 kg	1444 kg	1070 kg
Feed	Sugar Added	10 g/L feed @ 56 hr run time	No	No	10 g/L feed @ 49 hr run time
Feed	Target Glass yield	0.35 kg/kg	0.42 kg/kg	0.378 kg/kg	0.381 kg/kg
Feed	Average Feed Rate	11.7 kg/hr	15.1 kg/hr	14.4 kg/hr	10.5 kg/hr
Glass Produced	Poured	356 kg	591 kg	576 kg	326 kg
Glass Produced	Average Rate$	757 kg/m^2/day	1415 kg/m^2/day	1280 kg/m^2/day	710 kg/m^2/day
Glass Produced	Average Rate*	907 kg/m^2/day	1409 kg/m^2/day	1213 kg/m^2/day	888 kg/m^2/day
Glass Produced	Steady State Rate*	900 kg/m^2/day#	1600 kg/m^2/day	1200 kg/m^2/day	900 kg/m^2/day#
Glass Produced	Average Power Use	4.5 kW hr/kg glass	3.5 kW hr/kg glass	4.1 kW hr/kg glass	4.5 kW hr/ kg glass

$ - Rates calculated from glass poured.
*- Rates calculated from feed data.
- Rate estimated from the portion of the test after sugar was added to the feed.
Note: Rates do not take into account the time for water feeding and cold cap burn-off.

Table 1. Summary of Results from HLW Algorithm DM100 Matrix 1 Tests (continued).

Test		A	B1	B2	C
		+ 15% GFCs	Baseline	Na_2CO_3+H_3BO_3 Additives	- 15% GFCs
Target Test Condition		+ 15% GFCs	-	Replace borax	- 15% GFCs
Time	Feed Start	5/14/07 12:00	5/21/07 12:35	5/23/07 23:55	6/18/07 8:43
Time	Feed End	5/18/07 16:45	5/23/07 23:30	5/26/07 1:55	6/22/07 13:45
Time	Interval	100.8 hr	58.9 hr	50.0 hr	101.0 hr
Water Feeding for Cold Cap		0.8 hr	0.9 hr	0 hr	1.0 hr
Slurry Feeding		100.0 hr	58.0 hr	50.0 hr	100.0 hr
Feeding Interruptions		31 min	11 min	15 min	50 min
Cold cap burn		0.6 hr	NA	1.5 hr	1.4 hr
Feed	Glass	HLW98-86	HLW98-86	HLW98-86	HLW98-86
Feed	Used	1159 kg	579 kg	606 kg	1336 kg
Feed	Sugar Added	None	None	None	None
Feed	Target Glass yield	0.396 kg/kg	0.372 kg/kg	0.378 kg/kg	0.354 kg/kg
Feed	Average Feed Rate	11.6 kg/hr	10.0 kg/hr	10.5 kg/hr	13.4 kg/hr
Glass Produced	Poured	444 kg	208 kg	223 kg	482 kg
Glass Produced	Average Rate$	987 kg/m^2/day	797 kg/m^2/day	991 kg/m^2/day	1071 kg/m^2/day
Glass Produced	Average Rate*	1021 kg/m^2/day	827 kg/m^2/day	882 kg/m^2/day	1050 kg/m^2/day
Glass Produced	Steady State Rate*	1000 kg/m^2/day	1000 kg/m^2/day	1050 kg/m^2/day	1050 kg/m^2/day
Glass Produced	Average Power Use	4.2 kW hr/kg glass	4.8 kW hr/kg glass	4.9 kW hr/kg glass	4.3 kW hr/ kg glass

$ - Rates calculated from glass poured.
*- Rates calculated from feed data.
Note: Rates do not take into account the time for water feeding and cold cap burn-off.

Table 2. Summary of Measured Parameters for HLW Algorithm DM100 Matrix 1 Tests.

Test			W			X			Y			Z		
			AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX
TEMPERATURE (C)	Electrode	East Upper	1034	697	1110	1057	682	1110	1078	732	1129	1027	654	1099
		West Upper	1021	769	1086	1047	679	1106	1071	741	1107	1033	681	1083
		West Lower	1076	1050	1120	1081	1055	1104	1089	1044	1103	1077	1063	1102
		Bottom	775	743	795	723	709	733	729	675	746	796	782	802
	Glass	27" from bottom	1077	263	1178	1110	475	1174	1109	632	1161	1115	557	1185
		16" from bottom	1120	601	1182	1133	847	1163	1128	683	1157	1132	1012	1176
		10" from bottom	1152	1099	1194	1153	1126	1179	1154	1102	1180	1157	1130	1186
		5" from bottom	1153	1090	1196	1148	1124	1171	1152	1088	1177	1149	1122	1176
	Plenum	Exposed	458	142	710	518	222	758	470	329	641	453	104	645
		Thermowell	422	206	692	471	255	722	437	257	630	425	202	631
	Discharge	Chamber	1006	557	1067	1041	967	1071	1035	980	1064	1058	1035	1083
		Air Lift	991	793	1079	1013	906	1090	1017	926	1125	1027	994	1111
	Film Cooler Outlet		268	247	309	283	46	309	288	251	306	276	259	296
	Transition Line Outlet		259	205	307	271	60	299	280	240	315	264	211	284
Lance Bubbling (lpm)			8.9	1.4	9.2	9.0	8.8	9.1	8.9	1.3	9.1	8.9	8.8	9.0
Melter Pressure (inches water)			-1.06	-3.03	1.75	-0.98	-3.62	0.81	-0.92	-2.69	0.38	-0.97	-2.57	1.84
Total Electrode Voltage (V)			44.8	2.3	53.0	40.7	1.9	52.4	38.0	2.1	45.1	40.2	2.2	44.2
Total Power (kW)			18.4	0.3	24.1	22.2	0.3	25.6	22.7	0.3	26.2	17.9	0.3	21.1
Glass Resistance (ohms)			0.110	0.019	0.155	0.076	0.012	0.145	0.064	0.016	0.097	0.090	0.017	0.101

Table 2. Summary of Measured Parameters for HLW Algorithm DM100 Matrix 1 Tests (continued).

Test			A			B1			B2			C		
			AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX
TEMPERATURE (C)	Electrode	East Upper	1031	661	1120	1018	679	1121	1102	1056	1125	1052	723	1115
		West Upper	1062	692	1099	1008	686	1086	1064	1037	1084	1033	725	1079
		West Lower	1091	1068	1112	1071	1047	1089	1077	1066	1086	1075	1060	1094
		Bottom	788	781	810	755	721	766	769	762	774	801	786	845
	Glass	27" from bottom	1106	340	1179	1059	605	1178	1147	1093	1172	1101	632	1174
		16" from bottom	1118	246	1163	1129	613	1194	1151	1122	1175	1138	764	1176
		10" from bottom	1153	1133	1179	1156	1087	1189	1154	1133	1175	1156	1126	1175
		5" from bottom	1152	1127	1176	1144	1091	1170	1145	1126	1163	1141	1117	1169
	Plenum	Exposed	461	259	622	450	137	679	461	393	497	500	337	691
		Thermowell	434	337	608	420	289	651	417	353	455	445	382	655
	Discharge	Chamber	1046	1019	1068	956	583	1039	1044	1005	1061	1045	999	1088
		Air Lift	1021	962	1068	958	791	1046	1040	989	1102	1040	985	1092
	Film Cooler Outlet		281	209	305	275	256	306	276	267	291	274	267	308
	Transition Line Outlet		271	229	297	269	214	315	269	220	281	267	215	299
Lance Bubbling (lpm)			8.8	1.4	9.3	8.9#	1.9	10.3	9.0*	1.9	10.8	9.0	1.5	10.0
Melter Pressure (inches water)			-0.99	-3.58	1.02	-1.00	-2.28	6.66	-1.20	-1.95	0.92	-1.16	-3.88	1.08
Total Electrode Voltage (V)			41.8	2.1	53.4	40.8	1.5	51.0	41.3	39.3	42.9	45.1	1.5	53.0
Total Power (kW)			19.2	0.3	22.1	17.8	0.3	22.5	19.6	18.9	20.6	20.6	0.3	23.5
Glass Resistance (ohms)			0.091	0.016	0.130	0.094	0.008	0.145	0.087	0.078	0.092	0.099	0.008	0.127

- Value not representative of entire test
* - Electronic data collected for first 40 hours of test

Table 3. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test W (wt%).

Sample Type		Melter Feed		Glass Discharged After 356 kg Production	
Sample Name		BLP-F-125B		BLQ-G-23A	
Constituent	Target	XRF	%Dev.	XRF	%Dev.
Al_2O_3	8.54	9.09	6.49	8.73	2.20
As_2O_5	0.18	0.10	NC	0.08	NC
B_2O_3	5.02	5.02*	NC	9.04**	NC
BaO	0.23	<0.01	NC	0.26	NC
CaO	0.50	0.57	NC	0.50	NC
CdO	0.05	0.05	NC	<0.01	NC
Ce_2O_3	0.05	0.05	NC	0.02	NC
Cl	0.20	0.10	NC	0.09	NC
Cr_2O_3	0.15	0.17	NC	0.19	NC
Cs_2O	§	<0.01	NC	0.01	NC
CuO	0.08	0.09	NC	0.09	NC
F	0.05	NA	NC	NA	NC
Fe_2O_3	8.04	8.02	-0.22	7.18	-10.59
I	§	<0.01	NC	<0.01	NC
K_2O	0.06	0.11	NC	0.12	NC
La_2O_3	0.30	0.27	NC	0.23	NC
Li_2O	2.01	2.01*	NC	2.58**	NC
MgO	0.12	0.14	NC	0.20	NC
MnO	5.02	4.80	-4.49	4.18	-16.82
Na_2O	12.25	10.50	-14.33	12.39	1.12
Nd_2O_3	§	<0.01	NC	<0.01	NC
NiO	0.10	0.10	NC	0.17	NC
P_2O_5	0.50	0.51	NC	0.44	NC
PbO	0.31	0.28	NC	0.24	NC
Sb_2O_3	0.02	0.03	NC	0.02	NC
SeO_2	0.20	0.05	NC	0.06	NC
SiO_2	47.27	48.81	3.26	45.53	-3.68
SO_3	0.10	0.15	NC	0.11	NC
SrO	5.02	4.84	-3.69	4.00	-20.42
TiO_2	0.08	0.14	NC	0.18	NC
Tl_2O	§	<0.01	NC	<0.01	NC
V_2O_5	0.08	0.08	NC	0.06	NC
ZnO	2.01	2.02	0.40	1.67	-16.63
ZrO_2	1.51	1.89	25.21	1.64	8.63
Sum	100.00	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 4. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test X (wt%).

Sample Type		Melter Feed		Glass Discharged After 591 kg Production	
Sample Name		BLQ-F-68A		BLQ-G-82C	
Constituent	Target	XRF	%Dev.	XRF	%Dev.
Al_2O_3	1.93	3.92	103.54	3.61	87.05
As_2O_5	§	<0.01	NC	0.01	NC
B_2O_3	10.35	10.35*	NC	10.30**	NC
BaO	0.04	0.07	NC	0.08	NC
CaO	0.33	0.41	NC	0.42	NC
CdO	§	<0.01	NC	<0.01	NC
Ce_2O_3	0.05	0.04	NC	0.04	NC
Cl	§	0.01	NC	0.01	NC
Cr_2O_3	0.50	0.56	NC	0.62	NC
Cs_2O	§	<0.01	NC	0.01	NC
CuO	§	<0.01	NC	0.01	NC
F	0.03	NA	NC	NA	NC
Fe_2O_3	12.52	12.08	-3.53	12.55	0.23
I	§	<0.01	NC	<0.01	NC
K_2O	0.12	0.18	NC	0.16	NC
La_2O_3	0.10	0.09	NC	0.10	NC
Li_2O	2.02	2.02*	NC	2.04**	NC
MgO	0.10	0.23	NC	0.19	NC
MnO	6.92	6.39	-7.69	6.71	-2.98
Na_2O	17.43	16.00	-8.21	15.51	-11.01
Nd_2O_3	0.08	0.09	NC	0.09	NC
NiO	1.00	0.95	-4.54	1.05	NC
P_2O_5	0.10	0.12	NC	0.13	NC
PbO	0.20	0.16	NC	0.18	NC
Sb_2O_3	§	<0.01	NC	<0.01	NC
SeO_2	§	<0.01	NC	<0.01	NC
SiO_2	45.90	45.78	-0.27	45.31	-1.30
SO_3	0.05	0.12	NC	0.14	NC
SrO	§	0.01	NC	0.17	NC
TiO_2	0.04	0.17	NC	0.16	NC
Tl_2O	§	<0.01	NC	<0.01	NC
V_2O_5	§	<0.01	NC	<0.01	NC
ZnO	0.03	0.05	NC	0.13	NC
ZrO_2	0.16	0.20	NC	0.27	NC
Sum	100.00	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 5. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test Y (wt%).

Sample Type		Melter Feed		Glass Discharge After 576 kg Production	
Sample Name		BLQ-F-100A		BLQ-G-155C	
Constituent	Target	XRF	%Dev.	XRF	%Dev.
Al_2O_3	10.34	10.74	3.87	10.22	-1.11
As_2O_5	§	<0.01	NC	<0.01	NC
B_2O_3	13.86	13.86*	NC	13.71**	NC
BaO	0.04	0.06	NC	0.06	NC
CaO	0.36	0.43	NC	0.45	NC
CdO	0.03	<0.01	NC	<0.01	NC
Ce_2O_3	0.06	0.06	NC	0.06	NC
Cl	§	<0.01	NC	0.01	NC
Cr_2O_3	0.50	0.60	NC	0.61	NC
Cs_2O	§	<0.01	NC	<0.01	NC
CuO	§	<0.01	NC	<0.01	NC
F	0.03	NA	NC	NA	NC
Fe_2O_3	4.40	4.88	10.92	5.61	27.41
I	§	<0.01	NC	<0.01	NC
K_2O	0.14	0.20	NC	0.20	NC
La_2O_3	0.11	0.06	NC	0.06	NC
Li_2O	2.02	2.02*	NC	2.02**	NC
MgO	0.10	0.13	NC	0.14	NC
MnO	§	0.09	NC	0.61	NC
Na_2O	17.42	16.12	-7.44	15.60	-10.45
Nd_2O_3	0.09	0.12	NC	0.13	NC
NiO	0.75	0.79	5.47	0.83	NC
P_2O_5	0.11	0.13	NC	0.14	NC
PbO	0.22	0.21	NC	0.22	NC
Sb_2O_3	§	<0.01	NC	<0.01	NC
SeO_2	§	0.01	NC	<0.01	NC
SiO_2	43.81	45.12	2.99	43.96	0.35
SO_3	0.06	0.07	NC	0.13	NC
SrO	§	0.01	NC	0.09	NC
TiO_2	§	0.04	NC	0.06	NC
Tl_2O	§	<0.01	NC	<0.01	NC
V_2O_5	§	<0.01	NC	<0.01	NC
ZnO	1.79	1.83	2.30	1.70	-5.11
ZrO_2	3.76	2.43	-35.47	3.36	-10.74
Sum	100.00	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 6. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test Z (wt%).

Sample Type		Melter Feed		Glass Discharge After 326 kg Production	
Sample Name		BLR-F-17A		BLR-G-68A	
Constituent	Target	XRF	%Dev.	XRF	%Dev.
Al_2O_3	5.52	6.26	13.46	6.78	22.91
As_2O_5	0.05	0.02	NC	0.02	NC
B_2O_3	9.18	9.18*	NC	9.65**	NC
BaO	0.06	<0.01	NC	0.08	NC
CaO	0.50	0.53	NC	0.52	NC
CdO	0.50	0.40	NC	0.39	NC
Ce_2O_3	0.05	0.04	NC	0.01	NC
Cl	0.20	0.04	NC	0.09	NC
Cr_2O_3	0.04	0.04	NC	0.12	NC
Cs_2O	§	<0.01	NC	<0.01	NC
CuO	0.02	0.02	NC	0.02	NC
F	0.05	NA	NC	NA	NC
Fe_2O_3	10.03	9.15	-8.84	8.96	-10.73
I	§	<0.01	NC	<0.01	NC
K_2O	0.06	0.11	NC	0.13	NC
La_2O_3	0.30	0.26	NC	0.24	NC
Li_2O	3.71	3.71*	NC	3.54**	NC
MgO	0.12	0.22	NC	0.22	NC
MnO	3.51	3.04	-13.56	2.94	-16.21
Na_2O	9.03	9.04	0.07	9.21	1.95
Nd_2O_3	§	<0.01	NC	<0.01	NC
NiO	0.80	0.74	-7.65	0.73	-8.55
P_2O_5	0.50	0.51	NC	0.49	NC
PbO	0.08	0.04	NC	0.06	NC
Sb_2O_3	0.05	0.06	NC	0.06	NC
SeO_2	0.15	0.03	NC	0.03	NC
SiO_2	49.17	50.28	2.27	49.49	0.67
SO_3	0.10	0.09	NC	0.09	NC
SrO	1.51	1.33	-11.47	1.22	-19.15
TiO_2	0.03	0.09	NC	0.09	NC
Tl_2O	0.14	<0.01	NC	0.02	NC
V_2O_5	0.02	0.02	NC	<0.01	NC
ZnO	2.01	1.91	-4.65	1.87	-7.05
ZrO_2	2.51	2.84	13.03	2.91	16.11
Sum	100.00	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 7. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test A (wt%).

Sample Type		Melter Feed		Glass Discharged After 444 kg Production	
Sample Name		BLR-F-90A		BLR-G-137A	
Constituent	Target	XRF	%Dev.	XRF	%Dev.
Al_2O_3	5.01	5.80	15.69	6.39	27.43
As_2O_5	0.17	0.12	NC	0.11	NC
B_2O_3	9.72	9.72*	NC	9.71**	NC
BaO	§	<0.01	NC	<0.01	NC
CaO	0.27	0.41	NC	0.44	NC
CdO	§	<0.01	NC	0.06	NC
Ce_2O_3	§	<0.01	NC	<0.01	NC
Cl	0.10	0.05	NC	0.07	NC
Cr_2O_3	0.07	0.09	NC	0.11	NC
Cs_2O	0.05	0.05	NC	0.06	NC
CuO	0.04	0.06	NC	0.05	NC
F	§	NA	NC	NA	NC
Fe_2O_3	11.35	12.35	8.77	11.93	5.03
I	0.09	<0.01	NC	<0.01	NC
K_2O	§	0.18	NC	0.17	NC
La_2O_3	0.22	0.19	NC	0.19	NC
Li_2O	3.12	3.12*	NC	3.15**	NC
MgO	1.05	1.01	-3.98	0.93	-11.33
MnO	3.61	3.08	-14.74	3.05	-15.32
Na_2O	12.20	11.28	-7.55	10.78	-11.61
Nd_2O_3	0.14	0.16	NC	0.14	NC
NiO	0.16	0.15	NC	0.24	NC
P_2O_5	0.09	0.10	NC	0.16	NC
PbO	0.13	0.10	NC	0.11	NC
Sb_2O_3	0.23	0.25	NC	0.26	NC
SeO_2	0.33	0.11	NC	0.10	NC
SiO_2	48.53	48.33	-0.41	48.17	-0.74
SO_3	§	0.10	NC	0.11	NC
SrO	0.83	0.75	NC	0.80	NC
TiO_2	0.13	0.14	NC	0.14	NC
Tl_2O	§	<0.01	NC	<0.01	NC
V_2O_5	§	<0.01	NC	<0.01	NC
ZnO	2.14	2.03	-4.92	1.94	-9.16
ZrO_2	0.23	0.27	NC	0.61	NC
Sum	100.00	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 8. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test B (wt%).

Sample Type		Melter Feed				Glass Discharged After 431 kg Production	
Sample Name		BLR-F-149A		BLS-F-26A		BLS-G-48C	
Constituent	Target	XRF	%Dev.	XRF	%Dev.	%Dev.	%Dev.
Al_2O_3	5.29	6.20	17.15	6.22	17.52	6.12	15.61
As_2O_5	0.19	0.13	NC	0.11	NC	0.13	NC
B_2O_3	9.39	9.39*	NC	9.39*	NC	9.40**	NC
BaO	§	<0.01	NC	<0.01	NC	<0.01	NC
CaO	0.30	0.45	NC	0.45	NC	0.45	NC
CdO	§	<0.01	NC	<0.01	NC	<0.01	NC
Ce_2O_3	§	<0.01	NC	<0.01	NC	<0.01	NC
Cl	0.11	0.06	NC	0.04	NC	0.08	NC
Cr_2O_3	0.08	0.09	NC	0.08	NC	0.11	NC
Cs_2O	0.05	0.06	NC	0.06	NC	0.05	NC
CuO	0.04	0.06	NC	0.05	NC	0.05	NC
F	§	NA	NC	NA	NC	NA	NC
Fe_2O_3	12.59	11.96	-4.98	12.38	-1.63	12.53	-0.44
I	0.10	<0.01	NC	<0.01	NC	<0.01	NC
K_2O	§	<0.01	NC	0.05	NC	0.06	NC
La_2O_3	0.24	0.23	NC	0.20	NC	0.21	NC
Li_2O	3.01	3.01*	NC	3.01*	NC	3.01**	NC
MgO	1.17	1.24	5.99	1.20	2.54	1.19	1.67
MnO	4.00	3.67	-8.11	3.44	-13.90	3.52	-11.90
Na_2O	11.84	11.10	-6.18	10.97	-7.29	11.38	-3.81
Nd_2O_3	0.15	0.15	NC	0.16	NC	0.17	NC
NiO	0.17	0.16	NC	0.16	NC	0.20	NC
P_2O_5	0.09	0.11	NC	0.12	NC	0.12	NC
PbO	0.14	0.13	NC	0.08	NC	0.10	NC
Sb_2O_3	0.26	0.29	NC	0.27	NC	0.27	NC
SeO_2	0.37	0.10	NC	0.08	NC	0.11	NC
SiO_2	47.04	48.17	2.41	48.45	3.00	47.49	0.96
SO_3	§	0.06	NC	0.06	NC	0.07	NC
SrO	0.92	0.80	NC	0.70	NC	0.76	NC
TiO_2	0.14	0.22	NC	0.15	NC	0.17	NC
Tl_2O	§	<0.01	NC	<0.01	NC	<0.01	NC
V_2O_5	§	<0.01	NC	<0.01	NC	<0.01	NC
ZnO	2.07	1.88	-9.02	1.79	-13.41	1.87	-9.53
ZrO_2	0.26	0.28	NC	0.31	NC	0.37	NC
Sum	100.00	100.00	NC	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 9. XRF Analyzed Compositions of Vitrified Melter Feed and Glass Discharged at the End of HLW Algorithm DM100 Matrix 1 Test C (wt%).

Sample Type		Melter Feed		Glass Discharge After 482 kg Production	
Sample Name		BLS-F-65A		BLS-G-109C	
Constituent	Target	XRF	%Dev.	XRF	%Dev.
Al_2O_3	5.64	6.54	15.95	6.63	17.54
As_2O_5	0.21	0.16	NC	0.15	NC
B_2O_3	8.97	8.97*	NC	8.99**	NC
BaO	§	<0.01	NC	<0.01	NC
CaO	0.34	0.51	NC	0.50	NC
CdO	§	<0.01	NC	<0.01	NC
Ce_2O_3	§	<0.01	NC	<0.01	NC
Cl	0.12	0.11	NC	0.07	NC
Cr_2O_3	0.09	0.10	NC	0.11	NC
Cs_2O	0.06	0.06	NC	0.07	NC
CuO	0.05	0.06	NC	0.06	NC
F	§	NA	NC	NA	NC
Fe_2O_3	14.11	14.30	1.32	14.29	1.23
I	0.11	<0.01	NC	<0.01	NC
K_2O	§	0.21	NC	0.21	NC
La_2O_3	0.27	0.23	NC	0.22	NC
Li_2O	2.87	2.87*	NC	2.88**	NC
MgO	1.31	1.39	6.31	1.39	5.92
MnO	4.48	3.78	-15.70	3.65	-18.69
Na_2O	11.38	10.96	-3.69	10.74	-5.60
Nd_2O_3	0.17	0.19	NC	0.19	NC
NiO	0.19	0.18	NC	0.20	NC
P_2O_5	0.11	0.13	NC	0.13	NC
PbO	0.16	0.15	NC	0.13	NC
Sb_2O_3	0.29	0.33	NC	0.35	NC
SeO_2	0.42	0.12	NC	0.08	NC
SiO_2	45.19	45.15	-0.08	45.43	0.53
SO_3	§	0.18	NC	0.14	NC
SrO	1.03	0.96	-6.91	0.97	-6.12
TiO_2	0.16	0.17	NC	0.18	NC
Tl_2O	§	<0.01	NC	<0.01	NC
V_2O_5	§	<0.01	NC	<0.01	NC
ZnO	1.99	1.83	-7.72	1.85	-6.66
ZrO_2	0.29	0.35	NC	0.38	NC
Sum	100.00	100.00	NC	100.00	NC

* - Target values for melter feed sample
** - Target values calculated based on simple well-stirred tank model (discharged glass)
§ - Not a target constituent
NA – Not analyzed
NC – Not calculated

Table 10. Comparison of Target and Measured Test Conditions for HLW Algorithm DM100 Matrix 1 Tests W, X, Y, and Z.

	W	X	Y	Z
Test	High Viscosity	Low Viscosity Low Al_2O_3 Maximum NiO High MnO	High Conductivity Low Fe_2O_3	$T_{1\%}$ criterion (& Low Conductivity)
Glass	HLW02-24	HLW-ALG-17	HLW-ALG-16	HLW02-46
Target Test Condition	112 P @ 1150°C MnO = 5% SrO = 5%	19 P @ 1150°C Al_2O_3 = 1.93% NiO = 1.00% MnO = 6.91%	0.68 S/cm @ 1200°C Fe_2O_3 = 4.4 %	$T_{1\%}$ = 963°C (0.23 S/cm @ 1150°C)
Parameters Measured on Glass from End of Test	108.3 P @ 1150°C MnO = 4.18% SrO = 4.00%	29.2 P @ 1150°C Al_2O_3 = 3.61% NiO = 1.05% MnO = 6.71%	0.628 S/cm @ 1200°C Fe_2O_3 = 5.61 %	(0.226 S/cm @ 1150°C)
Other Parameters Measured on Glass from End of Test	0.252 S/cm @ 1150°C	0.415 S/cm @ 1150°C	65.1 P @ 1150°C	85.1 P @ 1150°C

Table 11. Average Concentrations [ppmv] of Selected Species in Off-Gas Measured by FTIR Spectroscopy during Algorithm DM100 Matrix 1 Tests.

Test	W		X	Y	Z		A	B		C
	No Sugar	Sugar			No Sugar	Sugar		B1	B2	
N_2O	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NO	11.3	1.2	12.5	12.3	9.0	<1.0	20.0	7.9	13.8	20.1
NO_2	<1.0	<1.0	9.1	<1.0	<1.0	<1.0	<1.0	<1.0	3.8	<1.0
NH_3	<1.0	6.5	<1.0	<1.0	<1.0	5.4	<1.0	<1.0	<1.0	<1.0
H_2O [%]	4.4	4.7	5.8	5.4	4.8	4.7	5.3	4.7	6.0	6.4
CO_2	1607	2267	2680	1891	1481	1945	1500	1343	1985	1867
Nitrous Acid	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Nitric Acid	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
HCN	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
SO_2	<1.0	<1.0	<1.0	<1.0	1.2	4.7	<1.0	<1.0	<1.0	1.1
CO	<1.0	15.8	1.1	<1.0	<1.0	14.3	<1.0	<1.0	<1.0	<1.0
HCl	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1.0
HF	1.1	<1.0	<1.0	<1.0	<1.0	<1.0	1.5	1.2	1.4	2.6

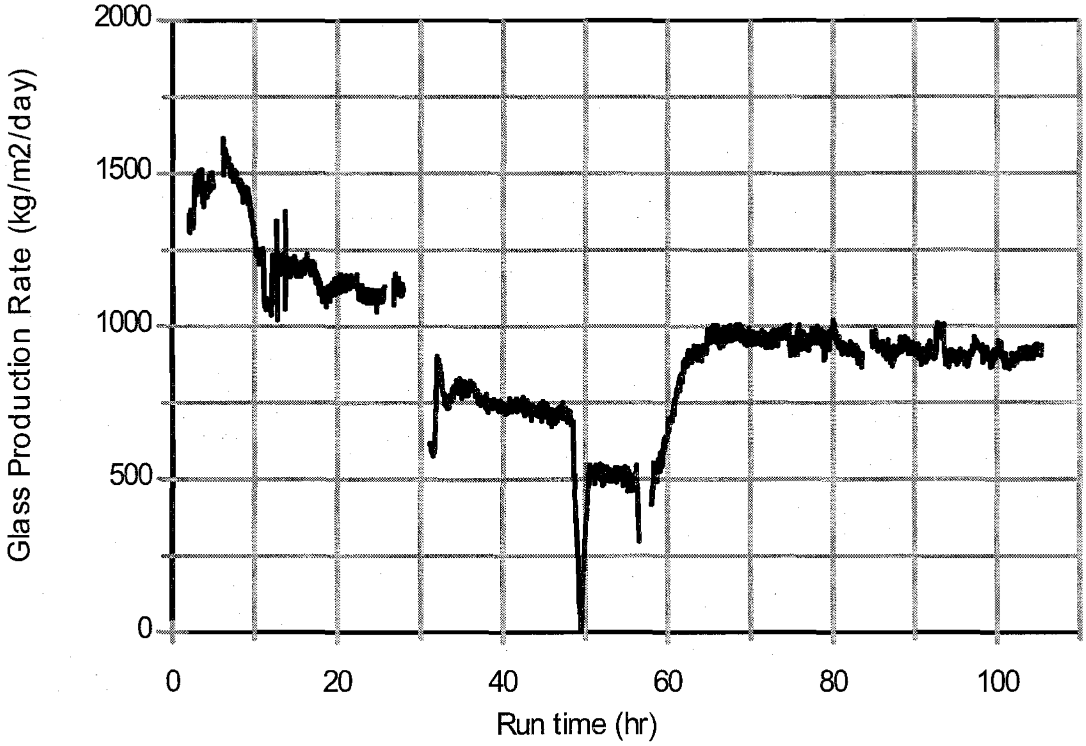

Figure 1. Glass production rate (hourly averaged) during DM100 Test W.

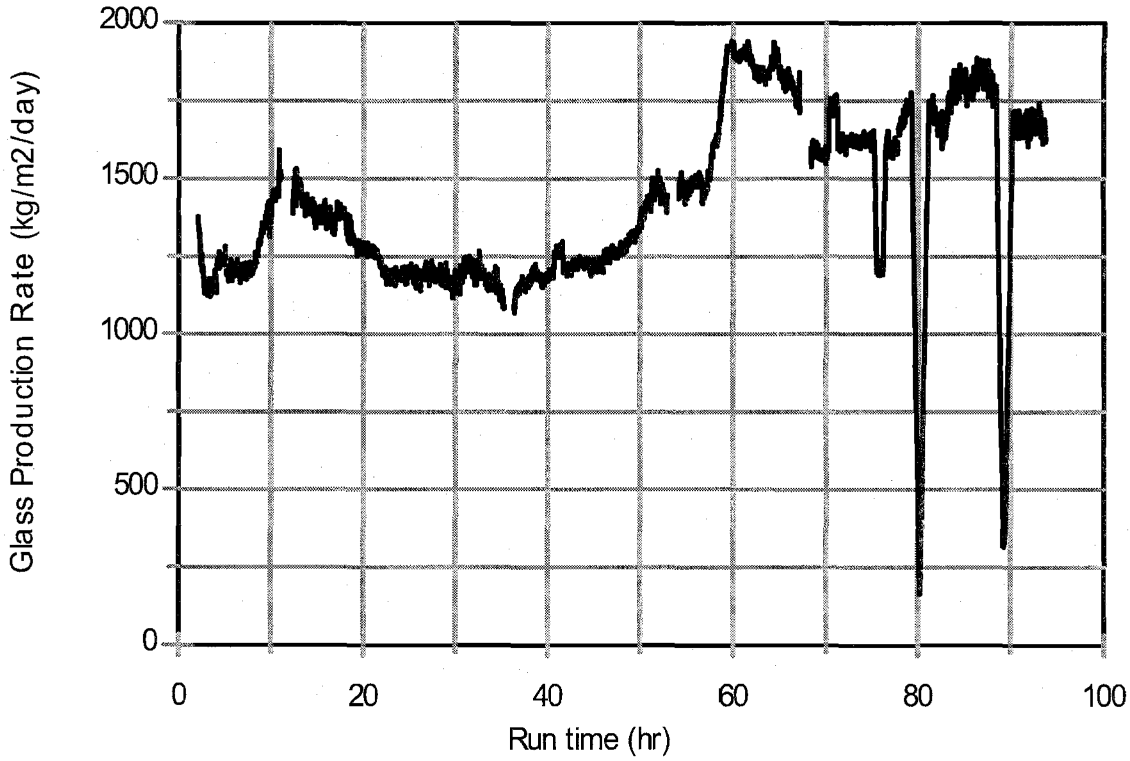

Figure 2. Glass production rate (hourly averaged) during DM100 Test X.

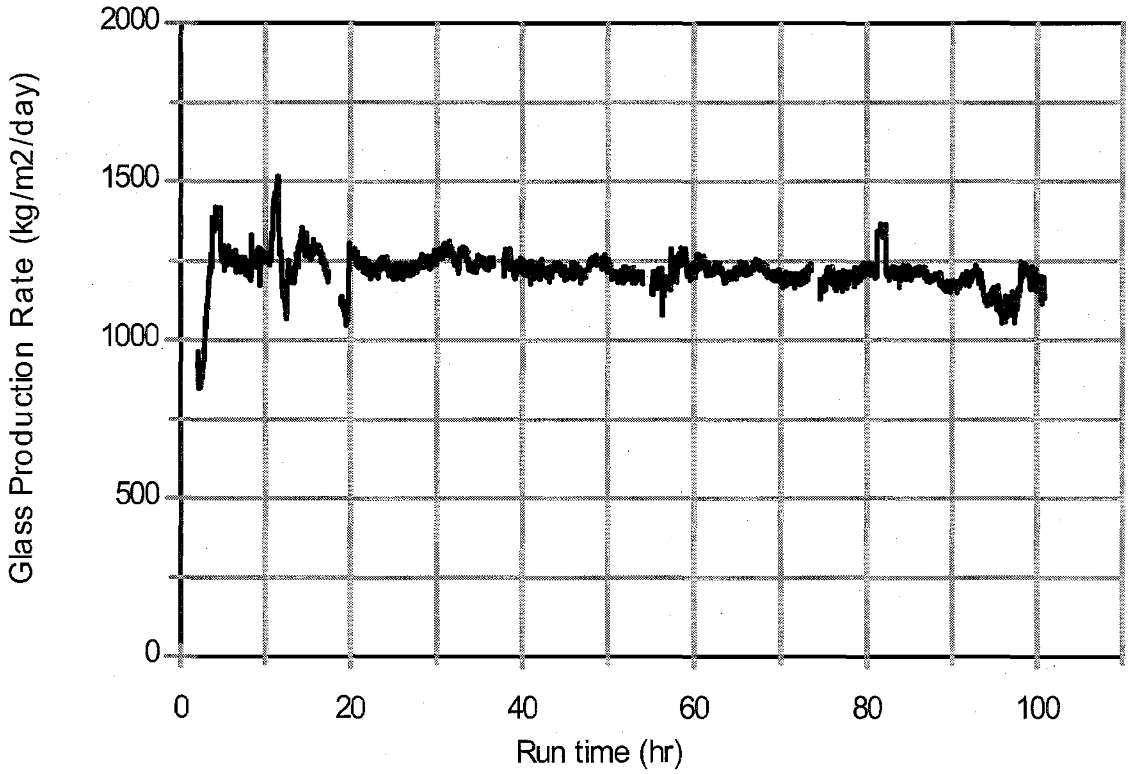

Figure 3. Glass production rate (hourly averaged) during DM100 Test Y.

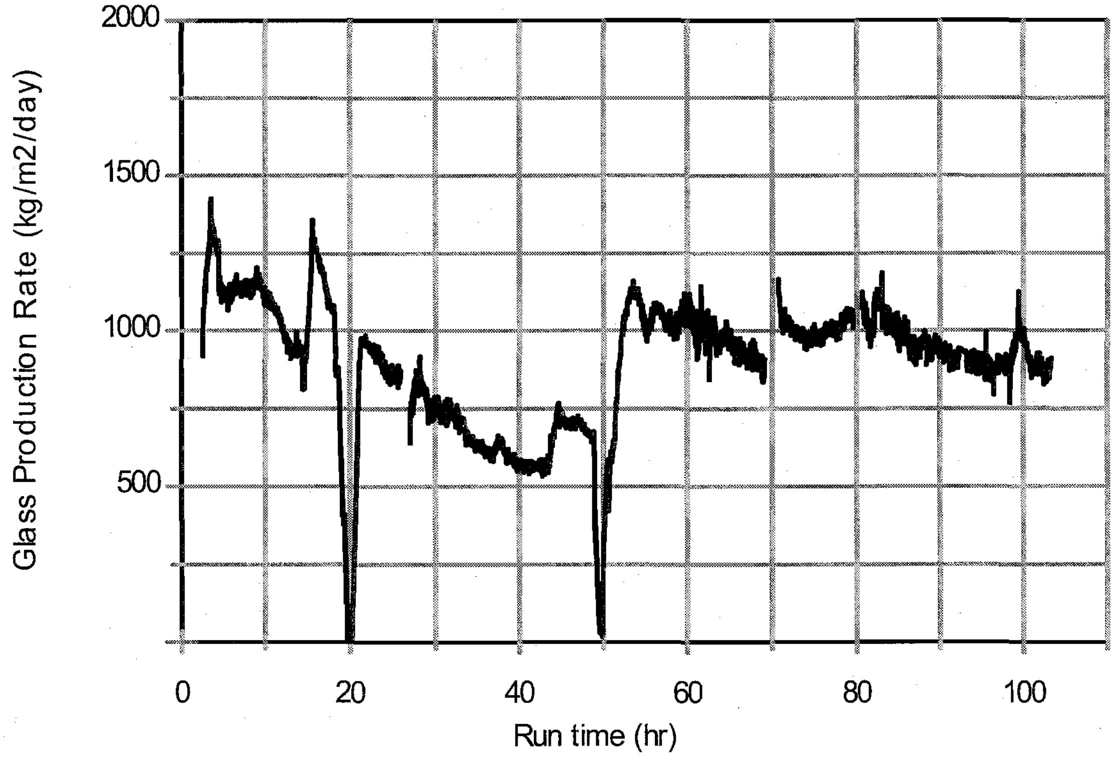

Figure 4. Glass production rate (hourly averaged) during DM100 Test Z.

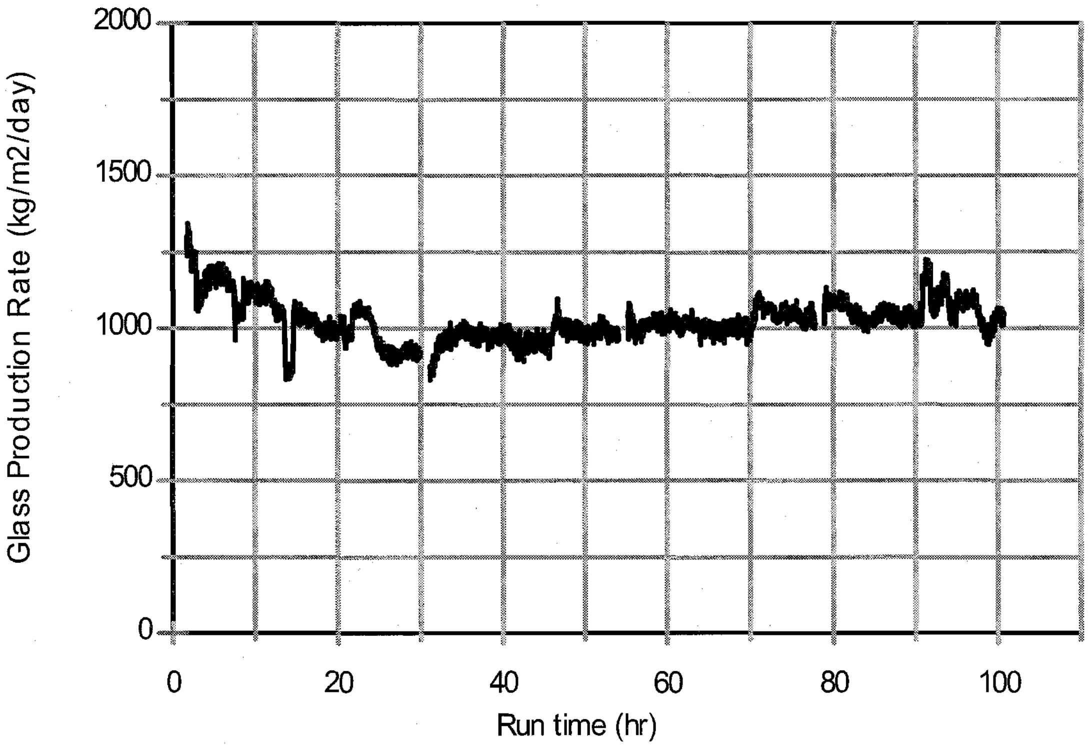

Figure 5. Glass production rate (hourly averaged) during DM100 Test A.

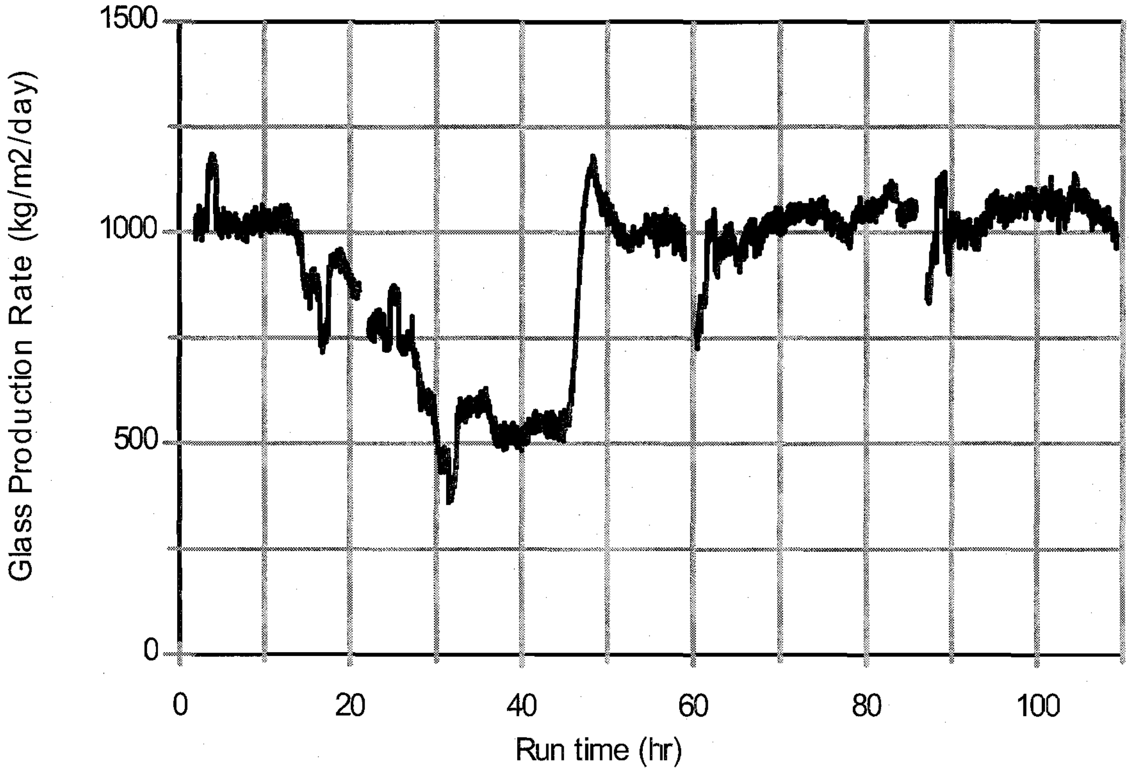

Figure 6. Glass production rate (hourly averaged) during DM100 Test B.

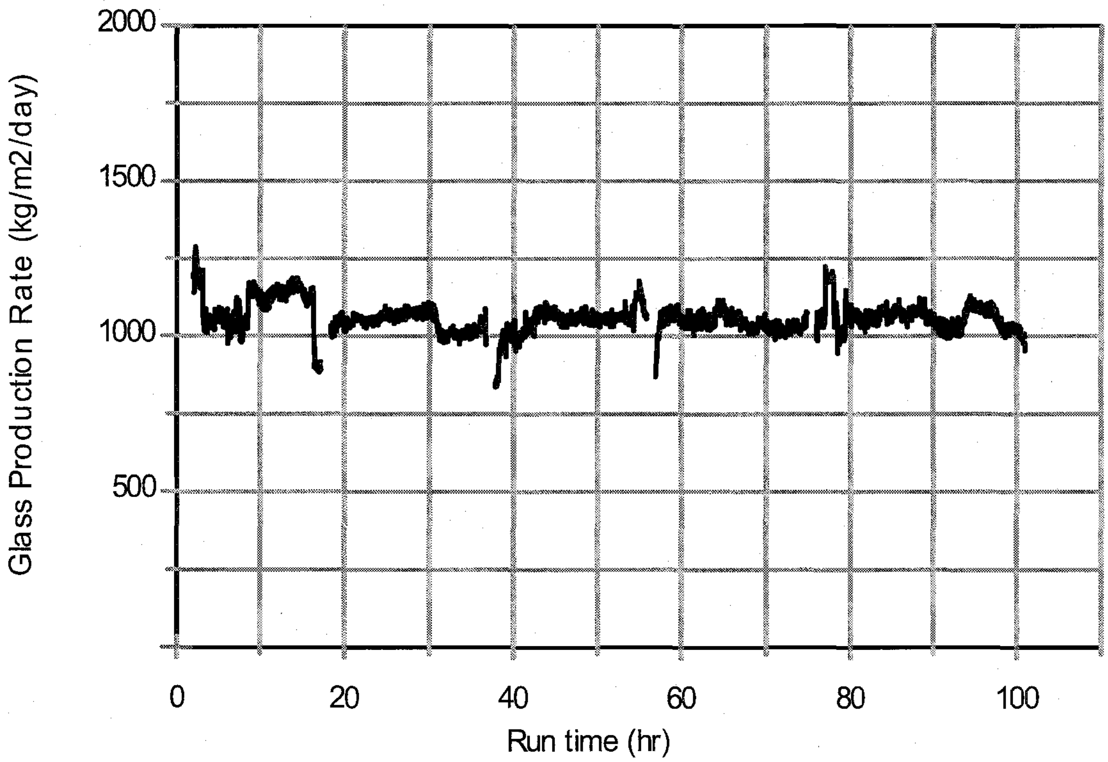

Figure 7. Glass production rate (hourly averaged) during DM100 Test C.

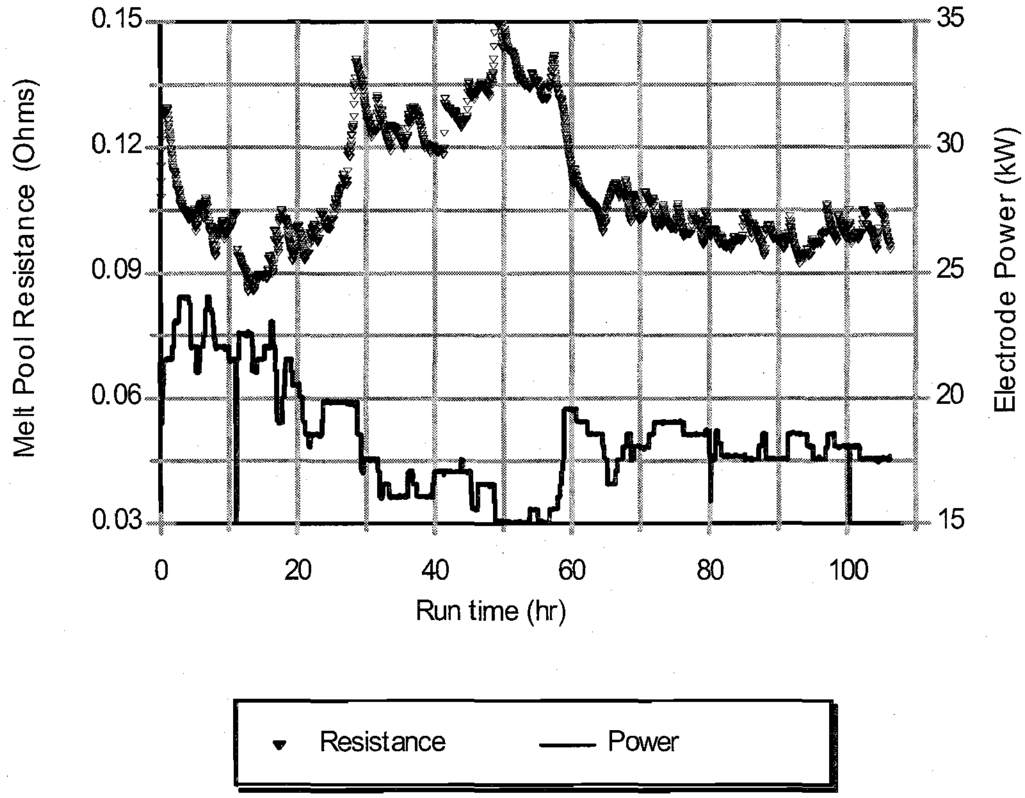

Figure 8. Glass resistance and electrode power during DM100 Test W.

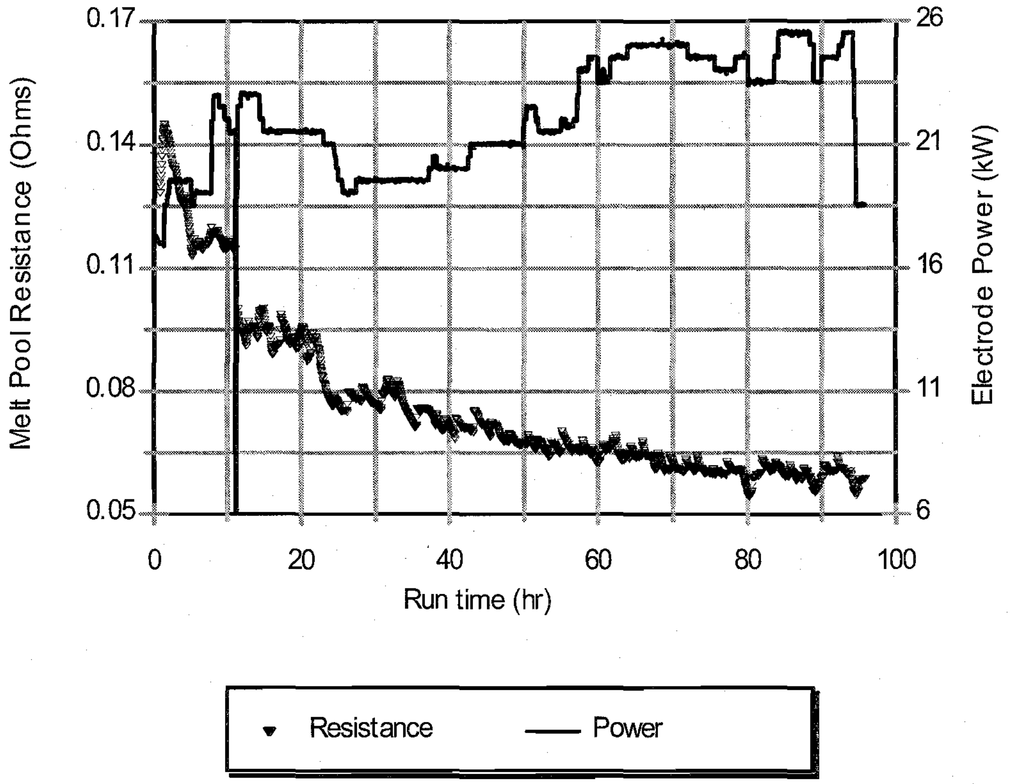

Figure 9. Glass resistance and electrode power during DM100 Test X.

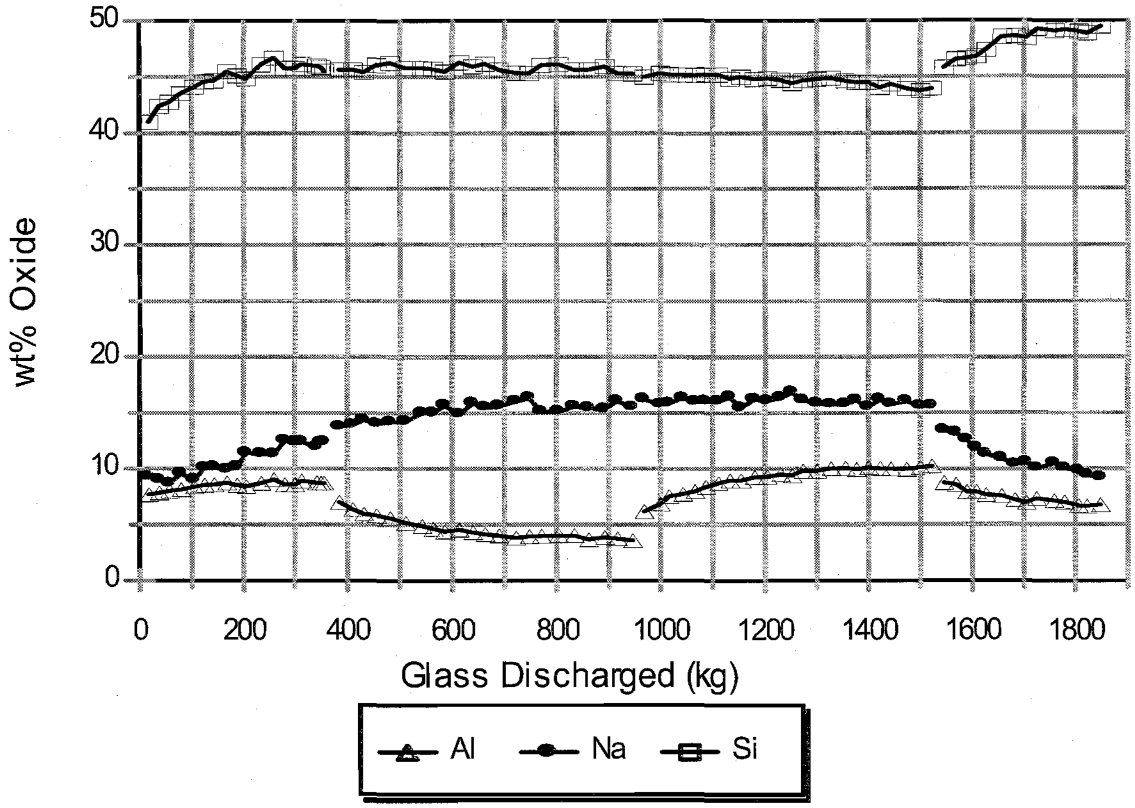

Figure 10.a. Alumina, soda, and silica concentrations determined by XRF in glasses from Tests W, X, Y and Z.

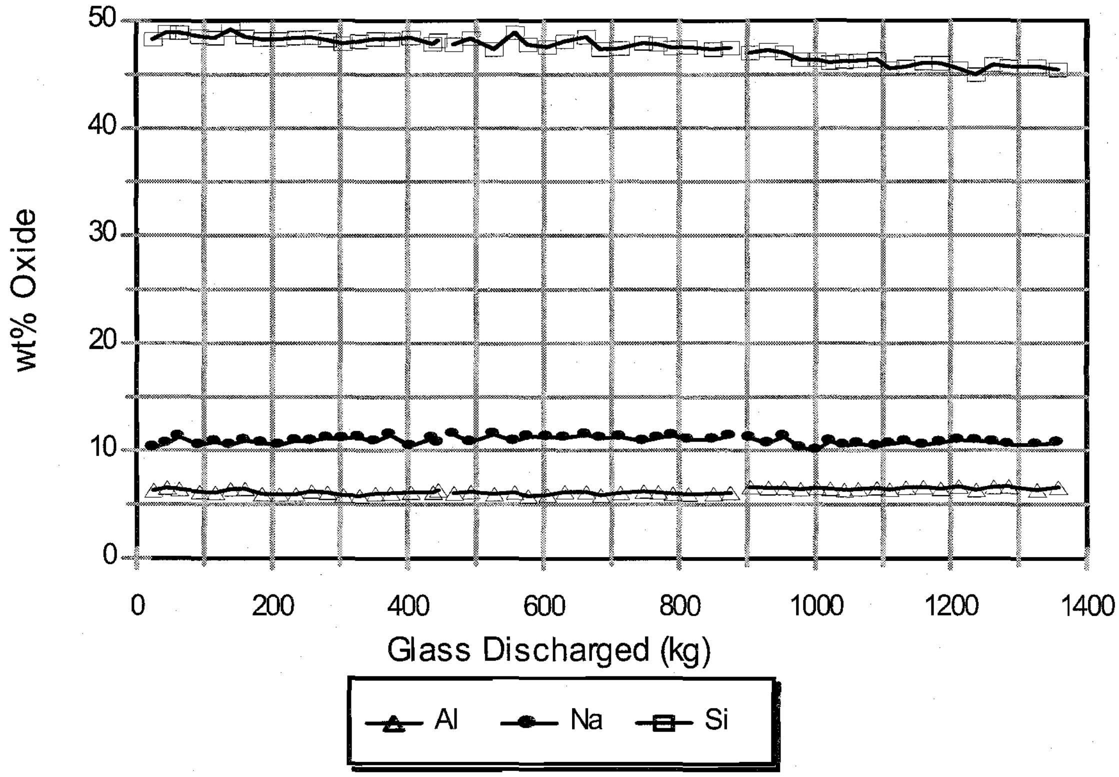

Figure 10.b. Alumina, soda, and silica concentrations determined by XRF in glasses from Tests A, B and C.

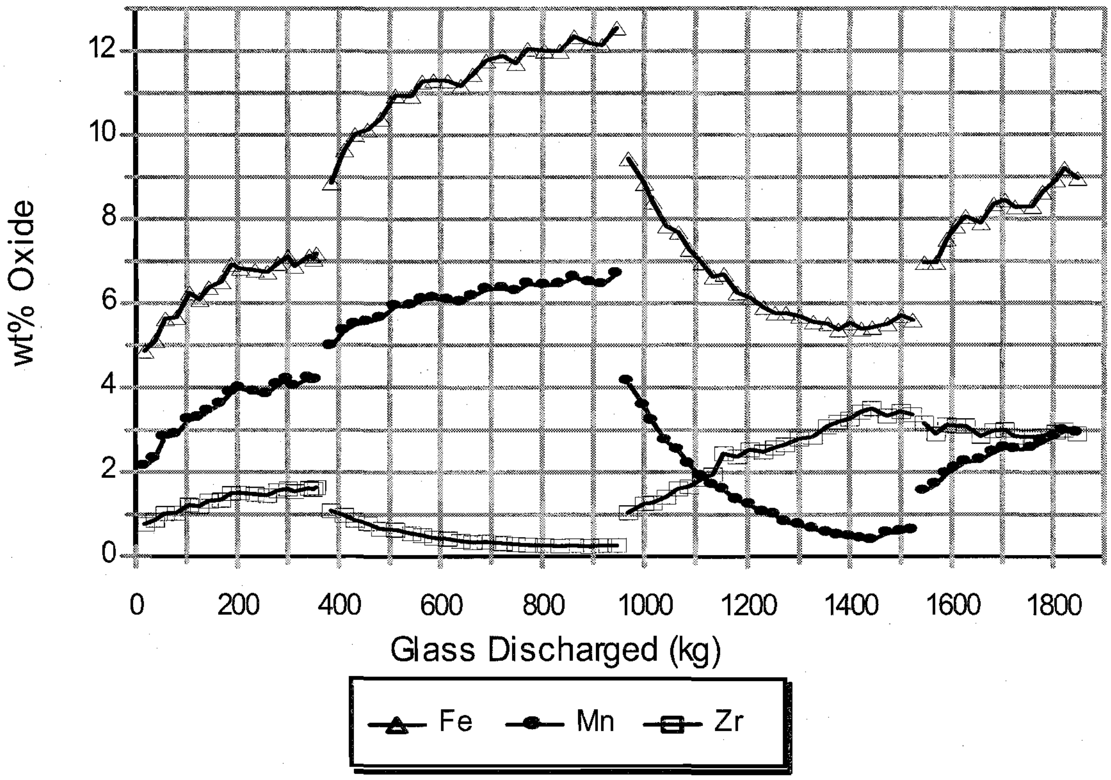

Figure 11.a. Iron, manganese, and zirconium oxide concentrations determined by XRF in glasses from Tests W, X, Y and Z.

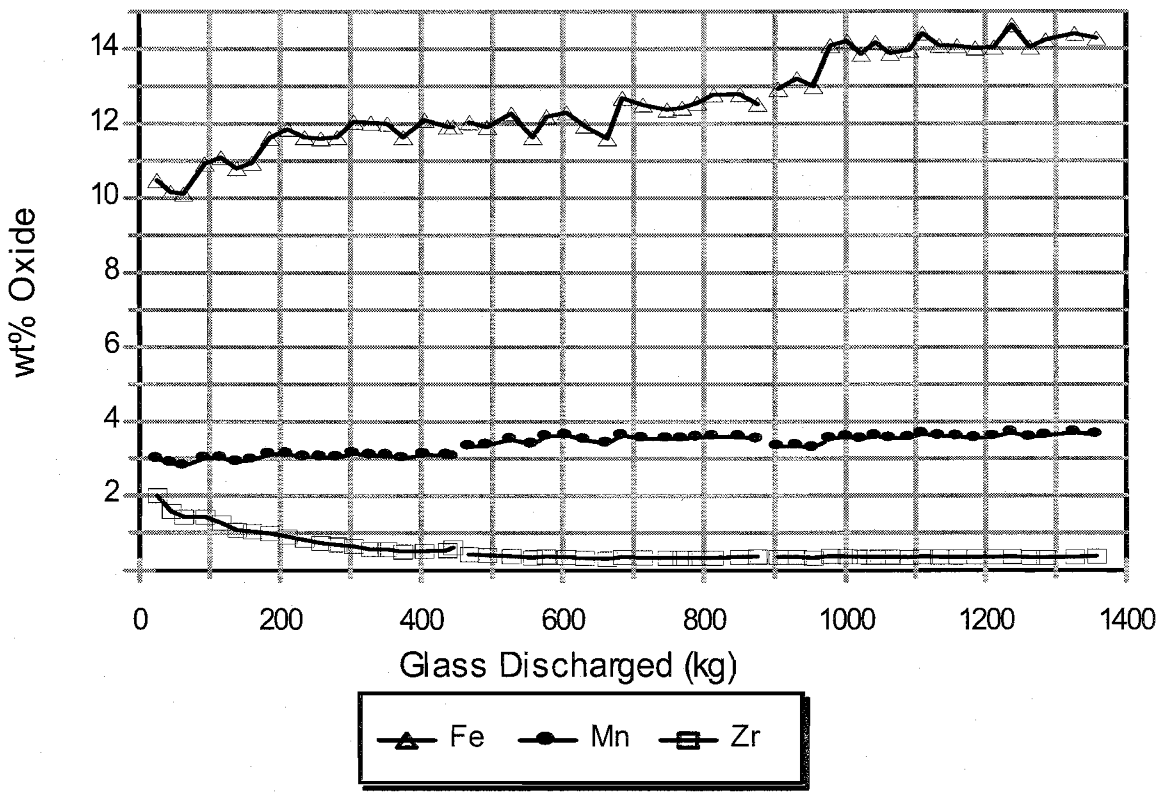

Figure 11.b. Iron, manganese, and zirconium oxide concentrations determined by XRF in glasses from Tests A, B and C.

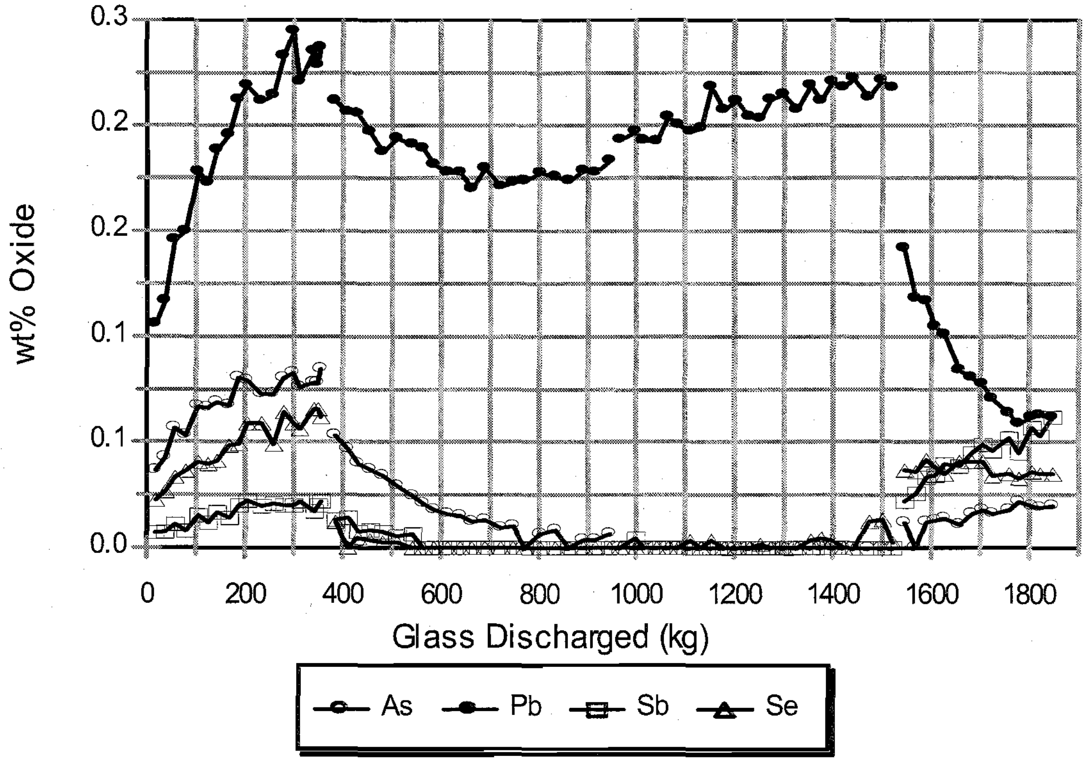

Figure 12.a. Select toxic metals concentrations determined by XRF in glasses from Tests W, X, Y and Z.

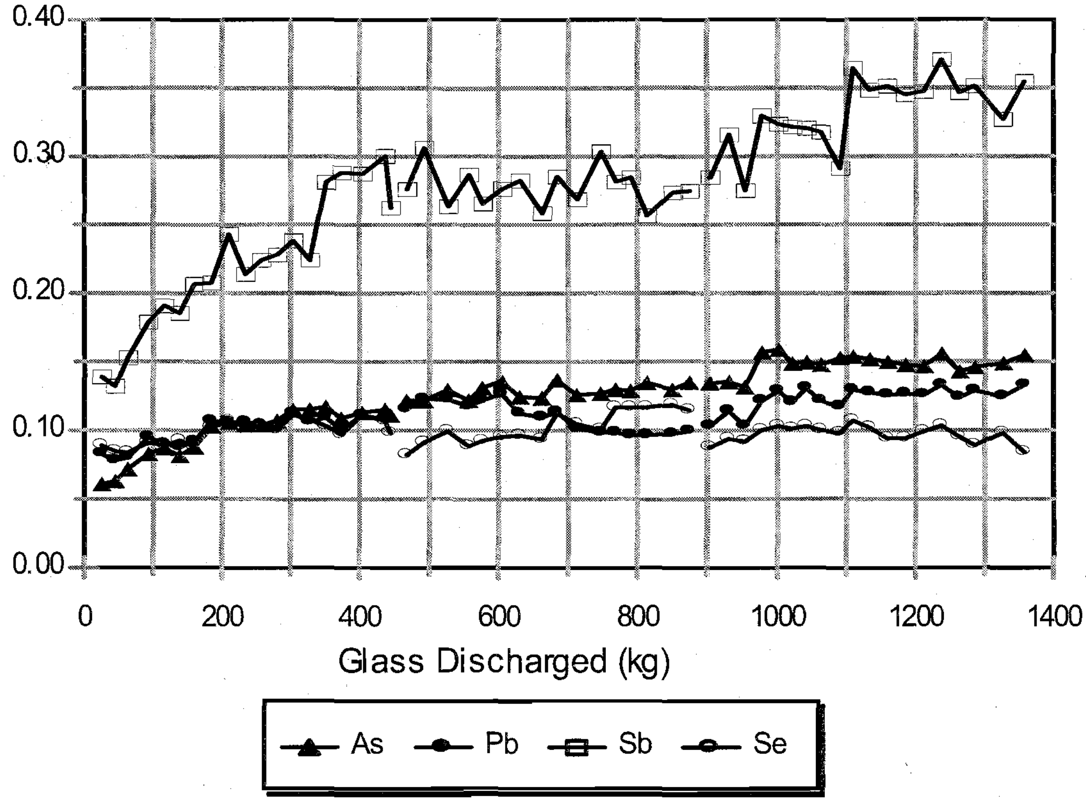

Figure 12.b. Select toxic metals concentrations determined by XRF in glasses from Tests A, B, and C.

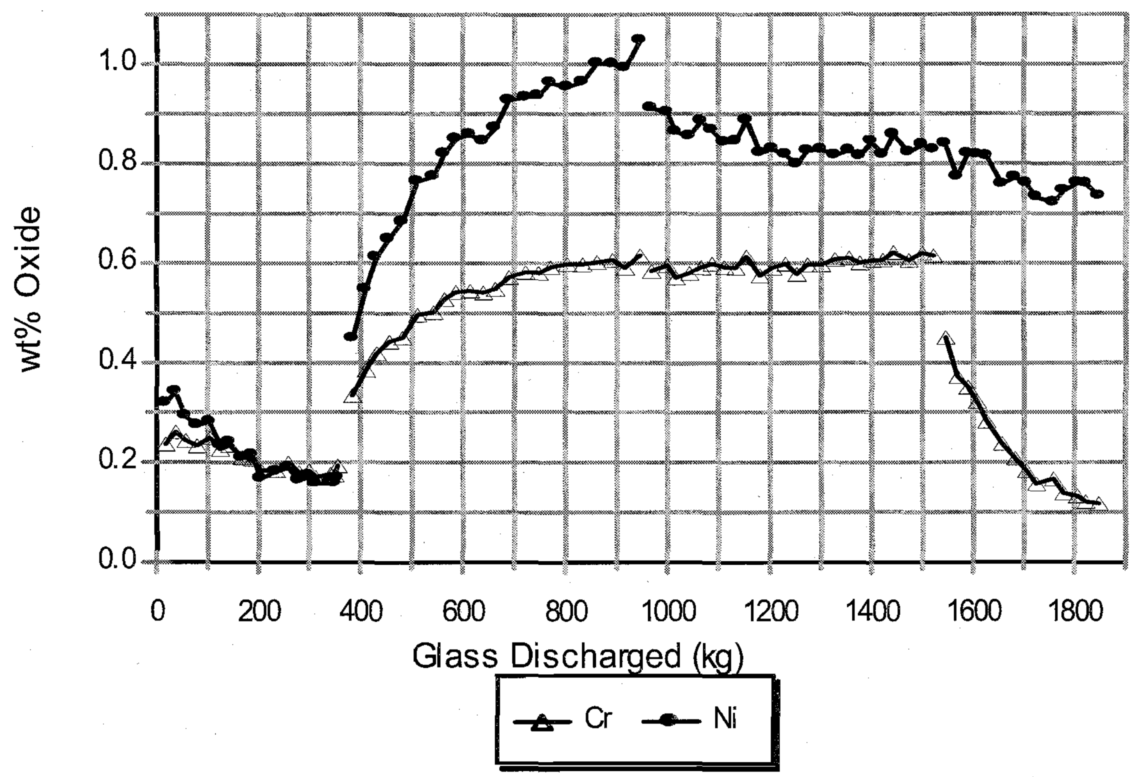

Figure 13.a. Chromium and nickel oxide concentrations determined by XRF in glasses from Tests W, X, Y and Z.

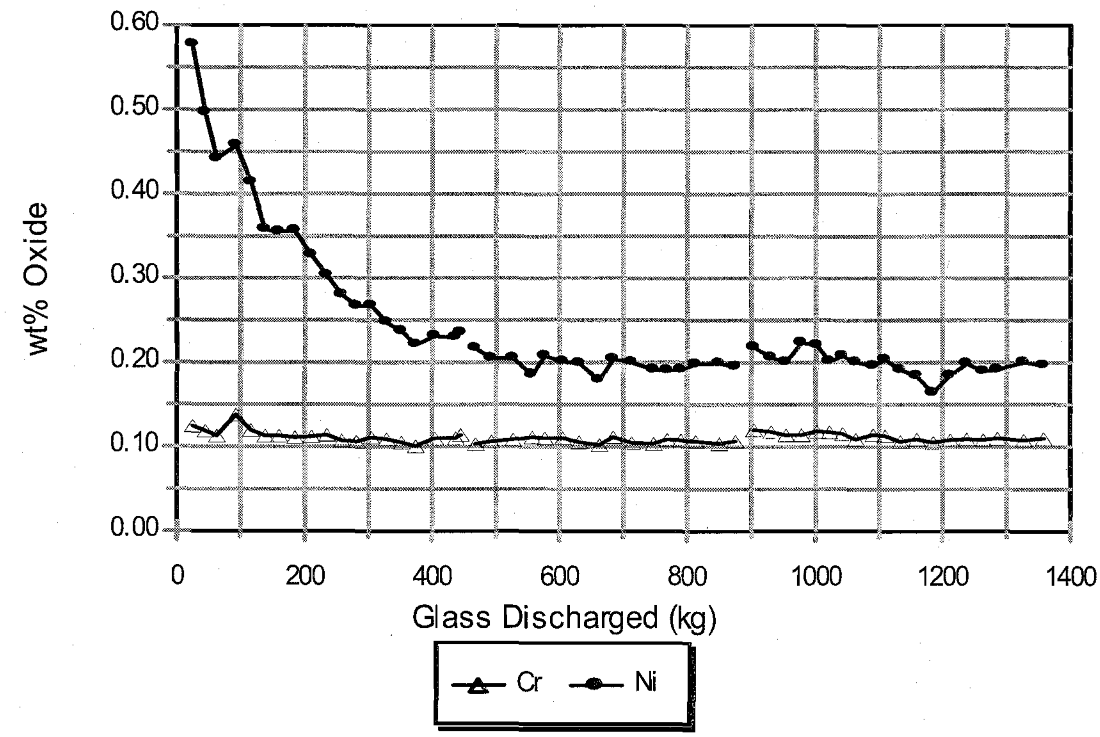

Figure 13.b Chromium and nickel oxide concentrations determined by XRF in glasses from Tests A, B and C.