

## Tests of Simultaneous Melt Rate and Waste Loading Enhancement for DWPF HLW Streams - 10254

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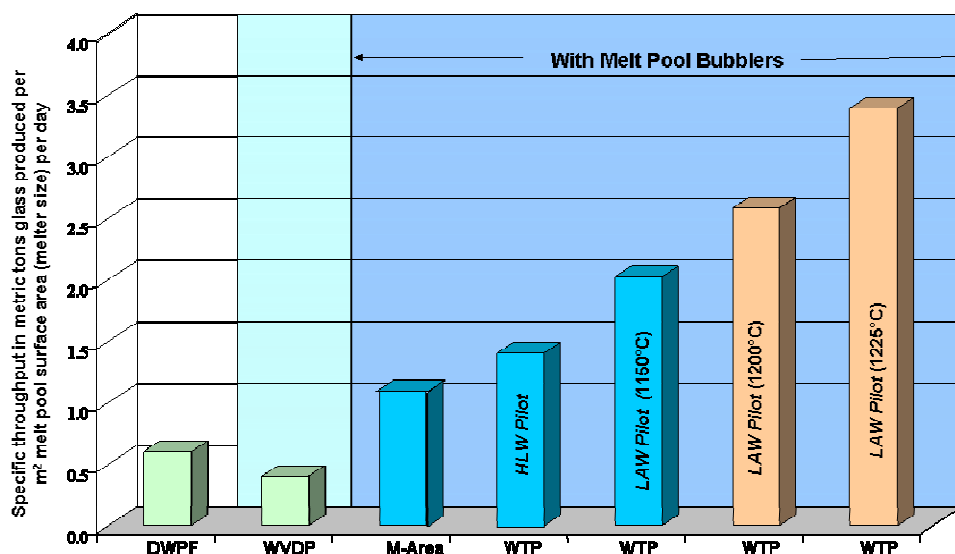
### ABSTRACT

This paper describes the results of a series of tests that were performed to assess the potential benefits of bubbler technology for DWPF HLW streams. The testing was performed on one of the DM100 joule-heated melter systems installed at the Vitreous State Laboratory. The first test employed a simulant of DWPF Sludge Batch 3 with Frit 418 and was intended to provide a calibration of the DM100 melt rate data against full-scale DWPF data obtained using actual Sludge Batch 3 with Frit 418. The DM100 specific glass production rates (i.e., calculated on a per unit melt surface area basis) observed without bubbling were close to but slightly lower than those observed at DWPF, suggesting that the small-scale melter results are conservative. In contrast, with melt pool bubbling, the specific glass production rates with the same feed increased by nearly a factor of *five*. This increase is consistent with the range of melt rate improvements that we have demonstrated previously with a wide variety of other waste compositions. Subsequent testing employed a projected future DWPF HLW composition that has among the highest expected aluminum contents but which will not be processed for several years. Fully compliant, high-waste-loading glass formulations containing ~20 wt% Al<sub>2</sub>O<sub>3</sub> were developed for that stream and a corresponding new frit composition was specified. This composition was also optimized with respect to melt rate based on small-scale melt rate tests. *Without* bubbling, DM100 tests with this waste and glass composition showed glass production rates that were slightly higher than those for the Sludge Batch 3 simulant without bubbling. DM100 tests *with* bubbling again showed a nearly five-fold improvement in glass production rates. Finally, tests were performed with the high aluminum waste in combination with a simulated SWPF stream, which resulted in 4.4 wt% TiO<sub>2</sub> in the glass product; similar increases in glass production rates were observed. All product glasses showed PCT releases well below the HLW requirements. In addition, off-gas data were collected throughout the melter tests to support mass balance calculations. The melt rate enhancements that were demonstrated in these tests are likely well beyond what the balance of the DWPF facility could support. However, the results indicate a potential approach for removing the melter as a bottleneck for overall facility throughput, in which case, subsequent efforts could be beneficially focused on improvements elsewhere in the system.

### INTRODUCTION

Since 1996, the Savannah River Site's Defense Waste Processing Facility (DWPF) has been vitrifying high level waste (HLW) sludge stored in the facility's underground tanks. Now in the early years of its second decade of operation, the plant has produced over 2700 canisters of stabilized HLW glass (over 10.7 million pounds of glass). The early HLW feed compositions

have been predominantly high in iron, whereas many of the future batches will have increasingly higher aluminum contents. In addition, once the Salt Waste Processing Facility (SWPF) comes on line, streams from that facility will also impact the DWPF feed compositions, particularly with respect to titanium content. The ability to increase the waste loading of these HLW feeds in the product glass can reduce overall waste treatment cost by reducing the amount of glass that must be produced and subsequently disposed. However, previous testing in support of DWPF has shown that waste loadings and melt rates at DWPF are coupled, such that melt rates decline at high waste loading. This effect tends to offset some of the benefits reaped from increased waste loadings. Thus, there would be considerable advantages to process enhancements that could break this relationship, such that higher waste loadings and higher melt rates could be realized simultaneously. Extensive previous testing that we have performed for other vitrification plants, including the Hanford Tank Waste Treatment and Immobilization Plant (WTP) high level waste (HLW) and low-activity waste (LAW) facilities, has shown that active melt pool agitation using appropriately designed and deployed gas bubbling systems can indeed provide this double benefit of increased waste loadings and increased melt rates as illustrated in Figure 1.



**Fig. 1. Comparison of glass production rates with conventional (DWPF and WVDP) and bubbled JHCs and the further enhancements demonstrated by combining modest operating temperature increases with bubbling.**

Under a support contract for WTP, the Vitreous State Laboratory (VSL) is developing and testing glass formulations for WTP HLW waste compositions to provide data to meet the WTP contract requirements and to support system design activities [1-3]. That work is based upon small-scale batch melts (“crucible melts”) using waste simulants. Selected formulations have also been tested in small-scale, continuously fed, joule-heated melters (DM100) [4-7] and, ultimately, in the one-third scale HLW DM1200 Pilot Melter [6-14]. Additional tests using the DM10 and DM100 melter systems were conducted for the Office of River Protection (ORP) to demonstrate the vitrification of waste streams with waste loading limiting concentrations of aluminum, bismuth and chromium [15]. Such melter tests provide information on key process

factors such as feed processing behavior, dynamic effects during processing, secondary phase formation, processing rates, off-gas amounts and compositions, foaming control, etc., that cannot be reliably obtained from crucible melts. This sequential scale-up approach in the vitrification testing program ensures that maximum benefit is obtained from the more costly melter tests and that the most effective use is made of those resources.

The primary objectives of the test described in this paper were to demonstrate that significant increases in glass production rates and waste loadings are possible at the DWPF by deploying bubblers and advanced glass formulation technologies and to demonstrate that the projected SWPF streams can be accommodated into the DWPF feed stream without deleterious effects on the vitrification process or glass product. The tests were performed with two DWPF waste compositions and two glass compositions. The first is the Batch 3 composition that has been run at the DWPF. Data collected on the DM100 provide a baseline for direct comparison with the DWPF performance as well as a demonstration of the effects of glass bubbling and increased processing temperature on glass production rate. The second composition was based on the SRS high-aluminum waste that the DWPF is likely to have to deal with in increased quantities in the future. A high waste loading glass formulation was developed for this high-aluminum waste stream with a corresponding glass frit composition. Suitable quantities of the waste simulant and glass frit were then procured and used to perform the remaining melter tests.

The first two tests used chemical simulants of the SRS Batch 3 HLW that were prepared on the basis of currently available waste characterization and flow-sheet data. Tests using this simulant are to compare the DWPF baseline processing rate against the higher throughput possible with modestly higher temperature (1175°C versus 1150°C) and bubbling. The remaining four tests were conducted using projections of SRS high-aluminum waste compositions available at the time this work was performed (2006) and SWPF product. Glass formulations were developed for the waste on the basis of crucible melts and subsequent characterization of the glass that is produced. Testing included melt viscosity, electrical conductivity, liquidus temperature, and leach testing using the PCT procedure (ASTM 1285).

## **WASTE COMPOSITION AND SIMULANTS FOR SB3 AND SB4**

In March 2004, the Defense Waste Processing Facility (DWPF) transitioned to the processing of a blend of Sludge Batch 2 and Sludge Batch 3. The blended sludge was designated as SB3 (or SB2/3 in a number of references). A frit change was implemented at the same time from Frit 320 to Frit 418 [16]. The first two tests included in the current test matrix employed the waste composition of SB3 together with Frit 418 to provide a baseline for comparison with the DWPF performance. The various projections made for the composition of the next sludge batch (Sludge Batch 4, SB4) to be processed at DWPF formed the basis of the waste composition used for Tests 3 through 6 in the test matrix. It should be noted that at the time this work was performed, the blending strategy for SB4 had yet to be finalized at DWPF; consequently, the actual SB4 composition processed at DWPF was different (e.g., *much* lower in aluminum) from the one selected here for testing. The selected SB4 waste composition is based on the waste preparation scenario Set 2, Case 15, Batch 1 [17], which we selected because it was one of the highest in aluminum content. Two Case 15-based waste compositions were tested—one with no blending

of waste products from the SWPF (for Tests 3 through 5) and the other with SWPF products blended (Test 6).

The blended sludge batch SB3 at DWPF was a mixture of Sludge Batch 2 in Tank 40 and Sludge Batch 3 from Tank 51. The waste composition of SB3 sludge estimated for the present tests was based on the characterization data of actual samples (Sludge Receipt and Adjustment Tank (SRAT) products) from Sludge Batch 2 [18] and Sludge Batch 3 [19], together with the calculated blending ratio. Table I lists the compositions of the SRAT products for the two sludge batches on both elemental and oxide bases. It can be seen that the compositions of the two samples are generally quite similar, with the major differences found in Fe (22.3 wt% in Batch 2 vs. 12.5 wt% in Batch 3) and Na (7.88 wt% vs. 13.2 wt%).

**Table I. Compositions of the SRTC SRAT Products from Sludge Batches 2 and 3.**

Elemental Wt% <sup>a</sup>			Oxide Wt%		
Elements	Sludge Batch 2 [22]	Sludge Batch 3 [23]	Oxides	Sludge Batch 2 [22]	Sludge Batch 3 [23]
Al	5.56%	4.77%	Al <sub>2</sub> O <sub>3</sub>	13.99%	14.06%
B	0.03%	0.317%	B <sub>2</sub> O <sub>3</sub>	0.13%	1.59%
Ca	2.19%	1.22%	CaO	4.08%	2.66%
Cr	0.15%	0.086%	Cr <sub>2</sub> O <sub>3</sub>	0.29%	0.20%
Cu	0.04%	<0.021%	CuO	0.07%	0.00%
Fe	22.3%	12.5%	Fe <sub>2</sub> O <sub>3</sub>	42.45%	27.88%
Hg	-	<0.023%	HgO	-	0.00%
K	0.04%	0.06%	K <sub>2</sub> O	0.06%	0.11%
Li	0.07%	<0.058%	Li <sub>2</sub> O	0.20%	0.00%
Mg	1.77%	1.28%	MgO	3.91%	3.31%
Mn	2.97%	3.82%	MnO	5.11%	7.70%
Na	7.88%	13.2%	Na <sub>2</sub> O	14.14%	27.76%
Ni	1.13%	0.813%	NiO	1.91%	1.61%
Si	0.99%	0.916%	SiO <sub>2</sub>	2.82%	3.06%
Ti	0.02%	0.015%	TiO <sub>2</sub>	0.04%	0.04%
U	6.85%	5.42%	UO <sub>3</sub>	10.76%	9.97%
Zr	0.02%	0.023%	ZrO <sub>2</sub>	0.04%	0.05%
TOTAL	52.01%	44.44%	TOTAL	100.0%	100.0%

<sup>a</sup>Weight % of total dried solids.

The blending ratio for preparing SB3 was based on the expected volume of Sludge Batch 2 that remained in Tank 40 at the time of addition of Batch 3. The volumes of Batches 2 and 3 were expected to be 263,000 gallons and 355,000 gallons, respectively [20]. Additional information required to calculate the mass ratio for blending of solids include the densities of the sludge samples (1.14 g/ml for Batch 2 and 1.22 g/ml for Batch 3 [20]) and the measured total solids contents (18.4 wt% for Batch 2 [20] and 27.2 wt% for Batch 3 [19]). The calculated mass ratio for blending *solids* is 31.9 wt% Batch 2 mixed with 68.1 wt% Batch 3 solids. The estimated

waste composition for SB3, based on the calculated blending ratio, is listed in Table II. The major components in this waste are, in order of decreasing concentrations, Fe, Na, Al, and U. The estimated composition is similar to that found for the actual SB3 sample (referred as SB2/3 in [20]) used as the SRAT cycle *feed*: 34 wt% Fe<sub>2</sub>O<sub>3</sub>, 22 wt% Na<sub>2</sub>O, 14 wt% Al<sub>2</sub>O<sub>3</sub>, and 11 wt% U<sub>3</sub>O<sub>8</sub> [20].

**Table II. Waste Compositions (wt% oxide basis) of SB3 and SB4.**

Oxides	Calculated Composition for SB3	Adjusted SB3 Composition for Tests 1 and 2	Composition for SB4 [21]*	Adjusted SB4 Composition for Tests 3 to 6
Al <sub>2</sub> O <sub>3</sub>	14.04%	13.84%	44.36%	46.08%
B <sub>2</sub> O <sub>3</sub>	1.13%	1.11%	0.10%	0.10%
CaO	3.11%	3.07%	1.66%	1.73%
Ce <sub>2</sub> O <sub>3</sub>	-	-	0.00%	0.00%
Cr <sub>2</sub> O <sub>3</sub>	0.23%	0.22%	0.19%	0.20%
CuO	0.02%	-	0.00%	0.00%
Fe <sub>2</sub> O <sub>3</sub>	32.53%	32.06%	17.91%	18.61%
HgO	-	-	-	-
K <sub>2</sub> O	0.10%	-	0.62%	0.64%
Li <sub>2</sub> O	0.06%	-	0.11%	0.11%
MgO	3.50%	3.45%	0.79%	0.82%
MnO	6.87%	6.77%	3.85%	4.00%
Na <sub>2</sub> O	23.42%	23.28%	17.65%	18.33%
Nd <sub>2</sub> O <sub>3</sub>	-	5.03%	-	-
NiO	1.71%	1.69%	1.39%	1.45%
PbO	-	-	0.00%	0.00%
SO <sub>3</sub>	-	1.15%	1.06%	1.10%
SiO <sub>2</sub>	2.98%	2.94%	6.35%	6.59%
ThO <sub>2</sub>	-	-	0.13%	0.00%
TiO <sub>2</sub>	0.04%	0.31%	0.03%	0.03%
U <sub>3</sub> O <sub>8</sub>	10.22%	-	3.61%	0.00%
ZnO	-	-	0.00%	0.00%
ZrO <sub>2</sub>	0.04%	5.08%	0.20%	0.20%
TOTAL	100.0%	100.0%	100.0%	100.0%

\* Values are slightly different than those in [21] because of conversion of SO<sub>4</sub> to SO<sub>3</sub>.

Adjustments were made to the estimated SB3 waste composition to prepare for the melter tests. The adjustments included the substitution of non-radioactive components for the radioactive uranium. The selected surrogates were Nd<sub>2</sub>O<sub>3</sub> and ZrO<sub>2</sub> and the substitution was made on a weight basis (i.e., half of the U<sub>3</sub>O<sub>8</sub> by weight is replaced by Nd<sub>2</sub>O<sub>3</sub> and the other half by ZrO<sub>2</sub>). Minor components (i.e., ≤ 0.1 wt%) were also omitted to minimize the number of components in the simulant. The total amount of minor oxides omitted was less than 0.2 wt%, which is not expected to have any significant effect on the results of the melter tests. Another adjustment

made is the inclusion of sulfate, which has been analyzed in an actual SB3 sample to be 2300 mg/kg of slurry [20]. The corresponding SO<sub>3</sub> content in the oxide-based waste is 1.15 wt%. Finally, Na<sub>2</sub>O and TiO<sub>2</sub> were increased in the SB3 waste in an attempt to account for the contribution of monosodium titanate (MST) from blending of SWPF products. However, due to a lack of data during the early development of the waste composition, the increases in Na<sub>2</sub>O and TiO<sub>2</sub> are limited (e.g., < 0.3 wt% TiO<sub>2</sub>) and considerably less than the amounts included for Test 6 (see below). The increases therefore represent a minor perturbation to the SB3 waste composition and *no* SWPF products are *in effect* included. Table II summarizes the final adjusted SB3 waste composition used for Tests 1 and 2.

The waste compositions for Tests 3 through 6 are based on SB4. Of the many SB4 blending and preparation scenarios, Case 15 Batch 1 of Set 2 was selected [25], the projected composition which is presented in Table II (sulfur is listed as SO<sub>3</sub> in Table II instead of sulfate as reported in reference [25]). Note that the values shown in Table II have been adjusted for the conversion of SO<sub>4</sub> to SO<sub>3</sub> and are therefore slightly different than those found in reference [25]. As is the case with SB3, the major components in the SB4 waste are Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and Na<sub>2</sub>O. In contrast, however, Al<sub>2</sub>O<sub>3</sub> is significantly higher in SB4 waste and may become the waste loading-limiting component, instead of Fe<sub>2</sub>O<sub>3</sub> for the SB3 waste (see below). With the exception of omitting the radioactive components (i.e., ThO<sub>2</sub> and U<sub>3</sub>O<sub>8</sub>), no adjustments were made to the composition for the melter tests. Since the concentrations of the radioactive components are lower than in SB3 (< 4 wt%), surrogates were not used in this instance and the waste composition was renormalized after the removal of ThO<sub>2</sub> and U<sub>3</sub>O<sub>8</sub>. Table II also lists the renormalized waste composition to be tested.

Products from SWPF processing are included for Test 6. The blending of SWPF products effectively increases the concentrations of Na<sub>2</sub>O, TiO<sub>2</sub>, and Cs<sub>2</sub>O. The increased amounts are based on the estimates that 594 kg of MST and 9.75 kg of Cs will be added per SRAT batch [21]. The sludge in the SWPF stream is assumed to be of identical composition to that of the sludge batch. Based on the expected production of 6 canisters of glass per SRAT batch, with 4000 pounds of glass per canister [22], this is equivalent to the addition of 4.36 wt% of TiO<sub>2</sub>, 0.85 wt% of Na<sub>2</sub>O, and 0.10 wt% of Cs<sub>2</sub>O per SRAT batch of glass.

The waste compositions for SB3 and SB4 sludges are discussed above on an oxide basis. In order to prepare feed for melter testing, additional information on the volatile components is needed to complete the formulation of the simulants. Based on the analytical data obtained for the actual SB3 SRAT product, there are negligible amounts of fluoride, chloride, nitrite, phosphate, and bromide [20]. The major anionic species measured included sulfate (see above), formate (51,600 mg/kg slurry), nitrate (28,200 mg/kg slurry), and oxalate (1,100 mg/kg slurry) [20]. These values were used in the simulant formulation for both SB3 and SB4 wastes. The simulants were prepared as slurries of 45-wt% solids [23].

## GLASS COMPOSITIONS

The first two tests employed chemical simulants of the SRS SB3 and Frit 418 in order to provide a baseline for comparison with the DWPF performance. Before the DWPF began processing SB3 with Frit 418 in 2004, a series of tests were performed to investigate the effect of waste loading

on the melt rate [24]. Waste loadings ranging from 31 wt% to 43 wt% were tested and 34 wt% was recommended as the starting point for DWPF based on the observation that the melt rate of the SB3-Frit 418 system reached a peak at that loading. The actual waste loadings at DWPF varied and exceeded 34 wt% in some instances. For example, analysis of an actual glass sample produced at DWPF showed that the  $\text{Li}_2\text{O}$  content was 4.96 wt% [25]. If it is assumed that all the lithium originated from the glass frit, the waste loading for the analyzed glass (Canister S02312) is calculated to be 38 wt%. In view of this range, a waste loading of 36 wt% was selected for Tests 1 and 2.

The high aluminum glass composition developed from crucible tests for subsequent melter testing (Tests 3 – 5, 7) has a waste loading of 43 wt% on an oxide basis. The selected glass meets all processability and product performance requirements. In particular, at 1150°C, the melt viscosity is 44.8 P and the electrical conductivity is 0.375 S/cm. The selected glass also outperforms the benchmark glass (Environmental Assessment (EA) glass) in PCT testing by wide margins, with the 7-day normalized leachate concentrations being 1.386 g/l for B, 1.253 g/l for Li, and 0.816 g/l for Na. These can be compared with the normalized concentrations for the DWPF-EA glass of 16.695 g/l, 13.346 g/l, and 9.565 g/l for B, Na, and Li, respectively [26]. The glass composition used in Test 6 incorporates 40.00 wt% of SB4 waste and 5.30 wt% of SWPF products, for a total waste loading of 45.30 wt%. Measured glass properties are well within acceptable ranges; melt viscosity (28.34 P at 1150°C), electrical conductivity (0.406 S/cm at 1150 °C), and PCT normalized concentrations (0.654 g/l for B, 1.599 g/l for Li, and 1.119 g/l for Na). These formulations were also optimized with respect to melt rate based on small-scale melt rate tests.

## **MELTER FEED PREPARATION**

Simulants for both SB3 and SB4 wastes were procured from Noah Technologies Corporation for melter testing. For SB4 waste with blended SWPF products, the simulant was prepared at VSL by adding  $\text{TiO}_2$  and  $\text{Na}_2\text{CO}_3$  (and other spikes) to the SB4 simulant manufactured by Noah Technologies. During feed preparation with tests using the SB4 waste composition, perchloric acid and cesium hydroxide were added to the simulant in proportions to target glass concentrations of 0.1 wt% on an oxide basis. Glass frit was blended with the simulants and de-ionized water at VSL to achieve the target glass compositions. The formulated frits were procured from Specialty Glass, Inc. to support the melter tests.

## **DM100 MELTER SYSTEMS**

### **D100 Feed System**

The melter feed is introduced in batches into a feed container that is mounted on a load cell for weight monitoring. The feed is stirred with a variable speed mixer and constantly recirculated except for periodic, momentary interruptions during which the weight is recorded. Feed is introduced into the melter from a recirculation loop that extends to the top of the melter where feed is diverted from the recirculation loop through a peristaltic pump and into the melter through a Teflon-lined feed line and water-cooled, vertical feed tube.

## **Melter System**

The DM100-BL unit is a ceramic refractory-lined melter fitted with five electrodes: two pairs of opposing Inconel 690 plate electrodes and a bottom electrode. Power can be supplied in either three-phase or single-phase configurations. All of the tests in the present work were performed with the upper and lower electrodes on each side connected and powered by a single-phase supply; the bottom electrode was not powered. Melt pool agitation is achieved by either a removable lance entering from the top of the melter or a permanent bubbler installed through the bottom electrode. In these tests the lance bubbler was used. The glass product is removed from the melter by means of an airlift discharge system. The melter has a melt surface area of 0.11 m<sup>2</sup> and a variable glass inventory of between 110 kg, when only the bottom pair of electrodes is used, and about 180 kg when both pairs of electrodes are used, which was the case in the present tests.

## **Off-Gas System**

For operational simplicity, the DM100-BL is equipped with a dry off-gas treatment system involving gas filtration operations only. Exhaust gases leave the melter plenum through a film cooler device that minimizes the formation of solid deposits. The film-cooler air has constant flow rate and its temperature is thermostatically controlled. Consequently, under steady-state operating conditions, the exhaust gases passing through the transition line (between the melter and the first filtration device) can be sampled at constant temperature and airflow rate. The geometry of the transition line conforms to the requirements of the 40-CFR-60 air sampling techniques. Immediately downstream of the transition line are cyclonic filters followed by conventional pre-filters and HEPA filters. The temperature of the cyclonic filters is maintained above 150°C while the temperatures in the HEPAs are kept sufficiently high to prevent moisture condensation. The entire train of gas filtration operations is duplicated and each train is used alternately. An induced draft fan completes the system.

## **DM100 MELTER TESTS**

Melter tests conducted on the DM100-BL produced almost 1.9 metric tons of glass from more than four metric tons of simulated waste (1447 kg SRS Batch 3 and 1224 kg SRS high aluminum) and over two metric tons of glass frit. Prior to feeding each of the two major glass compositions, the glass inventory was reduced from about 180 kg to about 100 kg in order to decrease the feeding time required to change over the composition of the glass pool. The series of seven tests were divided as follows:

- DWPF Batch 3 baseline – 656 kg of Glass Produced
  - 1175°C glass temperature, optimized bubbling, lid heaters, 73 hours.
  - 1150°C glass temperature, no bubbling, lid heaters, 37 hours.
- High Aluminum Waste – 1224 kg of Glass Produced
  - 1175°C glass temperature, optimized bubbling, lid heaters, 75 hours.
  - 1175°C glass temperature, optimized bubbling, 25 hours.
  - 1150°C glass temperature, optimized bubbling, 24 hours.



- 1150°C glass temperature, no bubbling, 24 hours.
- 1150°C glass temperature, optimized bubbling, SWPF products, 33 hours.

Attempts were made to replicate the melter configuration and operating conditions used for previous tests with HLW simulants [4-8, 14, 15, 27]. These conditions include a near-complete cold cap, which is between 80-95% melt surface coverage for the DM100 since a 100% cold cap tends to lead to "bridging" in smaller melters. The bubbling rate was optimized to achieve the maximum production rate in many of the tests. The approach used in these tests permits the evaluation of the effects of waste composition, glass temperature, and glass pool bubbling on production rate. Steady-state production rates from the present tests are shown in Figure 2; these are compared to relevant results from previous tests [4, 14, 15] in Table III. All parameters tested, including waste composition, additive form, glass temperature, glass pool bubbling, and the use of plenum heaters, had an effect on glass production rate. As expected, glass production rates increased dramatically with the use of optimized bubbling and to a lesser extent with a 25°C increase in glass pool temperature and the use of plenum heaters. Steady state production rates ranged from 1000 to 1950 kg/m<sup>2</sup>/day for melter tests with optimized bubbling while ranging from only 350 to 650 kg/m<sup>2</sup>/day without bubbling. Interestingly, the production rate for the SRS Batch 3 waste composition with optimized bubbling was 50 kg/m<sup>2</sup>/day higher than the SRS aluminum limited waste whereas without bubbling the trend is reversed. Glass production rates while processing the SRS aluminum limited waste were 3.7 times higher with optimized glass pool bubbling, were 1.12 times higher while using plenum heaters, and were essentially unaffected by a 25°C increase in glass pool temperature and inclusion of SWPF products in the waste. Overall, there were no significant difficulties in processing these feed and glass compositions during these tests. The feed was relatively fluid spreading out relatively evenly across the melt pool surface.

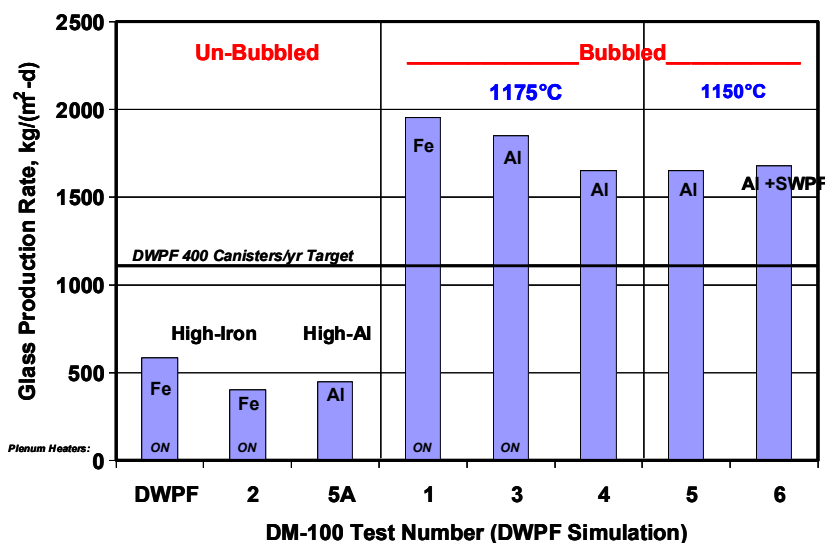


Fig. 2. DM100 melter production rates determined on simulated DWPf feeds. Both high iron and high aluminum type SRS HLW compositions were evaluated, with and without bubbling, with and without lid heaters, at two melt pool operating temperatures, and with the addition of SWPF product. All test cases with bubbling surpassed the production rate required to produce 400 canisters per year.

**Table III. Steady-State Production Rates Achieved on the DuraMelter 100 with HLW Compositions and Comparison to Previous Results with High-Iron Feeds.**

Bubbling	HLW Waste	Additive Forms	Glass Yield (g/L)	Plenum Heaters	Glass Temperature (°C)	Production Rate kg/m <sup>2</sup> /day
Optimized	SRS Batch 3	Frit	470	ON	1175	1950
	SRS Aluminum Limited	Frit	460	ON	1175	1850
	SRS Aluminum Limited	Frit	460	OFF	1175	1650
	SRS Aluminum Limited	Frit	460	OFF	1150	1650
	SRS Aluminum Limited with SWPF Products	Frit	460	OFF	1150	1675
	WTP Bismuth Limited [15]	Reagent Chemicals, Minerals	500	OFF	1175	1200
	WTP Aluminum Limited [15]	Reagent Chemicals, Minerals	500	OFF	1175	1000
			500	OFF	1150	1000
	WTP Aluminum Limited [28]	Reagent Chemicals, Minerals	500	OFF	1150	1900
	WTP Aluminum and Sodium Limited [15]	Reagent Chemicals, Minerals	500	OFF	1175	1400
500			OFF	1150	1250	
WTP C-106/AY-102, High Waste Loading [14]	Reagent Chemicals, Minerals	420	OFF	1150	1350	
Without bubbling	SRS Batch 3	Frit	470	ON	1150	400
	SRS Aluminum Limited	Frit	460	OFF	1150	450
	WTP AZ-101	Frit	570	OFF	1150	650
	WTP AZ-101 [4]	Reagent Chemicals, Minerals	350-540	OFF	1150	350-430
	WTP Nitrated AZ-101 [4]	Reagent Chemicals, Minerals	420	OFF	1150	490
	WTP AZ-101[4]	Reagent Chemicals, Minerals	540	ON	1150	530

The amount of bubbling required to maximize production rate was higher during tests conducted at lower temperatures and without plenum heaters to compensate for the lower energy input, as expected. The test-average optimized bubbling rates were about one-and-a-half to two times higher than the nominal bubbling rate of 9 lpm used in several previous tests [4, 5, 14, 15]. Bulk glass temperatures (measured at 5 and 10 inches from the bottom of the melt pool) were largely within 10°C of the target glass temperatures of 1175°C and 1150°C throughout the vast majority of the tests. The test-segment-average bulk glass temperatures were 1166 - 1178°C and 1148 - 1161°C for tests targeting glass temperatures of 1175°C and 1150°C, respectively. Power supplied to the electrodes typically varied between 9 and 26 kW. As expected, more power was required as the bubbling rate and, therefore, production rate increased. The opposite trend was observed when power usage is normalized to glass production due to the amount of energy required to maintain the glass pool at the target melting temperature.

## Chemical Durability of Discharge Glasses

Glass discharge samples from the end of each test with the high aluminum waste and optimized glass formulation were evaluated for chemical durability using the PCT method. The PCT results are compared to those for the benchmark DWPF-EA glass in Table IV. All measured PCT normalized concentrations of discharge glass samples are at least an order of magnitude lower than the corresponding values for the DWPF-EA glass. These results confirm that glasses can be formulated from waste rich in aluminum and titanium at high loadings without compromising the quality of the vitrified product.

**Table IV. PCT Results (ASTM C1285, 7-days at 90°C) for Melter Glasses.**

Test		3	4	5	7	6	DWPF EA Glass
Glass Samples		BLP-G-37A	BLP-G-56B	BLP-G-70A	BLP-G-82A	BLP-G-115B	
7-Day PCT Normalized Concentrations, g/L	B	0.59	0.61	0.53	0.61	0.97	16.70
	Li	0.64	0.66	0.59	0.65	0.93	9.57
	Na	0.33	0.43	0.40	0.47	0.64	13.35
	Si	0.37	0.32	0.31	0.32	0.34	3.92

## CONCLUSIONS

The first test employed a simulant of DWPF Sludge Batch 3 with Frit 418 and was intended to provide a calibration of the DM100 melt rate data against full-scale DWPF data obtained using actual Sludge Batch 3 with Frit 418. The DM100 specific glass production rates (i.e., calculated on a per unit melt surface area basis) observed without bubbling were close to but slightly lower than those observed at DWPF, suggesting that the small-scale melter test results are conservative. In contrast, with melt pool bubbling, the specific glass production rates with the same feed increased by nearly a factor of *five*. This increase is consistent with the range of melt rate improvements that we have demonstrated previously with a wide variety of other waste compositions. Subsequent testing employed a projected future DWPF HLW composition that has among the highest expected aluminum contents but which will not be processed for several years. Fully compliant, high-waste-loading glass formulations containing ~20 wt% Al<sub>2</sub>O<sub>3</sub> were developed for that stream and a corresponding new frit composition was specified. This composition was also optimized with respect to melt rate based on small-scale melt rate tests. *Without* bubbling, DM100 tests with this waste and glass composition showed glass production rates that were slightly higher than those for the Sludge Batch 3 simulant without bubbling. DM100 tests *with* bubbling again showed a nearly five-fold improvement in glass production rates. Finally, tests were performed with the high aluminum waste in combination with a simulated SWPF stream, which resulted in 4.4 wt% TiO<sub>2</sub> in the glass product and a total waste oxide loading of 45.3 wt%; similar increases in glass production rates were observed. The highest production rates of 1950 and 1850 kg/m<sup>2</sup>/day were obtained from the Batch 3 and the high-aluminum Batch 4 waste compositions, respectively. Without bubbling, production rates

did not exceed 450 kg/m<sup>2</sup>/day. It is interesting to compare the large melt rate increases with bubbler technology demonstrated in the present work with those achieved with the DWPF glass pump [29, 30], which has shown a typical melt rate increase of ~6% in full-scale service at DWPF [31]. All product glasses showed PCT releases well below the HLW requirements. In addition, off-gas data were collected throughout the melter tests to support mass balance calculations. The melt rate enhancements that were demonstrated in these tests are likely well beyond what the balance of the DWPF facility could support. However, the results indicate a potential approach for removing the melter as a bottleneck for overall facility throughput, in which case, subsequent efforts could be beneficially focused on improvements elsewhere in the system.

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