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Continuous Laboratory-Scale Melter Runs for System Evaluation

June 2020

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

The Waste Treatment and Immobilization Plant (WTP) will process and stabilize waste that is stored in underground tanks on the Hanford Site. Currently, the first phase of the planned WTP startup and operation, called Direct Feed Low-Activity Waste (DFLAW), involves directly feeding only the liquid portion of the waste to electric melters in the WTP Low-Activity Waste (LAW) Vitrification Facility without full pretreatment. A second portion of the tank waste, called high-level waste (HLW), is set to contain most of the radioactivity inventory.

To meet the acceptance criteria at the WTP LAW Facility, the LAW will undergo solids filtration and cesium removal by ion exchange. After these processes, the waste will be combined with glass-forming chemicals to form a mixed aqueous and solid slurry, called melter feed, that can be charged into the melters. During vitrification, a stable glass is produced while water, volatile waste components, and a portion of semi-volatiles from the waste-to-glass conversion process are driven into the offgas treatment system. Due to the high cost of immobilization and the wide variation in Hanford tank wastes, there is a need for a small-scale melter system that can generate processing and product stream partitioning data during vitrification of obtainable volumes of Hanford tank waste.

The continuous laboratory-scale melter (CLSM) was designed and constructed at Pacific Northwest National Laboratory with these needs in mind. This study was conducted to assess the performance of the CLSM system as a relevant scaled-melter test platform by comparing the results from multiple runs of simulated waste streams with each other, with the previously reported radioactive waste runs, and with results from other scaled-melter systems in literature. A LAW melter feed designed after the composition of the supernatant present in Hanford tank AN-105 and a high-alumina, HLW melter feed, called AlF2-05, were selected for processing in the CLSM.

The AN-105 melter feed was run three times in the CLSM. During these runs, when the operation was steady with the desired processing characteristics, the production results, average glass production rate, bubbling flux rate (bubbling rate divided by the CLSM vessel glass surface area), and plenum temperature, achieved a normal operation range that was similar to the ranges observed in similar scaled melter systems processing the same composition of melter feed. The recovery of all the major glass components during these runs was 90% to 100%, as typically observed in similar scaled melter systems. The retention of Re, a non-radioactive surrogate for ^{99}Tc, was calculated during each run, and the average single pass value while processing AN-105 melter feed in the CLSM was determined to be 35% with a standard deviation of 3%.

Chemical analysis of the glass product from the AN-105 melter feed CLSM runs revealed that composition spikes in the content of primary glass components (>1.00 wt%) reached their target value within one turnover of the CLSM glass inventory (2 kg), while spikes in the content of minor impurity components (<1500 ppm) reached 10% of initial levels within three turnovers. Volatile components in the glass composition accumulated in the CLSM offgas system in a similar fashion to a prototypic system.

The AlF2-05 melter feed, a composition designed with an experimentally high target Al_2O_3 content of 34 wt% in the produced glass, was successfully vitrified in the CLSM. The composition of Al_2O_3 in the glass product poured during the CLSM run was within 1% of the target value, revealing that it is possible to vitrify a waste glass composition with up to 34 wt% of Al_2O_3.

Based on the consistency of the production data ranges defined during the processing of these and other melter feeds in the CLSM and the similarity of those ranges and results to other melter systems from literature, it is concluded that the CLSM system is a viable option for testing Hanford waste vitrification.

Acknowledgments

The authors thank Jackie Ranger and the team at the Southwest Research Institute for performing the chemical analysis of all radioactive and non-radioactive products from the continuous laboratory-scale melter system. We thank Renee Russell for reviewing all the data, calculations, and figures associated with this technical report. We also thank Ewa Ronnebro for investigating and recommending the use of the AN-105 melter feed composition for testing. The authors gratefully acknowledge the financial support provided by the U.S. Department of Energy Waste Treatment and Immobilization Plant Project and the project direction provided by Dr. Albert A. Kruger.

Acronyms and Abbreviations

APEL	Applied Process Engineering Laboratory
CLSM	continuous laboratory-scale melter
DF	decontamination factor
DFLAW	Direct Feed Low-Activity Waste
DOE	U.S. Department of Energy
FIO	For Information Only
GFC	glass-forming chemical
HEPA	high-efficiency particulate air
HLW	high-level waste
ICP-MS	inductively coupled plasma -mass spectrometry
LAW	low-activity waste
M&TE	measurement and testing equipment
NQAP	Nuclear Quality Assurance Program
ORP	Office of River Protection
PNNL	Pacific Northwest National Laboratory
QA	quality assurance
R&D	research and development
RPL	Radiochemical Processing Laboratory
SBS	submerged bed scrubber
sccm	standard cubic centimeters per minute
SwRI	Southwest Research Institute
VSL	Vitreous State Laboratory
WRPS	Washington River Protection Solutions, LLC
WTP	Waste Treatment and Immobilization Plant

Contents

Figures

Tables

1.0 Introduction

1.1 Background

The primary mission of the U.S. Department of Energy (DOE) Office of River Protection (ORP) is to retrieve and process approximately 56 million gallons of radioactive waste from 177 underground tanks located on the Hanford Site. The Hanford waste tanks are currently operated and managed by Washington River Protection Solutions, LLC (WRPS). As part of tank farm operations, WRPS supports ORP's waste retrieval mission. An important element of the ORP mission is the construction and operation of the Waste Treatment and Immobilization Plant (WTP), which will process and stabilize the waste. Currently, the first phase of the planned WTP startup and operation, called Direct Feed Low-Activity Waste (DFLAW), involves directly feeding only the liquid portion of the waste to electric melters in the WTP Low-Activity Waste (LAW) Vitrification Facility without full pretreatment (Bernards et al. 2017). A second portion of the tank waste, called high-level waste (HLW), is set to contain most of the radioactivity inventory (Bernards et al. 2017).

To meet the acceptance criteria at the WTP LAW Facility (Bechtel 2015), the LAW will undergo solids filtration and cesium removal by ion exchange. After these processes, the waste will be combined with glass-forming chemicals (GFCs) to form a mixed aqueous and solid slurry, called melter feed, that can be charged into the melters. During vitrification, a stable glass is produced while water, volatile waste components, and a portion of semi-volatiles from the waste-to-glass conversion process are driven into the offgas treatment system.

The processing characteristics of melter feed slurry and the partitioning of specific waste components into these two product streams, glass and offgas, during vitrification are commonly determined through crucible melting of dried melter feed (Xu et al. 2015; Jin et al. 2014, 2015; Luksic et al. 2016, 2018) or scaled-melter testing with melter feed slurry simulants (Matlack et al. 2010a,b, 2011, 2012a,b, 2016, 2017). The crucible melting method is a batch process and thus is limited by nature in its ability to generate data representative of the dynamic process of vitrification. Scaled-melter testing can dynamically generate glass production rate and component partitioning data but may require high volumes of input waste simulant and high resource commitment in order to do so. An additional drawback is that the size of the footprint of scaled melter systems, with the necessary supporting equipment, makes it difficult to fit such a system in a space capable of handling radioactive components of interest, such as technetium-99 (^{99}Tc). This can often limit scaled melter system work to performance with melter feeds from waste simulants, thus preventing analysis of minor quantity, but highly radioactive waste components. Due to the high cost of immobilization and the wide variation in Hanford tank wastes, there is a need for a small-scale melter system that can generate processing and product stream partitioning data during vitrification of obtainable volumes of Hanford tank waste.

The continuous laboratory-scale melter (CLSM) was designed and constructed at Pacific Northwest National Laboratory (PNNL) with these needs in mind. A waste simulant-use CLSM system was assembled in the Applied Process Engineering Laboratory (APEL) while a duplicate CLSM system was assembled in a radioactive containment fume hood at the Radiochemical Processing Laboratory (RPL), making it capable of vitrifying Hanford tank waste samples. After assembly and system shakedown tests, the simulant CLSM in APEL was used to vitrify a simulant melter feed modeled after the waste in Hanford tank 241-AP-105 (hereafter called AP-105) (Dixon et al. 2018). The processability of the simulant AP-105 melter feed and the desired production characteristics were determined from the run in the simulant CLSM and then applied during operation of the radioactive CLSM in RPL with a sample of real waste from Hanford tank 241-AP-105. A volume of 12.4 L of AP-105 waste was provided to PNNL by WRPS, and this volume underwent filtration for solids removal (Geeting et al. 2018a) and ion exchange for cesium removal (Fiskum et al. 2018). GFCs were then added to the treated AP-105 waste and it was vitrified in the CLSM to produce 9.45 kg of glass product, the results of which are described by Dixon et al. (2018).

A second portion of waste was provided to PNNL by WRPS, this time from Hanford tank 241-AP-107 (hereafter called AP-107) (Dixon et al. 2019). The volume of waste totaled 8.6 L and, in the same manner as the AP-105 waste, underwent filtration for solids removal (Geeting et al. 2018b) and ion exchange for cesium removal (Rovira et al. 2018). GFCs were then added to the treated AP-107 waste and it was vitrified in the CLSM to produce 7.01 kg of glass product, the results of which are described by Dixon et al. (2019). The production results between the AP-105 and AP-107 runs in the radioactive CLSM were compared and discussed, and it was concluded that there was a difference in the processability of the two melter feed compositions (Dixon et al. 2019).

ORP has tasked PNNL to use the simulant CLSM system in APEL to assess the performance of the CLSM as a relevant scaled-melter test platform by operating the CLSM for multiple runs with the same composition of simulated waste and comparing the results with each other, with the previously reported radioactive runs using AP-105 and AP-107 wastes, and with results from other scaled-melter systems in literature. These additional runs with the same composition will allow evaluation of the variability of CLSM performance from run to run. Comparing between the additional runs and the AP-105 and AP-107 runs will lead to distinctions between unique melter feed compositions processed on the same system while allowing for association to the performance of other scaled-melter systems in literature.

The other scaled-melter systems in literature include the DM10 melter system operated by the Vitreous State Laboratory (VSL) of The Catholic University of America, which is similar in scale to the CLSM system, with a glass surface area of 0.021 m^2 and glass inventory of 8 kg. The system has been used to vitrify both HLW (Matlack et al. 2012a) and LAW (Matlack et al. 2010b, 2011, 2012b, 2016, 2017) simulant melter feeds. Many of the LAW melter feeds were spiked with rhenium, a non-radioactive surrogate for ^{99}Tc, or ^{99m}Tc, a short-lived isotope with a half-life of 6 hours. The Large C Melter system operated by Savannah River Technology Center is likewise at a similar scale to the CLSM system, with a glass surface area of 0.00771 m^2 and glass inventory of 2.31 kg, and it has been used to vitrify both a simulant of waste from Hanford tank 241-AN-102 (hereafter called AN-102) and a sample of real AN-102 waste (Zamecnik et al. 2002). Other scaled melter systems operated by the VSL are slightly larger, including the DM100 melter system, with a glass surface area of 0.108 m^2 and glass inventory of 115 to 120 kg (Matlack et al. 2010a, 2011), and the DM1200 melter system, with a glass surface area of 1.18 m^2 and glass inventory of 2.0×10^3 kg (Matlack et al. 2010a, 2011). All these scaled-melter systems are smaller than the WTP LAW melters, which have been designed with a glass surface area of 10.0 m^2 and glass inventory of $\sim 2.0 \times 10^4$ kg (Matlack et al. 2011; Zamecnik et al. 2002).

1.2 Quality Assurance (QA)

This work was performed in accordance with the PNNL Nuclear Quality Assurance Program (NQAP) Quality Assurance Manual (NQAP-2012) and associated QA procedures. The NQAP is based on the requirements of NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Application*, graded on the approach presented in NQA-1-2012, Subpart 4.2.1, *Guidance on Graded Application of Nuclear Quality Assurance (NQA) Standard for Research and Development*.

The NQAP works in conjunction with PNNL's laboratory-level Quality Management Program, which is based upon the requirements as defined in DOE Order 414.1D, *Quality Assurance*, and 10 CFR 830, *Nuclear Safety Management*, Subpart A, *Quality Assurance Requirements*. PNNL implements these requirements with a graded approach using the consensus standard ASME NQA-1-2000, *Quality Assurance Requirements for Nuclear Facility Applications*, graded on the approach presented in NQA-1-

2000, Subpart 4.2, *Guidance on Graded Application of Quality Assurance (QA) Standard for Nuclear-Related Research and Development*.

2.0 Test Conditions

This section describes the CLSM system, the preparation of the melter feed, and analytical methods used on the product samples from the CLSM test runs performed between September 2018 and July 2019.

2.1 Simulant CLSM System in APEL

All the testing described in this report was performed in the simulant CLSM system located in APEL. The CLSM system was designed to collect samples of glass, offgas solids, and offgas condensate without upsetting continuous operation. The CLSM was not designed to be fully prototypic of the WTP LAW melters, but to reproduce the feed-to-glass conversion process performed in the melters. A simplified flow diagram of the CLSM system is shown in Figure 2.1.

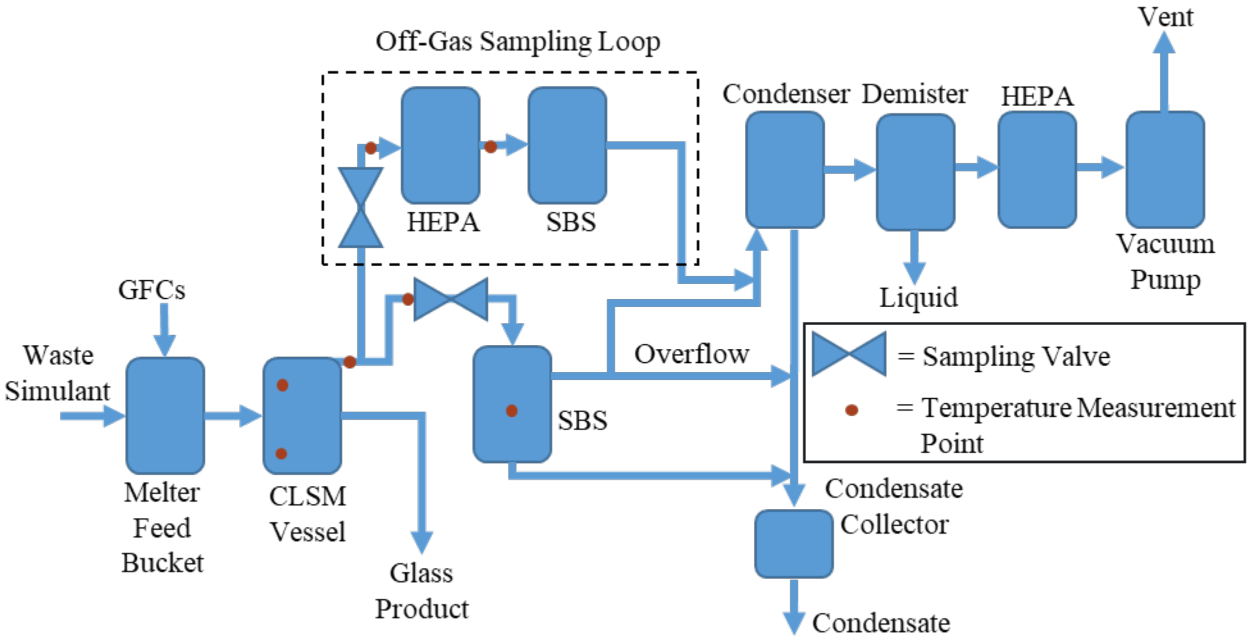

Figure 2.1. Simplified flow diagram of the CLSM system.

2.1.1 System Design

The waste simulant melter feed slurries (prepared as described in Section 2.3) were agitated by an overhead stirrer for at least 24 hours prior to processing in the CLSM system. During melter feed charging to the CLSM vessel, the slurries were in the melter feed bucket and remained continuously agitated by an overhead stirrer for the duration of the melter feed charging time. The melter feed was pumped from the melter feed bucket by a progressive cavity pump and charged into the CLSM vessel through quarter-inch, stainless-steel tubing, which could produce a continuous drip of melter feed at a steady rate. The stainless-steel feed tubing that entered the CLSM vessel was water-cooled to prevent evaporation of the melter feed slurry in the tubing that may result in feed line blockage.

The CLSM vessel was fabricated as an octagonal cross-sectional design using Inconel 690 plate. The vessel was sized to an equivalent cylindrical diameter of approximately 12.0 cm (4.7 in.), resulting in a cross-section and glass surface area of 0.0113 m^2. The glass inventory in the CLSM vessel was approximately 2.0 kg, resulting in a glass melt pool depth of ~6.4 cm (2.5 in.).

The lid of the CLSM vessel contained eight access ports (Figure 2.2): three for thermocouples ("TC" in the figure), one for an air bubbler, one for the feed tubing, one for a sight glass into the vessel ("Viewport" in the figure), one for the connection to the offgas system, and one for pressure relief ("Back-Up Offgas" in the figure). Heat was supplied externally to the CLSM vessel by a surrounding furnace. The hot zone of the furnace was located below and around the glass melt pool while the offgas head space, called the plenum, of the CLSM vessel was surrounded by insulation. The CLSM achieved continuous operation by periodically pouring glass out of the melt pool to a glass discharge box located below the CLSM vessel. Pouring was achieved by lowering the vacuum maintained on the CLSM vessel by the offgas system, which allowed glass to pour by rising through a discharge riser and passing over an overflow weir.

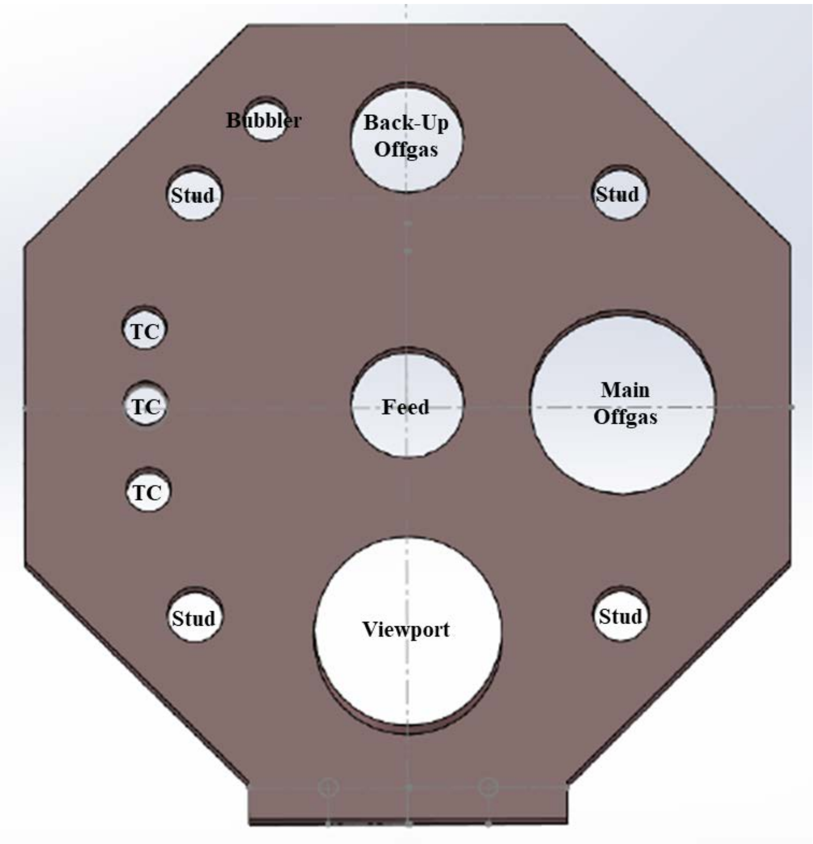

Figure 2.2. CLSM vessel lid and identified ports. The designation "TC" stands for a thermocouple port.

The offgas produced by the conversion of melter feed to molten glass was drawn off from a port in the CLSM vessel lid into the offgas system with a vacuum pump. The offgas system was constructed of stainless-steel piping and the units described subsequently. Except when the offgas stream was sampled, the offgas would flow through the primary pathway in the offgas system, which consisted of a submerged bed scrubber (SBS; referred to as the primary SBS), a condenser, a demister, and a high-efficiency particulate air (HEPA) filter (referred to as the primary HEPA filter). The primary SBS and the condenser worked together to both cool the offgas, causing condensation of steam, and perform scrubbing to remove other soluble gases and aerosols as possible. The cool liquid from the condenser along with the liquid overflow from the primary SBS drained into a collector where this condensate liquid could be drained periodically. Offgas from the condenser passed through a demister, which allowed any remaining liquid to accumulate before the primary HEPA filter captured any remaining difficult-to-remove particulates. After HEPA filtration, the offgas flowed through the vacuum pump and was released to the fume canopy ventilation system. When needed, the primary HEPA filter could be bypassed and the offgas could flow directly from the demister to the vacuum pump.

The total offgas stream could be sampled by closing the sampling valve in the primary offgas pathway to divert the full offgas flow through a sampling loop containing heated HEPA filters (referred to as the sampling HEPA filters) followed by an SBS (referred to as the sampling SBS). This sampling train consisted of three parallel banks of two sampling HEPA filters each. Each bank was available for discrete sampling evolutions. The sampled offgas stream was then released back into the primary offgas pathway before the condenser unit. Sampling of the total offgas stream avoided the inherent issues with offgas piping geometry and design with slip-stream sampling and ensured that the sample was representative. Offgas sampling durations were 10 to 30 minutes until the sampling HEPA filters became impassable.

2.1.2 System Configuration

The CLSM apparatus consisted of both commercially available and custom parts. In addition to the CLSM system described above and shown in Figure 2.1, supporting equipment included (1) a controller for the furnace; (2) a water chiller pumping system to cool the necessary locations in the CLSM system, such as the condenser and the primary SBS, with a separate liquid pump plumbed into the chiller line to transport cooling water to the feed nozzle at a controlled rate; (3) a water flush pump for washing out the melter feed pumping system; (4) a controller for the heat trace around the sampling and primary HEPA filters: and (5) a computer for controlling the CLSM system while continuously recording process data.

The CLSM system was assembled in metal framework that approximated the size of the RPL fume hood in which the radioactive CLSM was assembled (Dixon et al. 2018, 2019). The radioactive and simulant CLSM systems were designed to be functionally identical, though the radioactive system was assembled in a fume hood while the simulant system was located below a fume canopy. An image of the simulant CLSM system layout in APEL is shown in Figure 2.3.

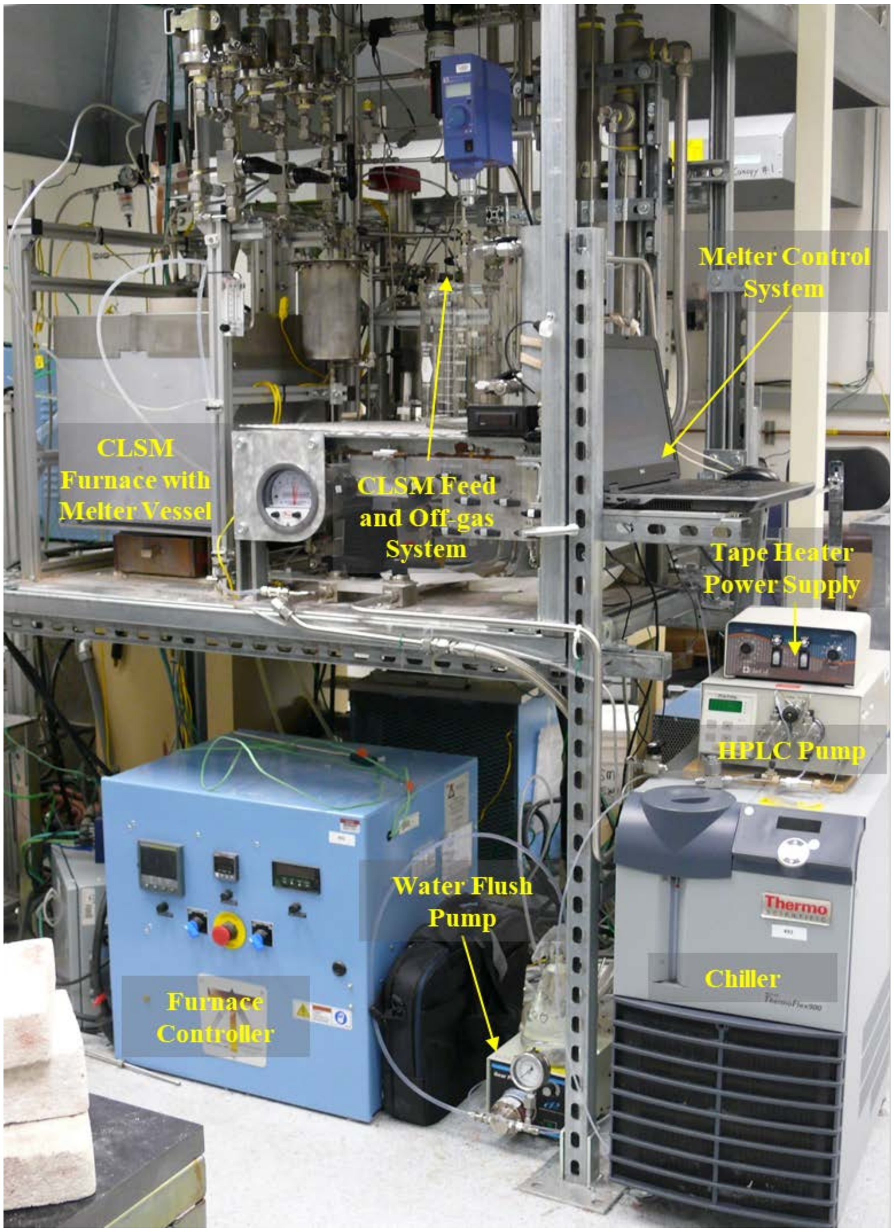

Figure 2.3. Simulant CLSM system layout in APEL fume canopy.

2.1.3 System Operation

The CLSM was operated to maintain a glass melt pool temperature of 1150 °C (± 30 °C) by manually adjusting the control temperature of the surrounding furnace as necessary. During feeding operations, the melter feed was charged onto the glass melt surface in the CLSM vessel, forming a batch blanket, called a cold cap, where the feed was heated and converted to glass (Dixon et al. 2015). The feeding rate (governed by the progressive cavity pump with an operational range from 0-36 revolutions per minute) and air bubbling rate (governed by a mass flow controller that could deliver air at 50 to 3000 standard cubic centimeters per minute [sccm] through a high-temperature 600 nickel alloy tube that was submerged in the glass melt pool) were varied to maintain a target cold-cap coverage over the glass melt surface of 75% to 95%. The cold-cap coverage was determined to be in the appropriate range when the temperature in the plenum fell into the 550 to 650 °C range, and this could be confirmed by visual observation through the viewport of the CLSM vessel lid. The CLSM briefly did produce glass melt pool and plenum temperatures above and below the target ranges. Typical of slurry-fed melters, the plenum temperature and cold-cap coverage were influenced by other factors, including feed composition and concentration, which may vary between different melter feeds (Matlack et al. 2011). The target glass production rate ranges for LAW and HLW melter feeds in the CLSM are listed in Table 2.1, and these values align with the designed operation rates at the WTP of 15 metric tons of glass per day [MTG d^{-1}] of immobilized LAW and 6-7.5 MTG d^{-1} with the HLW melter design (Bernards et al. 2017).

Table 2.1. Target CLSM Operating Conditions

Parameter	LAW Target	HLW Target
Target glass production rate, kg m^{-2} d^{-1}	1500-2000	700-1700
Target feeding rate, kg h^{-1}	1.39-1.85	0.95-2.30
Target feeding rate, L h^{-1}	0.82-1.10	0.66-1.60
Bubbling rate, sccm	50-2000	50-1700
Target glass melt temperature, °C	1150	1150
Plenum temperature range, °C	450-650	450-650
Plenum vacuum normal operation, in-H_2O	2-4	2-4
Offgas piping temperature range, °C	< 500	< 500
Primary SBS temperature, °C	15-30	15-30

The condenser in the offgas system was operated with chilled water and the condensate was drained periodically from a collector vessel. The liquid level in the primary SBS was maintained by overflow so that the pressure drop across the primary SBS remained relatively constant, and the temperature was maintained by circulating chilled water through cooling coils in the primary SBS. In the offgas sampling loop, the sampling HEPA filters were wrapped with heat trace and covered with insulation to maintain an elevated temperature (>100 °C) and prevent/reduce condensation prior to the sampling SBS. The offgas system vacuum pump was operated such that it pulled a vacuum on the CLSM vessel during feeding operation. The nominal operating vacuum was 2 to 4 in-H_2O. The CLSM vessel vacuum was reduced periodically to pour glass. At the end of the run, the bubbler air and viewport purge air were adjusted to increase the pressure in the melter, pouring controlled volumes of glass from the CLSM vessel until the remainder of the glass inventory had exited the vessel.

2.2 Melter Feeds for CLSM Runs

Both a LAW and an HLW simulant melter feed were selected for testing in the CLSM. The LAW simulant selected for testing in the CLSM was based on the waste composition in Hanford tank AN-105, the recipe for which (LAWE4H) was formulated by Matlack et al. (2010b, 2011, 2012b, 2016, 2017). GFCs were added to the waste simulant composition to form the melter feed, referred to as AN-105. The target oxide composition of the glass formed from vitrifying this melter feed is listed in Table 2.2 along with the chemical constituents of the feed needed to make 4.0 kg of glass. The target mass of Re_2O_7 in the batch corresponded with a Re concentration of 8.1 ppm in the final glass, if 100% was retained, which is the molar equivalent of 4.3 ppm of ^{99}Tc, the estimated concentration in the typical Hanford LAW glass (Kim et al. 2003).

Table 2.2. AN-105 Glass Composition and Melter Feed Chemicals Used to Produce 4.0 kg of Glass

Component	wt%	Starting Materials	Target Weight (g)
Al_2O_3	5.97	$Al(NO_3)_3 \cdot 9H_2O$	1548.69
		$Al(OH)_3$	207.65
		Kyanite	113.17
B_2O_3	9.79	Boric acid	1215.37
CaO	2.46	Wollastonite	355.74
Cl	0.20	NaCl	22.41
Cr_2O_3	0.08	Na_2CrO_4	11.75
F	0.08	NaF	11.99
Fe_2O_3	5.38	Hematite	383.25
K_2O	0.54	KOH	44.31
MgO	1.45	Olivine	176.68
Na_2O	21.27	NaOH	1377.80
		$NaNO_2$	751.56
		Sodium formate	19.22
		Sodium acetate	18.62
NiO	0.01	NiO	0.54
P_2O_5	0.12	$Na_3PO_4 \cdot 12H_2O$	44.92
PbO	0.01	PbO	0.53
SO_3	0.41	Na_2SO_4	50.76
SiO_2	44.50	Silica	2804.37
TiO_2	1.37	Rutile	100.25
ZnO	3.43	Zincite	241.87
ZrO_2	2.94	Zircon	305.32
		Re_2O_7 solution (814 mg-Re kg^{-1})	68.42
		Glycolic acid	16.33
		Sucrose	462.81

Three LAW CLSM runs were performed, with 8 liters of AN-105 melter feed being prepared for each run according to the recipe given in Table 2.2. These melter feeds were prepared on 12-12-18, 3-27-19, and 7-22-19 at a glass yield of 859 g of AN-105 glass per liter of melter feed slurry. Multiple runs with the same composition will allow for the evaluation of the variability of CLSM operation from run to run independent of composition as a performance variable.

The HLW simulant selected for testing in the CLSM was based on high-alumina HLW compositions such as batch 86b from the Tank Utilization Assessment (Jenkins et al. 2010) and batch 1285 from Scenario 1 (Baseline case) of the River Protection Project System Plan (Bernards et al. 2017). The glass composition, called AlF2-05 and shown in Table 2.3, was derived by Kroll et al. (2019) based on these wastes to satisfy the WTP processing and product quality constraints using previously published models (Vienna et al. 2009, 2016). The AlF2-05 melter feed slurry was designed given the stated glass composition and based on the starting materials used to batch HWI-Al-19 melter feed with gibbsite as an aluminum source by Matlack et al. (2010a, 2012a). The target weights of the AlF2-05 melter feed batch chemicals used to produce 1.5 kg of glass are given in Table 2.3.

Table 2.3. AlF2-05 Glass Composition and Melter Feed Chemicals Used to Produce 1.5 kg of Glass

Component	wt%	Starting Materials	Target Weight (g)
Al_2O_3	34.00	$Al(OH)_3$	783.47
B_2O_3	23.46	H_3BO_3	625.70
Bi_2O_3	0.34	Bi_2O_3	5.22
CaO	0.17	CaO	2.59
Cr_2O_3	0.19	$Cr_2O_3 \cdot 1.5H_2O$	3.28
Fe_2O_3	1.23	$Fe(OH)_3$ (15 wt% slurry)	165.44
K_2O	0.06	KNO_3	1.80
Li_2O	6.00	Li_2CO_3	224.80
MnO	1.36	MnO_2	25.03
Na_2O	8.05	Na_2CO_3	202.40
		NaOH	3.93
NiO	0.09	$Ni(OH)_2$	1.60
RuO_2	0.01	$RuNO(NO_3)_3$ (1.4 wt% slurry)	25.53
SiO_2	24.70	SiO_2	372.34
SrO	0.07	$SrCO_3$	1.44
ZrO_2	0.29	$Zr(OH)_4 \cdot 0.654H_2O$	6.11

The AlF2-05 melter feed for the HLW CLSM run was prepared on 9/20/18. The melter feed was batched according to the recipe given in Table 2.3 at a glass yield of 500 g of AlF2-05 glass per liter of melter feed slurry. Six total liters of AlF2-05 melter feed were prepared for the CLSM run.

2.3 Sample Analysis Methods

For every CLSM run, the mass of melter feed was weighed before and after the run. The masses of all product streams were weighed after the run; these included (1) the glass from each pour; (2) the total condensate; (3) the final sump from both the sampling SBS and primary SBS (the SBS sumps contained only the liquid from the final capacity of each SBS since, during operation, the SBS liquid would overflow into the condensate collector); (4) the liquid in the demister; (5) the wash of the offgas piping from the CLSM vessel to the primary SBS; (6) the wash of the offgas piping in the sampling loop; (7) the primary HEPA filters; and (8) the sampling HEPA filters. For each CLSM run, approximately 10-mL or 10-g samples (for liquid or solid streams, respectively) were taken of the melter feed and from selected product streams. Appropriate product streams were selected by the operational staff to gain insight into the operational behavior of each CLSM run. These selected samples, and whole primary/sampling HEPA filters, were sent to the Southwest Research Institute (SwRI) for cation and anion chemical analysis. The analysis methods employed by SwRI and each component scanned using each method are given in Table 2.4.

Table 2.4. Sample Chemical Analysis Method and Chemical Scanned

Analysis	Methods	Component
Cations	ICP-AES (inductively coupled plasma atomic emission spectroscopy) or ICP-MS (ICP-mass spectrometry) for Re and Ru	Ag, Al, As, Ba, Bi, B, Ca, Cd, Co, Cr, Cu, Fe, La, Li, K, Mg, Mn, Mo, Na, Ni, P, Pb, Re, Ru, Si, Sr, S, Sn, Ti, W, V, Y, Zn, and Zr
Anions	IC (ion chromatography) or ion-specific electrode	Chloride, Chromate, Fluoride, Nitrate, Nitrite, Phosphate, and Sulfate

3.0 CLSM Run Descriptions and Results

3.1 LAW Runs with AN-105 Melter Feed

3.1.1 Operation Descriptions

During each run, AN-105 melter feed was processed in the simulant CLSM in APEL. During setup of the CLSM system, approximately 2.0 kg of previously prepared AN-105 glass (acquired from the final pour of the previous run, for which the target composition is shown in Table 2.2 with a target Re composition of 8.1 ppm) were loaded into the CLSM vessel. The furnace surrounding the CLSM vessel was heated from room temperature to 1250 °C at 10 °C min^{-1}. Feeding of the AN-105 melter feed into the CLSM vessel for Run 1 began on December 13, 2018, at 10:42 a.m., Run 2 on March 28, 2019, at 10:00 a.m., and Run 3 on July 23, 2019, at 9:39 a.m.

The operation rate of the feed pump and the pressure of the feeding line at the inlet of the pump are reported for Runs 1, 2, and 3 in Figure 3.1, Figure 3.2, and Figure 3.3, respectively. The mass and time of each glass pour during feeding for Runs 1, 2, and 3 are reported in Table 3.1 along with the cumulative weight of glass accumulation. Following the termination of feeding, the cold cap burned off (all remaining melter feed in the cold cap was converted into glass) and the glass inventory was poured out of the CLSM vessel, corresponding with the final glass pour reported for each run. Other notes about the performance of each run follow.

Run 1:

- At hour 3.58, the pressure of the feeding line at the inlet of the feed pump began to slowly fall below its baseline level of ~12.0 psia, before rising rapidly and plateauing at a new value of ~14.0 psia, after which it was observed that the dripping of the melter feed on the cold cap had become variable and intermittent, indicating a blockage in the outlet section of the feed line. To mitigate this issue, the outlet side of the pump was flushed with water before the entire feeding system was switched from melter feed to water at hour 3.78.
- From hour 3.78 to 3.97, water was pumped into the CLSM vessel, causing the cold-cap coverage over the glass melt surface to decrease to ~50%. After this time, melter feed charging into the CLSM vessel returned to a steady rate and target cold-cap coverage was achieved for the remainder of the feeding time.

Run 2:

- This run was performed in two portions, the first on 3/28/2019 and the remainder on 5/7/2019.
- During the portion on 3/28/2019, at hour 3.48, the pressure of the feeding line began to slowly fall below its baseline level of ~13.1 psia before rising rapidly and plateauing at a new value of ~13.4 psia. During this time, it was observed that the dripping of the melter feed on the cold cap had stopped. To mitigate this issue, the outlet side of the pump was flushed with water.
- During the portion on 3/28/2019, from hour 3.48 to 3.96, melter feed charging into the CLSM vessel could not be fully restored and the cold cap slowly burned off. At hour 3.96, the entire feeding system was switched from melter feed to water.
- Between the two portions of the run, the spindle used to mix the melter feed was replaced with a different style design that could better sweep the bottom of the melter feed bucket and provide a steadier mixing motion to reduce the agglomeration of solid particulates in the slurry that may have

been sucked into the feeding line. Testing of the new spindle design resulted in no blockages in the feeding system.

- During the portion of the run on 5/7/2019, at hour 1.33, a slight jump in the pressure of the feeding line at the inlet of the pump from ~13.0 psia to ~13.1 psia was observed and the dripping of the feed into the CLSM vessel became intermittent. Water flushes on both the inlet and outlet sides of the feeding pump were performed, but the dripping of feed did not return to a normal condition.
- On 5/7/2019, feeding was stopped at hour 1.90 and the pump was flushed with water until hour 2.81.
- On 5/7/2019, feeding began again at hour 2.81, with dripping remaining intermittent but not completely stopping, resulting in a cold-cap coverage of ~50%. Glass slowly dripped from the CLSM vessel during the remainder of the feeding time.
- After Run 2 ended, a flexible, corrugated portion of the stainless-steel feed tubing between the outlet of the progressive cavity pump and the CLSM vessel was replaced with a hard-lined stainless-steel tube. This section of the feeding line was about 46 cm (1.5 ft) long and was believed to contribute to the feeding issues.

Run 3:

- At hour 7.37, the pressure of the feeding line at the inlet of the progressive cavity pump began to slowly fall below its baseline level of ~12.3 psia. It was observed that the level of AN-105 melter feed in the bucket had begun to dip below the inlet of the feeding line located in the bucket, resulting in the pump sucking a fraction of air into the feeding system with the melter feed.

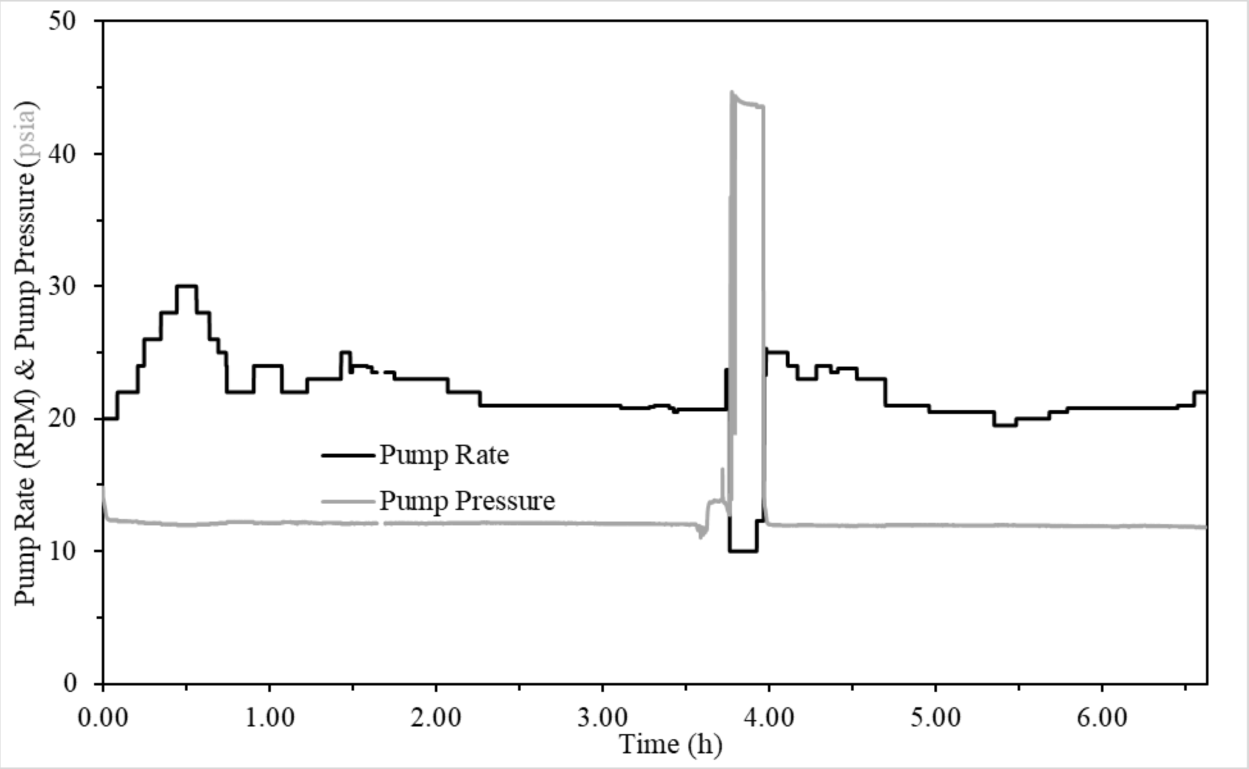

Figure 3.1. Progressive cavity pump pressure and rate during Run 1.

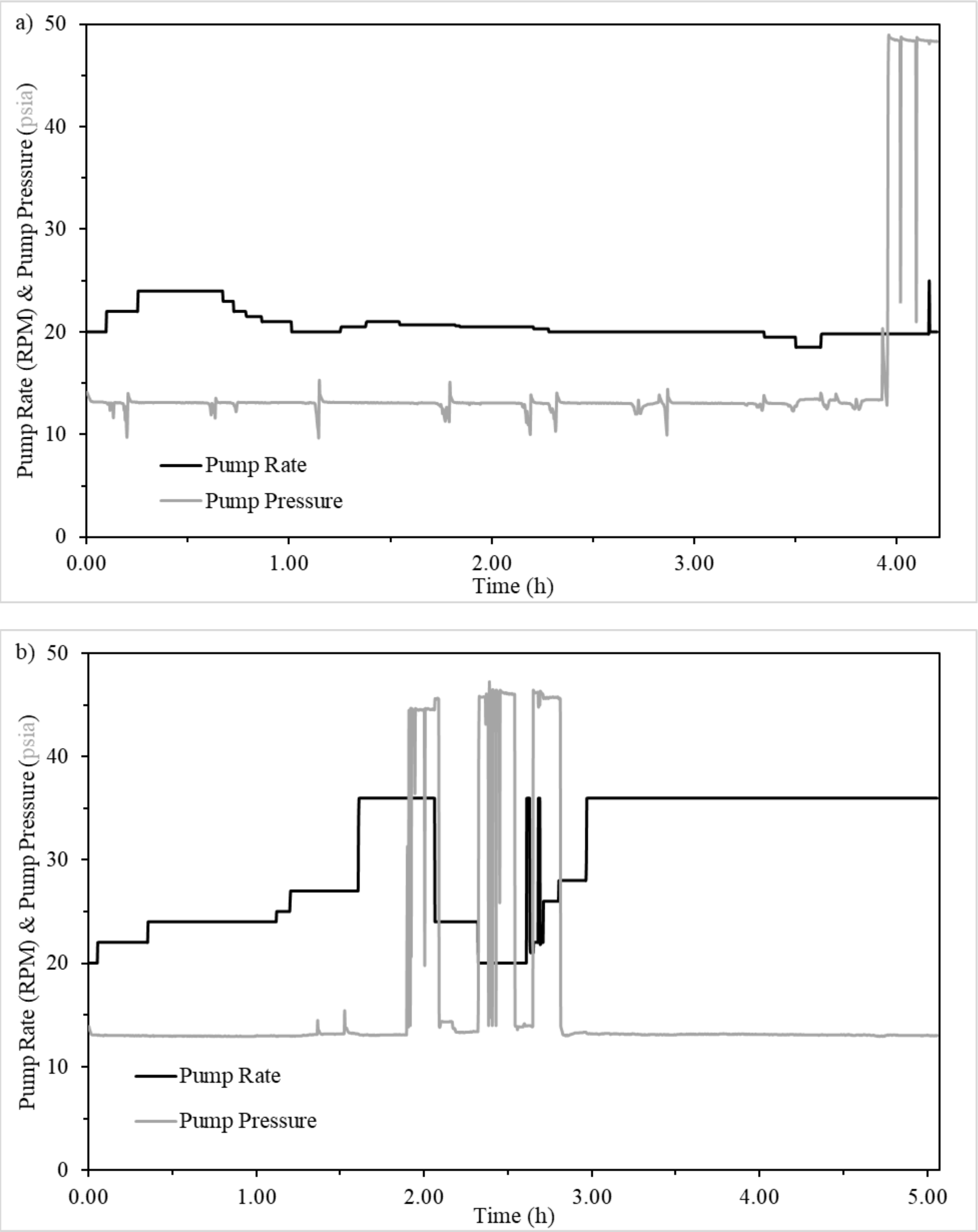

Figure 3.2. Progressive cavity pump pressure and rate for the portion of Run 2 on a) 3/28/2019 and b) 5/7/2019.

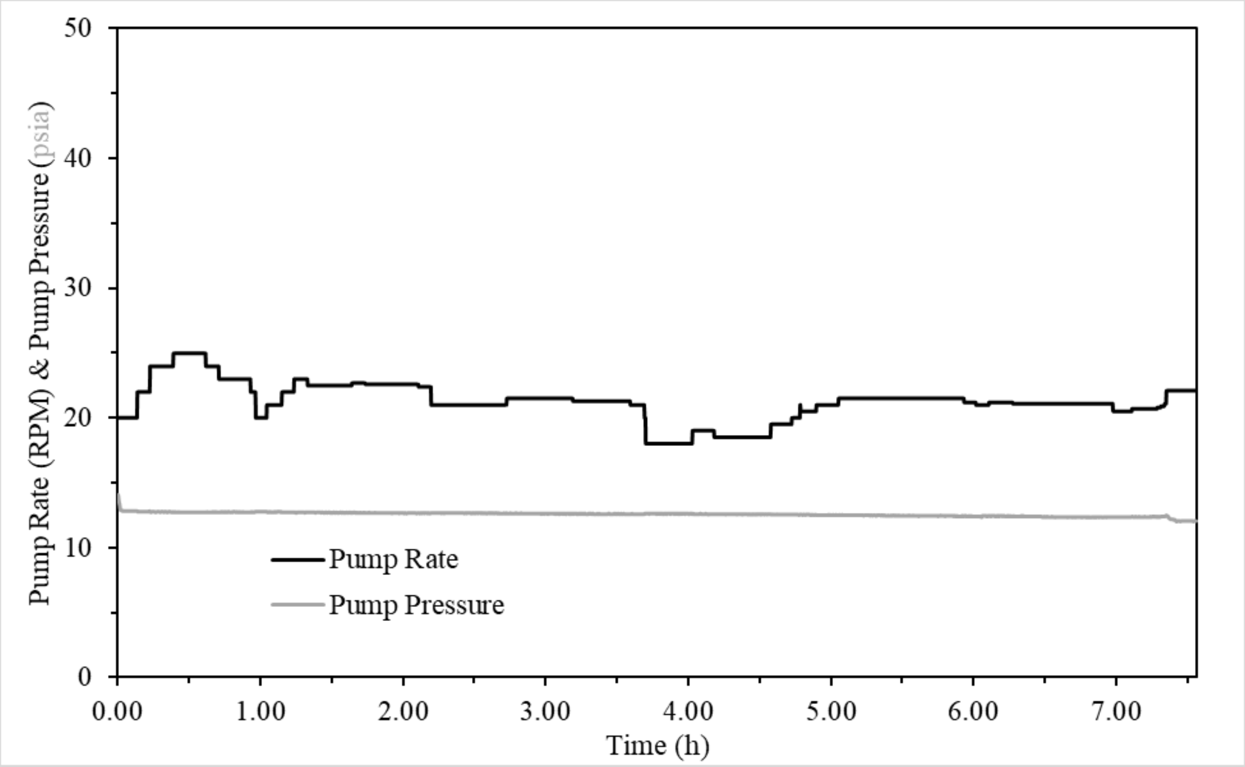

Figure 3.3. Progressive cavity pump rate and pressure during Run 3.

Table 3.1. Timing and Mass of Glass Pours During LAW Runs

Date	Pour Time (h)	Glass Weight (g)	Cumulative Weight (g)	Date	Pour Time (h)	Glass Weight (g)	Cumulative Weight (g)	Date	Pour Time (h)	Glass Weight (g)	Cumulative Weight (g)
12/13/2018	0.00	94.46	94.46	3/28/2019	0.00	43.18	43.18	7/23/2019	0.00	191.03	191.03
	0.83	394.61	489.07		1.06	169.91	213.09		0.86	331.90	522.93
	1.35	416.31	905.38		1.08	361.25	574.34		1.36	253.29	776.22
	1.88	373.45	1278.83		1.58 & 2.08	583.40	1157.74		1.38	278.37	1054.59
	2.38	455.44	1734.27		2.58	372.49	1530.23		1.87	380.83	1435.42
	3.20	621.60	2355.87		3.08	277.81	1808.04		2.37	380.29	1815.71
	4.20	521.08	2876.95		3.81	382.42	2190.46		2.87	468.75	2284.46
	4.88	435.80	3312.75		4.20	122.78	2313.24		3.49	620.35	2904.81
	5.38	347.83	3660.58		4.20	2165.34	4478.58		3.96	311.64	3216.45
	5.93	405.93	4066.51	5/7/2019	0.00	161.55	4640.13		4.31	326.38	3542.83
	6.46	368.57	4435.08		0.76	395.10	5035.23		4.64	286.71	3829.54
	6.62	2309.08	6744.16		1.29	478.98	5514.21		4.98	267.40	4096.94
					3.24	449.25	5963.46		5.31	253.26	4350.20
					4.64	397.21	6360.67		5.71	366.13	4716.33
					4.64	277.85	6638.52		6.04	278.78	4995.11
					5.06	79.04	6717.56		6.51	388.88	5383.99
					5.06	2550.89	9268.45		6.86	284.96	5668.95
									7.03	263.28	5932.23
									7.19	238.44	6170.67
									7.51	247.56	6418.23
									7.56	1968.26	8386.49

3.1.2 Production Data

Table 3.2 gives the production results from each run with AN-105 melter feed, which include the total values of the feeding time (and low flow duration within the feeding time), operational downtime, mass of glass produced, mass of melter feed consumed, and average values for the glass production rates, feeding rates, bubbling flux rates (bubbling rate in L min^{-1}, scaled by the glass surface area of the CLSM vessel), glass temperatures, and plenum temperatures. The glass and plenum temperatures were monitored by thermocouples with dual reading capabilities. The temperature data from each thermocouple was read and stored simultaneously by a calibrated measurement and testing equipment (M&TE) data logger and an FIO device.

Table 3.2. CLSM Production Results for LAW Runs

Parameter	Run 1	Run 2	Run 2	Run 3
Test Date	12/13/2018	3/28/2019	5/7/2019	7/23/2019
Feeding Duration, h	6.23	3.48	4.14	7.56
Low Flow Duration, h	0.00	0.00	2.78	0.00
Downtime, h	0.39	0.00	0.91	0.00
Glass Produced, kg	4.74	2.48	2.79	6.45
Melter Feed Consumed, kg	9.08	5.03	5.85	12.80
Average Glass Production Rate, kg m^{-2} d^{-1}	1616	1512	1430	1809
Average Feeding Rate, kg h^{-1}	1.46	1.44	1.41	1.69
Average Bubbling Flux Rate, L m^{-2} min^{-1}	110	108	33	122
Average Glass Temperature, °C	1158	1151	1147	1142
Average Plenum Temperature, °C	610	617	716	634

The following figures present the processing values recorded during melter feed charging for Run 1 (Figure 3.4), the portion of Run 2 on 3/28/2019 (Figure 3.5), the portion of Run 2 on 5/7/2019 (Figure 3.6), and Run 3 (Figure 3.7). These results include the glass and plenum temperatures, the effective glass production rate (based on the average glass production rates and the variable changes in the feeding pump rates), the bubbling flux rate, and the melter vessel vacuum measurements. Individual figures of each processing value for each AN-105 run can be found in Appendix A as well as the temperatures at the start of the offgas system, at the sampling valve, and of the primary SBS (measurement locations shown on Figure 2.1).

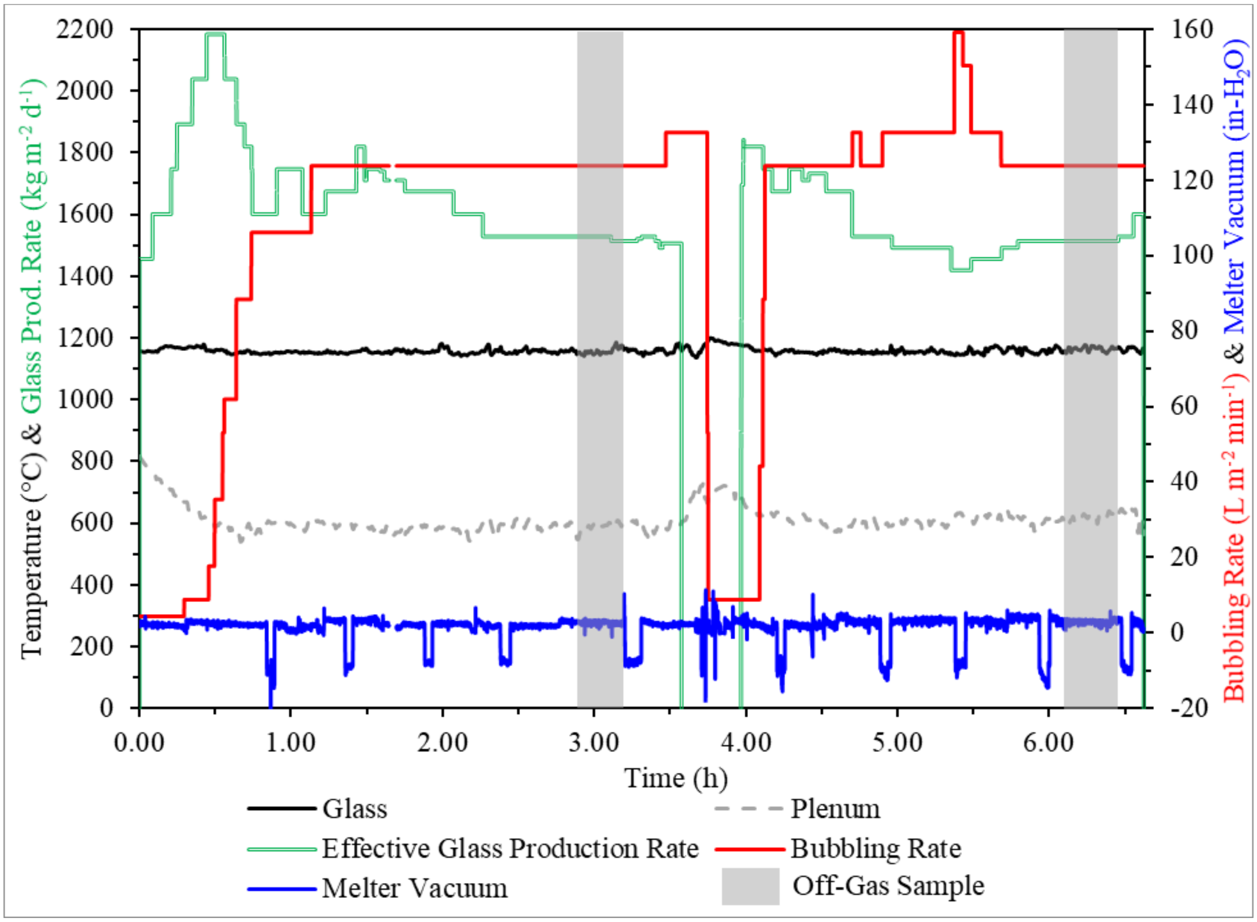

Figure 3.4. Processing values (glass and plenum temperatures, effective glass production rate, bubbling flux rate, and melter vacuum measurements) and offgas sample timing recorded during Run 1.

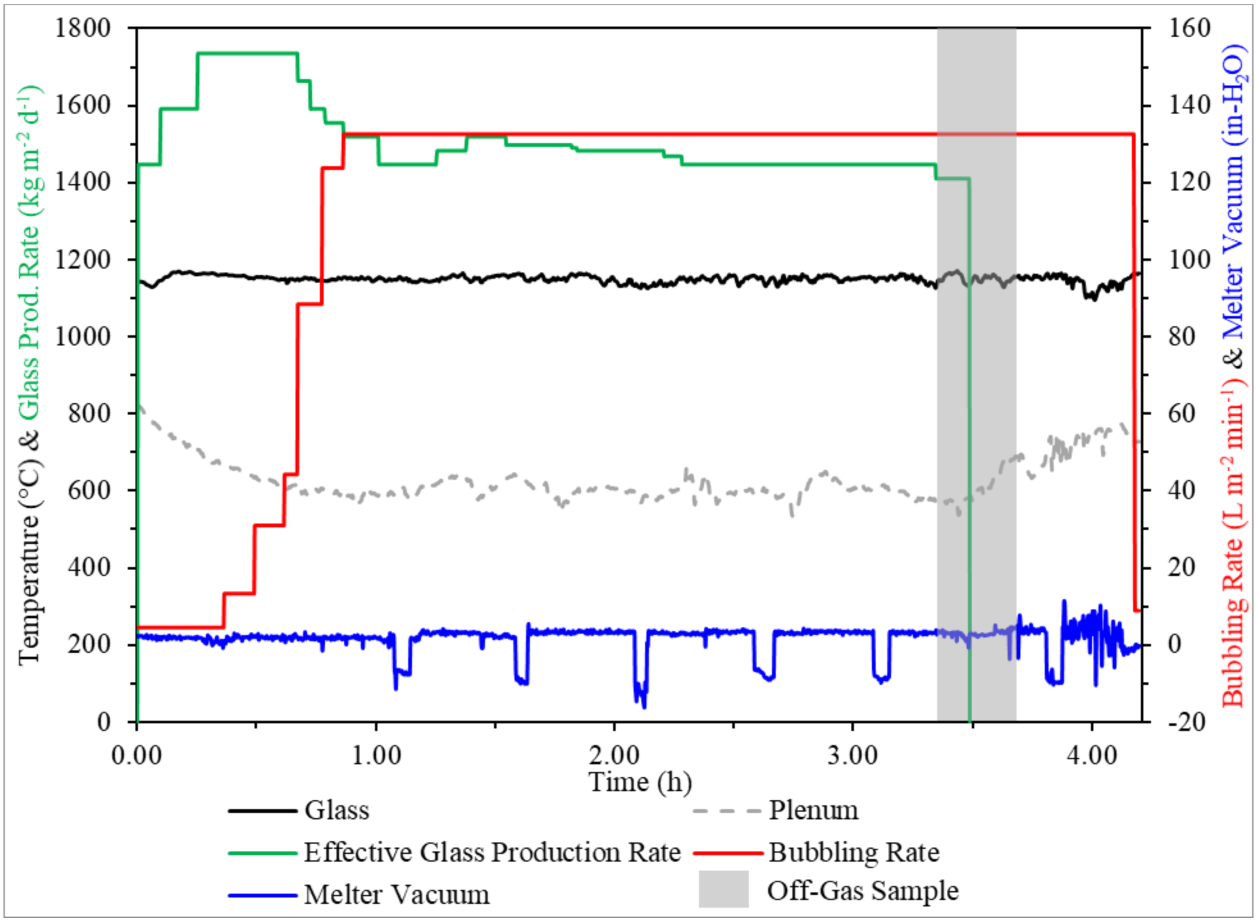

Figure 3.5. Processing values (glass and plenum temperatures, effective glass production rate, bubbling flux rate, and melter vacuum measurements) and offgas sample timing recorded during the portion of Run 2 on 3/28/2019.

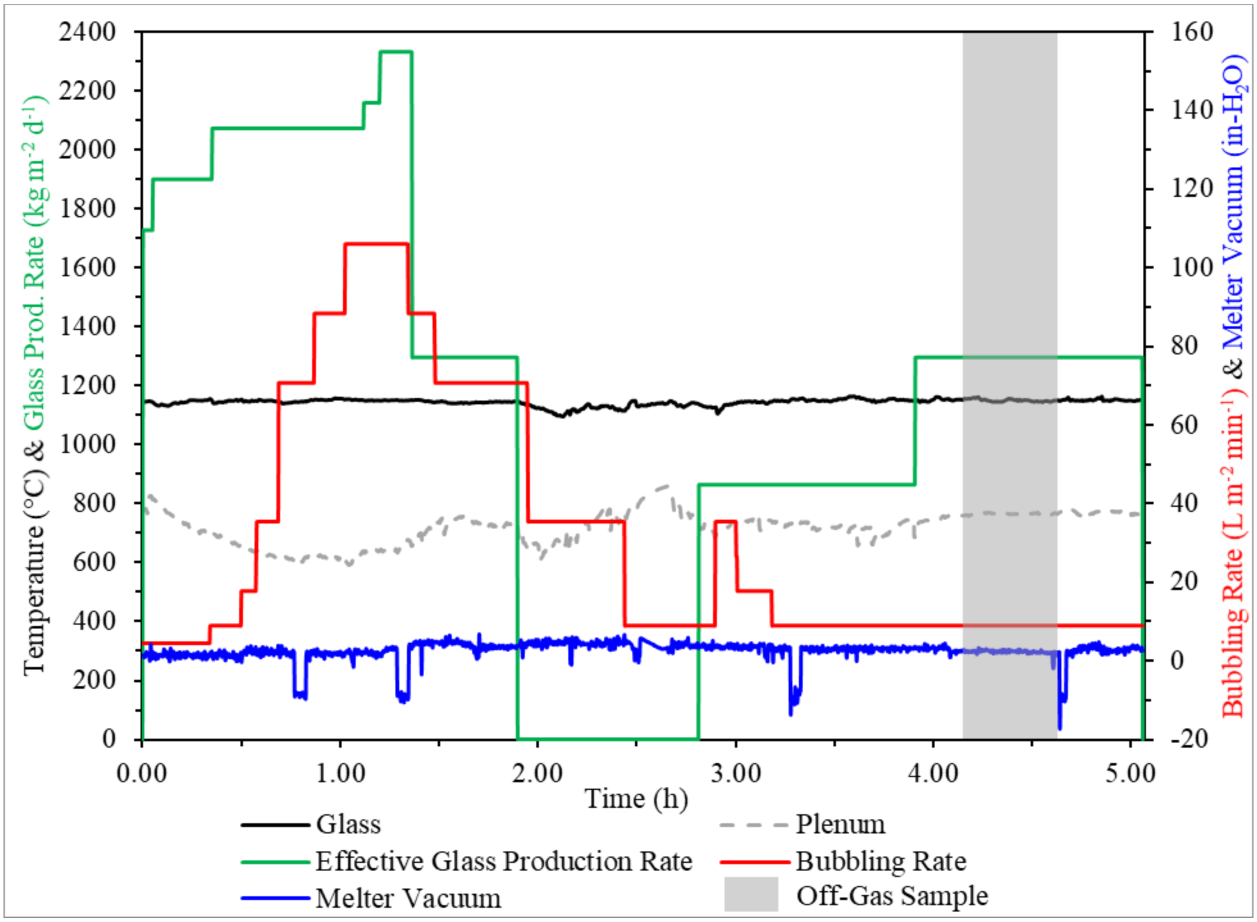

Figure 3.6. Processing values (glass and plenum temperatures, effective glass production rate, bubbling flux rate, and melter vacuum measurements) and offgas sample timing (captured while the cold cap had ~50% coverage) recorded during the portion of Run 2 on 5/7/2019.

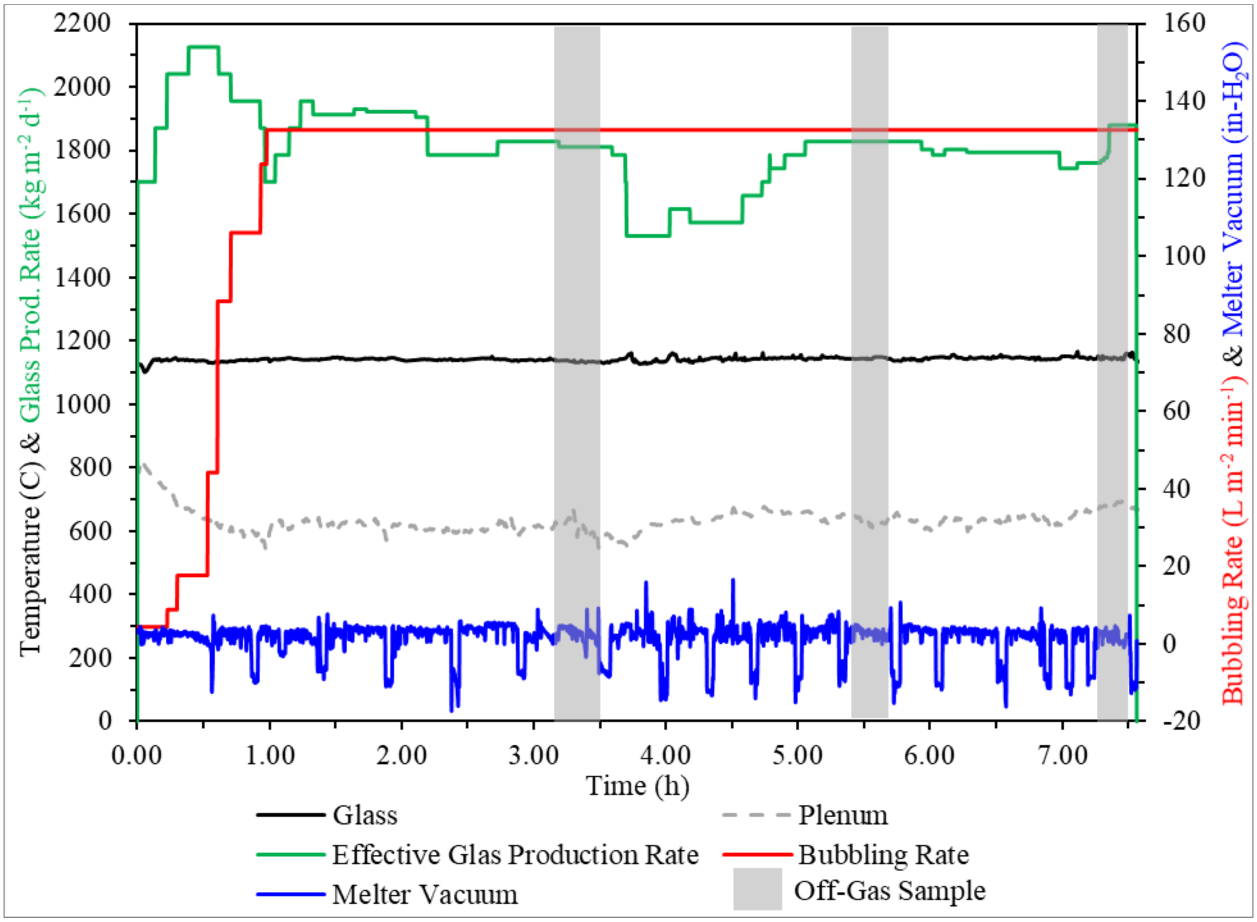

Figure 3.7. Processing values (glass and plenum temperatures, effective glass production rate, bubbling flux rate, and melter vacuum measurements) and offgas sample timing recorded during Run 3.

3.1.3 Offgas Samples

Two offgas samples were collected during Run 1 and Run 2 while three offgas samples were collected during Run 3. The timing and duration of the samplings are listed in Table 3.3. The occurrences of each offgas sample in the timeline of their respective runs are shown in relation to the processing values in Figure 3.4, Figure 3.5, Figure 3.6, and Figure 3.7. During the offgas sampling periods, the temperature at the offgas sampling valve and primary SBS, the measurement points shown in Figure 2.1 and temperature profiles in Appendix A, Figure A.13, Figure A.14, and Figure A.15, decreased while the temperature at the start of the offgas system remained at the same level. However, due to the low feeding and bubbling flux rates during the offgas sample collected during Run 2 on 5/7/2019, the temperature at the sampling valve did not decrease, as shown in Figure A.14b.

Table 3.3. Timing of Offgas Samples for LAW Runs

Run, Date	Sample Number	Offgas Sample Start on Test Run Timeline (h)	Offgas Sample End on Test Run Timeline (h)	Total Sampling Duration (min)
1, 12/13/2018	1	2.85	3.20	20.60
1, 12/13/2018	2	6.07	6.40	20.17
2, 3/28/2019	1	3.38	3.72	20.17
2, 5/7/2019	2	4.09	4.60	30.83
3, 7/23/2019	1	3.15	3.48	19.83
3, 7/23/2019	2	5.37	5.70	19.67
3, 7/23/2019	3	7.26	7.51	14.83

3.1.4 Sample Chemical Analysis

The samples selected for chemical analysis from Run 1, Run 2, and Run 3 are listed respectively in Table A.1, Table A.2, and Table A.3 in Appendix A. Since rhenium was added to the melter feed, the ICP-MS analysis was only performed for rhenium. For each run, the two condensate samples listed were separate aliquots taken from the same condensate source. Other notes about the samples sent for analysis include:

- For the collection of each offgas sample, two sampling HEPA filters were used and were thus combined and analyzed together.
- During Run 1, eight primary HEPA filters were used for the duration of the feeding time, but only three, the first, third, and seventh used, were sent for analysis. While only two offgas samples were collected during the run, upon disassembly of the offgas system, the third, unused set of sampling HEPA filters were discovered to be saturated with liquid. These filters were sent for analysis along with the two sets of sampling HEPA filters used to collect offgas samples.
- During Run 2, eight primary HEPA filters were used for the duration of the feeding time on each day of the run. Four primary HEPA filters, the second and the eighth used from the portion of the run on 3/28/2019 and the fifth and the sixth used during the portion of the run on 5/7/2019, were sent for analysis. The offgas system was not disassembled after the portion of Run 2 on 3/28/2019, so the wash samples and primary SBS liquid were the accumulation from both days of the run.
- During Run 3, seven primary HEPA filters were used for the duration of the feeding time, but only three – the first, second, and third used – were sent for analysis.

The values for the total mass of the streams from which each sample aliquot was gathered are listed in Table A.1, Table A.2, and Table A.3, along with the concentration of each analyzed cation and anion.

Where no numerical data are reported, the values were below the analysis detection limit. The effective glass production rate and plenum temperature for each run have been plotted together with the concentration of Re in each analyzed glass pour with respect to the timing of the glass pour, the overlays for each run are given in Figure A.16, Figure A.17, and Figure A.18 in Appendix A.

3.2 HLW Run with AlF2-05 Melter Feed

The AlF2-05 melter feed was processed in the simulant CLSM in APEL on September 25, 2018. The run was performed as basic research under NQAP. During setup of the CLSM system, approximately 1.8 kg of previously prepared AlF2-05 glass (target composition shown in Table 2.3) was loaded into the CLSM vessel. The furnace surrounding the CLSM vessel was heated from room temperature to 1250 °C at 10 °C min^{-1}. Feeding of the AlF2-05 melter feed into the CLSM vessel began at 10:01 a.m.

The operation rate of the feed pump and the pressure of the feeding line at the inlet of the pump are reported in Figure 3.8. The baseline pressure level at the inlet of the feed pump while pumping the AlF2-05 melter feed was ~13.5 psia, and deviations from that level indicated blockages in the feed line that were mitigated by brief flushes of water (for ~5 seconds) through the inlet section of the feeding line. The mass and time of each glass pour during feeding are reported in Table 3.4. Following the termination of feeding, the cold cap burned off and the glass inventory was poured out of the CLSM vessel, corresponding with the final glass pour in Table 3.4. Other notes about the run performance include the following:

- Hour 0.00 to 1.00 (Operational Segment 1): The frequency of feeding line blockages and flushes limited the size of the cold cap on the glass melt surface so that it fell below the desired operational range and reduced the glass production rate. At hour 0.83, it was discovered that the feed line into the melter feed bucket had been installed improperly, so the pump was briefly (0.04 hours) switched to water feeding while the line was re-installed. The average glass production rate during this operational segment is reported in Table 3.5.
- Hour 1.00 to 4.50 (Operational Segment 2): Feeding line blockages decreased and the target cold-cap coverage was achieved. System performance during this time frame was considered steady and the average glass production rate during this operational segment is reported in Table 3.5.
- Hour 4.50 to 5.38 (Operational Segment 3): The frequency of feeding line inlet blockages increased and then, at hour 5.12, a blockage in the outlet section of the feeding line caused the drip of feed on the cold cap to become intermittent. After an attempt to flush the outlet section of the feeding line failed to alleviate this blockage, feeding was terminated. During this time, cold-cap coverage fell below the desired operational range; the average glass production rate during this operational segment is reported in Table 3.5.

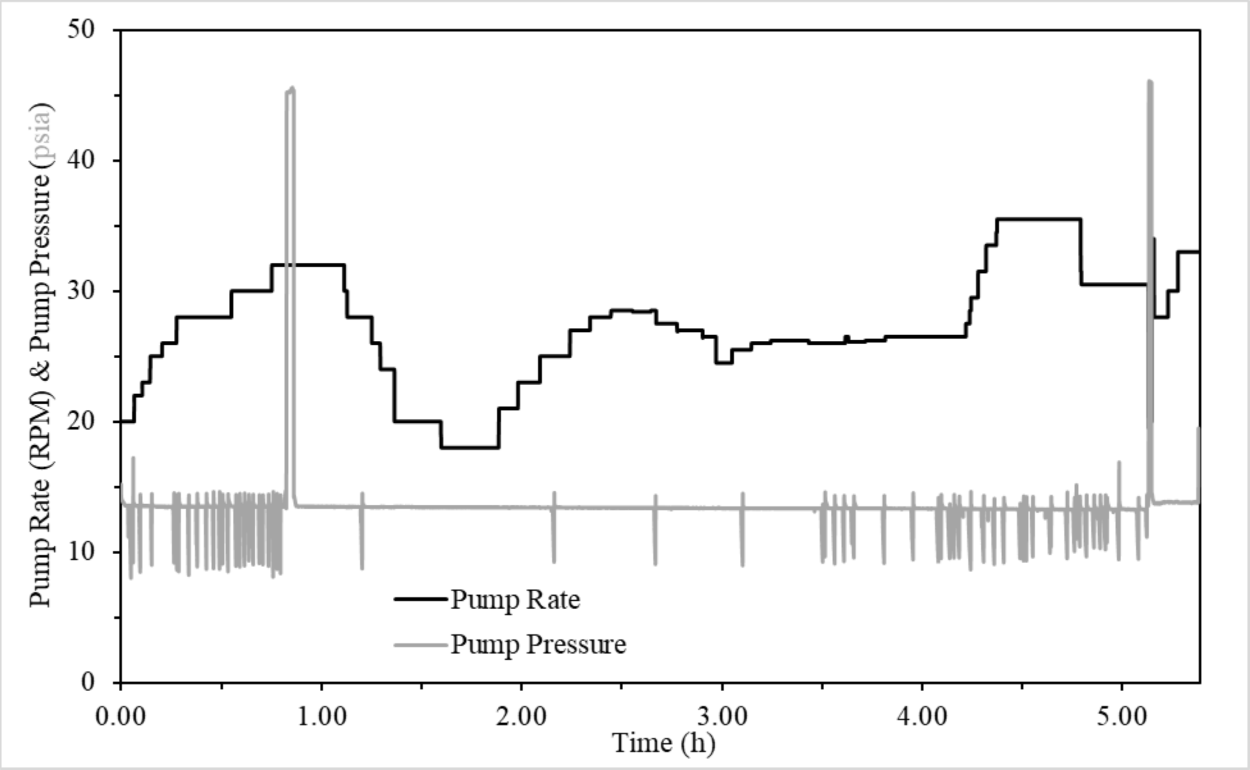

Figure 3.8. Progressive cavity pump rate and pressure during the AlF2-05 run.

Table 3.4. Timing and Mass of Glass Pours During the AlF2-05 Run

Pour Time (h)	Glass Weight (g)	Cumulative Weight (g)
1.00	192.20	192.20
1.50	241.13	433.33
2.00	321.20	754.53
2.47	171.41	925.94
2.97	192.86	1118.80
3.51	283.51	1402.31
4.01	279.44	1681.75
4.51	231.97	1913.72
5.01	216.51	2130.23
5.38	1879.15	4009.38

Table 3.5. Average Glass Production Rates During the Three Operational Segments of the AlF2-05 Run

Operational Segment	Glass Produced (g)	Time of Operational Segment (h)	Average Glass Production Rate (kg m^{-2} d^{-1})
1	192	1.00	408
2	1722	3.50	1043
3	296	0.87	718

The production results from the entire AlF2-05 melter feed run are given in Table 3.6 and the processing values recorded during melter feed charging are displayed in Figure 3.9. The parameters listed are the same as those given for the LAW runs in Section 3.1.2. Individual figures of each processing value can be found in Appendix B as well as the temperatures at the start of the offgas system, at the sampling valve, and of the primary SBS.

Table 3.6. CLSM Production Results for the AlF2-05 Run

Parameter	AlF2-05 Run
Test Date	9/25/2018
Feeding Duration, h	5.38
Low Flow Duration, h	1.87
Downtime, h	0.00
Glass Produced, kg	2.21
Melter Feed Consumed, kg	6.85
Average Steady Glass Production Rate, kg m^{-2} d^{-1}	1043
Average Overall Glass Production Rate, kg m^{-2} d^{-1}	872
Average Feeding Rate, kg h^{-1}	1.27
Average Bubbling Flux Rate, L m^{-2} min^{-1}	129
Average Glass Temperature, °C	1149
Average Plenum Temperature, °C	647

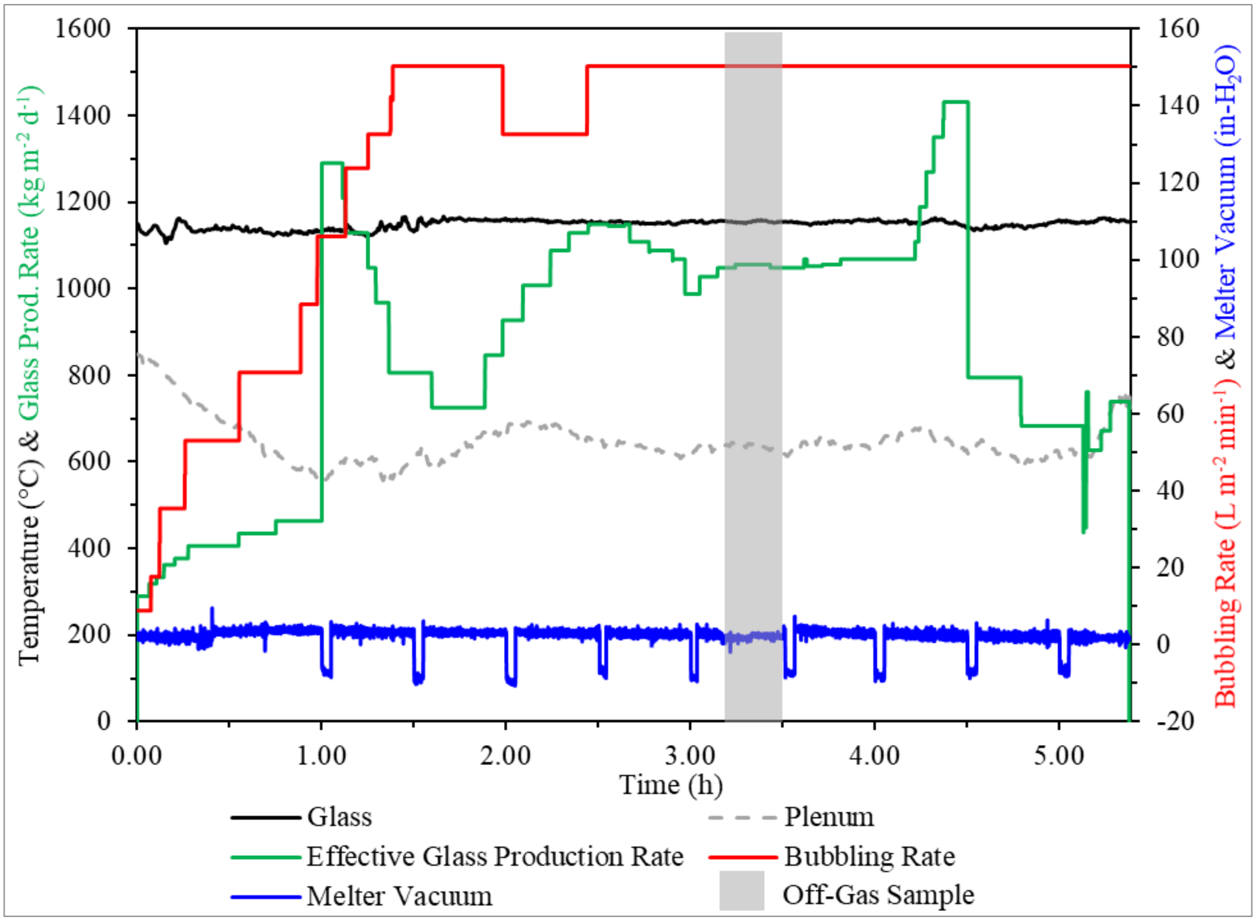

Figure 3.9. Processing values (glass and plenum temperatures, effective glass production rates, bubbling flux rates, and melter vacuum measurements) and offgas sample timing recorded during the AlF2-05 run.

One offgas sample was collected during the second operational segment. The timing and duration of the sampling is listed in Table 3.7 and its occurrence in the timeline of the run is shown in relation to the processing values in Figure 3.9.

Table 3.7. Timing of Offgas Sample for the AlF2-05 Run

Offgas Sample Start on Test Run Timeline (h)	Offgas Sample End on Test Run Timeline (h)	Total Sampling Duration (min)
3.17	3.51	20.10

The samples selected for chemical analysis are shown in Table B.1 in Appendix B. The two condensate samples listed were separate aliquots taken from the same condensate source of the combined condensate liquids collected during the full run. The two primary HEPA filters sent for analysis were used during the first ~1 hour of feeding operations, after which primary HEPA filter units were bypassed for the remainder of the run. The two sampling HEPA filters used during the one offgas sample were combined and analyzed together. The values for the total mass of the streams from which each sample aliquot was gathered are listed in Table B.1, along with the concentration of each analyzed cation and anion. Where no numerical data are reported, the values were below the analysis detection limit. The effective glass production rate and plenum temperature for the run has been plotted together with the concentration of Ru in each analyzed glass pours with respect to the timing of the glass pour, the overlay for which is given in Figure B.6 in Appendix B.

4.0 Discussion

4.1 Component Decontamination Factor, Retention, and Recovery

The decontamination factor (DF) of any component through any unit in a melter system is described as the mass flow rate of the component into the unit divided by the mass flow rate of the component out of the unit in the secondary product stream. In the CLSM system, there is one incoming mass flow stream, the melter feed, and there are two output mass flow streams, the glass produced from the CLSM and offgas exiting the CLSM. The CLSM offgas is composed of gaseous mass exiting the system, vapor that is condensed by the offgas system as condensate, and solids that settle or are filtered. Thus, the DF of any component through the CLSM vessel is defined as the mass flow rate of that component in the melter feed divided by the mass flow rate of that component in the offgas. Given a state of no component accumulation in the CLSM vessel, the mass flow rate in the offgas is equal to the mass flow rate in the melter feed minus the mass flow rate in the glass, meaning the DF for a component in the CLSM vessel can be given by Eq. (4.1):

$$\mathrm{DF}_i = \frac{\dot{m}_{i,feed}}{\dot{m}_{i,feed} - \dot{m}_{i,glass}} \tag{4.1}$$

where $\dot{m}_{i,feed}$ is the mass flow rate [mg min^{-1}] of a component (i) in the melter feed and $\dot{m}_{i,glass}$ is the mass flow rate [mg min^{-1}] of the same component in the glass product.

The retention (R) of any component in the glass produced from the CLSM vessel is then defined as the mass flow rate of that component in the glass product divided by the mass flow rate of the same component in the melter feed, and this value can be determined by Eq. (4.2):

$$R_i = \frac{\dot{m}_{i,glass}}{\dot{m}_{i,feed}} \tag{4.2}$$

The R_i value can be reported as a fraction or percentage.

Finally, the recovery (Rec) of any component in the CLSM system is defined as the mass flow rate of the component out of the system – the summation of the glass and offgas – divided by the mass flow rate of the same component into the system via the melter feed. The Rec_i value can be reported as a fraction or percentage and is defined in Eq. (4.3):

$$\mathrm{Rec}_i = \frac{\dot{m}_{i,glass} + \dot{m}_{i,offgas}}{\dot{m}_{i,feed}} \tag{4.3}$$

where $\dot{m}_{i,offgas}$ is the mass flow rate [mg min^{-1}] of a component (i) in the offgas as recovered by the units in the CLSM offgas system. For Eq. (4.1), Eq. (4.2), and Eq. (4.3), if the values are calculated for a fixed amount of time (e.g., the offgas sampling times or the total runtime) mass flow rates become total mass values (m_i; [mg]).

One component of interest in the CLSM glass product, in addition to the components in the target glass compositions, is the ^{99}Tc surrogate, Re in the LAW feed. Given the demonstrated volatility behavior of meta-stable technetium, ^{99m}Tc, from an idling glass melt (Matlack et al. 2010b; Pegg 2015) and the potential unsteady incorporation of components into the glass melt while the cold cap varies from its target coverage and thickness, the R_{Re} values were calculated both during the total runtime and during the offgas sampling time frames when the cold-cap characteristics were believed to be steady.

4.2 Glass Composition

4.2.1 Primary Glass Components

Table 4.1 compares the average glass composition (determined by converting the analyzed component concentrations in each glass sample listed in Table A.1, Table A.2, and Table A.3 in Appendix A to their associated oxides and averaging based on the mass of glass poured with each composition) from each LAW run with the target AN-105 glass composition shown in Table 2.2. The analytical method used to detect the halide (Cl and F) concentrations in the glass samples was insufficient to register concentrations above the detection limits, so their values were estimated based on a retention in the glass of 75% of the amount in the melter feed, as has been calculated for other small-scale melter systems (Matlack et al. 2010b). The percent difference between the component oxides in the glass composition from each run and those component oxides in the target glass composition are reported for all the primary glass components, those greater than 1.00 wt%.

Table 4.1. Comparison of AN-105 Glass Product from the LAW Runs with the Target Glass Composition

Component	Target AN-105 Composition (wt%)	LAW Run 1 Average AN-105 Composition (wt%)	Run 1 % Difference (%)	LAW Run 2 Average AN-105 Composition (wt%)	Run 2 % Difference (%)	LAW Run 3 Average AN-105 Composition (wt%)	Run 3 % Difference (%)
Al_2O_3	5.97	5.87	-1.7	5.88	-1.5	5.93	-0.7
B_2O_3	9.79	9.17	-6.3	9.56	-2.3	10.01	2.2
CaO	2.46	2.27	-7.7	2.26	-8.1	2.29	-6.9
Cl	0.20	0.15	--	0.15	--	0.15	--
Cr_2O_3	0.08	0.12	--	0.12	--	0.12	--
F	0.08	0.04	--	0.03	--	0.05	--
Fe_2O_3	5.38	5.69	5.8	5.46	1.5	5.39	0.2
K_2O	0.54	0.46	--	0.46	--	0.47	--
MgO	1.45	1.25	-13.8	1.17	-19.3	1.24	-14.5
Na_2O	21.27	20.30	-4.6	20.54	-3.4	20.38	-4.2
NiO	0.01	0.03	--	0.04	--	0.03	--
P_2O_5	0.12	0.15	--	0.14	--	0.04	--
PbO	0.01	0.01	--	0.01	--	0.01	--
SO_3	0.41	0.42	--	0.45	--	0.42	--
SiO_2	44.50	46.39	4.2	46.18	3.8	45.70	2.7
TiO_2	1.37	1.37	0.0	1.38	0.7	1.40	2.2
ZnO	3.43	3.56	3.8	3.47	1.2	3.67	7.0
ZrO_2	2.94	2.74	-6.8	2.71	-7.8	2.73	-7.1
Sum	100.01	99.99		100.01		100.03	

Values marked with '--' were not calculated because the component target concentrations were <1%.

Likewise, Table 4.2 compares the average glass composition (component concentrations in each glass sample listed in Table B.1 in Appendix B) from the AlF2-05 run with the target glass composition shown in Table 2.3 and reports the percent difference for all primary glass components. A different high-alumina, HLW simulant composition, called HWI-Al-19 (Matlack et al. 2010a), which is similar to AlF2-05 in terms of the content of the major glass-forming components, such as Al_2O_3, B_2O_3, and SiO_2, is also shown in Table 4.2.

Table 4.2. Comparison of AlF2-05 Glass Product from the AlF2-05 Run with the Target Glass Composition and the HWI-Al-19 Glass Composition

Component	Target AlF2-05 Composition (wt%)	Average AlF2-05 Composition (wt%)	% Difference (%)	Target HWI-Al-19 Composition (wt%)
Al_2O_3	34.00	34.24	0.7	23.97
B_2O_3	23.46	22.63	-3.5	19.19
BaO	--[a]	-- [a]	-- [b]	0.05
Bi_2O_3	0.34	0.34	-- [b]	1.14
CaO	0.17	0.19	-- [b]	5.58
CdO	-- [a]	-- [a]	-- [b]	0.02
Cr_2O_3	0.19	0.15	-- [b]	0.52
F	-- [a]	-- [a]	-- [b]	0.67
Fe_2O_3	1.23	1.16	-5.7	5.90
K_2O	0.06	0.07	-- [b]	0.14
Li_2O	6.00	6.15	2.5	3.57
MnO	1.36	1.33	-2.2	-- [c]
MgO	-- [a]	-- [a]	-- [b]	0.12
Na_2O	8.05	7.96	-1.1	9.58
NiO	0.09	0.08	-- [b]	0.40
P_2O_5	-- [a]	-- [a]	-- [b]	1.05
PbO	-- [a]	-- [a]	-- [b]	0.41
RuO_2	0.01	0.02	-- [b]	-- [c]
SO_3	-- [a]	-- [a]	-- [b]	0.20
SiO_2	24.70	25.38	2.8	27.00
SrO	0.07	0.07	-- [b]	-- [c]
TiO_2	-- [a]	-- [a]	-- [b]	0.01
ZnO	-- [a]	-- [a]	-- [b]	0.08
ZrO_2	0.29	0.24	-- [b]	0.39
Sum	100.02	100.01		99.99

(a) Components were not included in the ALF2-05 composition.
(b) Not calculated because the component target concentrations were <1%.
(c) Components were not included in the HWI-Al-19 composition.

Compositional trends for each component oxide in the analyzed glass product from the LAW runs, labeled as "Measured", with respect to the amount of glass discharged – the cumulative total from LAW Runs 1 through 3 in respective order – are shown in Figure C.1 through Figure C.18 in Appendix C. Each figure displays the AN-105 glass target composition for the particular component oxide, labeled as "Glass Target", with a gray block illustrating a ± 10% window around the target composition and the actual composition for the component oxide expected based on the analyzed feed sample from each LAW run, labeled as "Feed Actual". Similarly, the compositional trends for each component oxide in the analyzed glass product from the AlF2-05 run with respect to the amount of glass discharged are shown in Figure C.19 through Figure C.33, with the AlF2-05 glass target composition and actual composition expected based on the analyzed feed sample marked and labeled on each figure.

Of the primary glass components, only MgO, shown in Figure C.9, deviated from the AN-105 glass target by greater than 10%. The source of magnesium in the melter feed was the mineral olivine, which has been shown to settle in melter feed (Matlack et al. 2010b) and may have led to a disproportionate sample having been taken. In addition, the chemical purity of the olivine was ~10% less than initially estimated when batching the melter feed, which also may have contributed to the MgO composition in the glass product being lower than the AN-105 glass target.

Prior to the AlF2-05 run, AP-107 melter feed and glass, with a target Fe_2O_3 content of 5.52 wt% (Dixon et al. 2018), were processed in the CLSM. Although the AP-107 glass inventory was poured out of the CLSM vessel before the AlF2-05 run, a small amount of AP-107 glass remained on the vessel walls. The target Fe_2O_3 content in the AlF2-05 glass was 1.23 wt%, and as a result the Fe_2O_3 content in the first glass pour from the AlF2-05 run was ~0.2 wt% above its target iron value, outside of the desired 10% window as shown in Figure C.25 in Appendix C. After ~1.0 kg of glass had been poured, the Fe_2O_3 content had fallen within the 10% window of the target, and after ~1.5 kg of glass had been poured, the Fe_2O_3 content reached the target value. LAW Run 1 was performed after the AlF2-05 run and the glass inventory had been poured from the CLSM vessel. The Al_2O_3 content was over 5 times greater in the AlF2-05 compared to the AN-105 glass, and similarly the first AN-105 glass pour was ~0.7 wt% above its target alumina value while subsequent pours were within the desired target window, as shown in Figure C.4. For primary glass components, if the previous glass processed in the CLSM was at least 5 times greater in the component content, the increased concentration was eliminated and reached a steady state within one turnover of the glass inventory in the CLSM vessel.

The composition of all other primary glass components held relatively constant over the course of the LAW runs and the AlF2-05 run, fluctuating within the 10% glass target window based on minimal variation in the melter feed composition.

The primary purpose of the AlF2-05 run was to determine if the melter feed based on the AlF2-05 glass formulation could be vitrified in the CLSM and if the Al_2O_3 would remain in the glass product and not volatilize into the offgas product given the experimentally high target composition. To this end, the Al_2O_3 composition in the glass product held constant with every glass pour and was on average within 1% of the target composition, confirming within compositional experimental error the successful accomplishment of the goals for the AlF2-05 run. The HWI-Al-19 glass composition that was vitrified in the DM10 melter represented a potential high-alumina HLW glass formulation created from a Hanford HLW. However, mission planning models suggested that glasses with as high as 30 wt% alumina may be achievable (Marra 2009), and the successful processing of the AlF2-05 melter feed in the CLSM demonstrated that the vitrification of such glass formulations were achievable.

4.2.2 Minor Glass Components

The measured Cr_2O_3 and NiO content in the LAW (AN-105) and HLW (AlF2-05) glass product, as well as their glass target values, are shown in Figure 4.1. A spike in the Cr_2O_3 and NiO content was observed at the start of each run followed by a decrease with each subsequent glass pour. These trends indicated that when the initial glass inventory was idling in the CLSM vessel, during heat-up of the system, Cr and Ni from the walls of the CLSM vessel were incorporated into the glass melt due to corrosion of the vessel. The CLSM vessel is constructed from Inconel-690,[1] an alloy with a relative composition of a minimum of 58.0% Ni, a range of Cr content from 27.0% to 31.0%, and the balance provided by several additional components (Fe range from 7.0% to 11.0%, Si at 0.50% maximum, Mn at 0.50% maximum, S at 0.015% maximum, and Cu at 0.50% maximum). A similar phenomenon has been observed in the DM10 melter, which is lined with refractory at high Cr levels and heated by electrodes that have high Ni levels, after idling periods (Matlack et al. 2010b, 2011, 2016, 2017).

During the LAW runs, the Cr_2O_3 and NiO content in the glass was greater than both the target value and the actual value based on the melter feed analysis, seen in Figure C.15 and Figure C.16 in Appendix C, respectively. For the AlF2-05 composition, the desired glass target value for Cr_2O_3 was greater than 2 times and NiO was greater than 8 times the target values in the AN-105 composition, seen in Figure 4.1. As such, while the Cr_2O_3 and NiO content hadn’t decreased from their initial levels to reach their target

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[1] American Special Metals, Corp., Miami, Florida.

values during the LAW runs after up to 3+ turnovers of the glass inventory, both components had reached their targets within half of a turnover during the AlF2-05 run. Although Cr_2O_3 and NiO can be leached from the CLSM vessel during idling periods, the components can approach their target values at different rates depending on the magnitude of the target values.

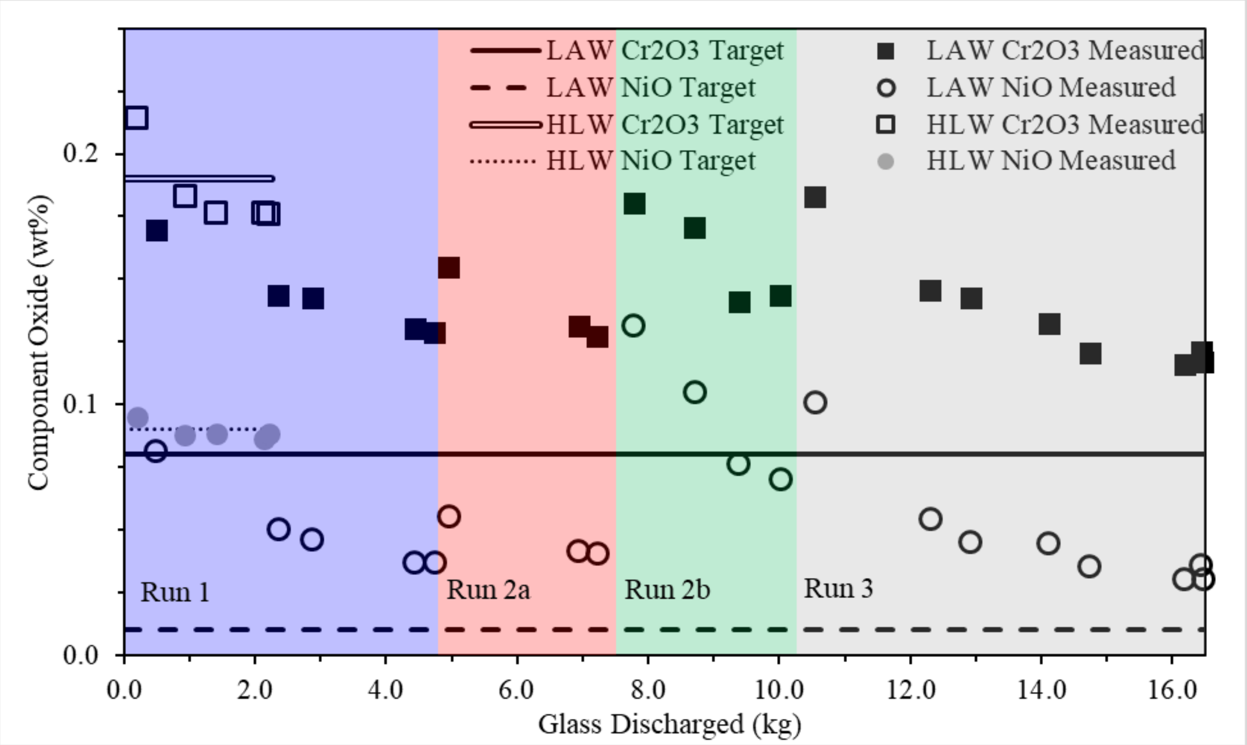

Figure 4.1. Cr_2O_3 and NiO content in the LAW runs and AlF2-05 run glass products. The glass discharged from each LAW run (Run 2a corresponds with the portion of LAW Run 2 on 3/28/2019 and Run 2b corresponds with the portion of LAW Run 2 on 5/7/2019) are marked with separate colored windows.

Several of the minor glass components present in the AN-105 composition (K_2O, Figure C.11; P_2O_5, Figure C.14; and PbO, Figure C.19; all located in Appendix C) and AlF2-05 composition (RuO_2, Figure C.33) varied by greater than 10% from their glass target value due to fluctuations in the melter feed batch preparations. The halides, Cl and F, content in the AN-105 glass composition for each LAW run was estimated based on their measured values in the melter feed, as described in Section 4.2.1.

As seen with the primary glass components, a few of the minor glass components were spiked above their target values due to glass residue from the previous CLSM remaining on the walls of the CLSM vessel. The CaO and ZrO_2 content in the glass composition processed prior to the AlF2-05 run were about 20 and 10 times greater, respectively, than in the AlF2-05 glass. As a result, both components were outside of the 10% glass target window during the first glass pour, while the ZrO_2 reached the window after ~1.0 kg of glass had been poured, see Figure C.27, and the CaO reached 10% of the measured value in the melter feed, which was outside of the glass target window, after ~1.5 kg of glass had been poured, see Figure C.29.

Minor glass components may potentially be present in the CLSM glass product outside of their 10% glass target window due to leaching of the component from the CLSM vessel (Cr_2O_2 and NiO), a spike from the trace remains of a prior glass composition, or melter feed batch fluctuations.

4.2.3 Minor Impurity Components

Several components were present as minor (1500 ppm or less) impurities in the initial AN-105 glass at the start of LAW Run 1. These components were observed to fall into two subsets of behavior in the glass: (1) components spiked at a maximum level initially that decreased with each subsequent glass pour and (2) components that remained at relatively consistent levels in each glass pour. The measured concentration of each component in the glass product with respect to the mass of glass discharged, and their measured concentrations in the melter feed (if above the analytical detection limit) marked by the inset line, are shown for subset 1 in Figure 4.2 and for subset 2 in Figure 4.3.

Of the components in subset 1, Bi, Li, Mn, and Sr were known to be present in the AlF2-05 glass, run prior to the LAW runs, so the source of the initial spike is expected to be the result of the traces of AlF2-05 glass remaining in the CLSM vessel, as observed for several of the primary glass components, discussed in Section 4.2.1. The additional components in subset 1, Ba, Cd, La, and Mo, were assumed to result from the glass batching process. The concentrations of all subset 1 components fell from their initials level to within 10% of their expected glass values (based on their concentrations in the melter feed) once 5 to 7 kg of glass had been poured. This indicates that it takes three turnovers of the CLSM glass inventory for minor impurities to reach a chemical steady state.

Of the components in subset 2, Co, Cu, and W were present in the glass at concentrations expected based on their concentrations in the melter feed. The additional components in subset 2, Sn, V, and Y, remained at consistent concentrations greater than those expected based on their concentrations in the melter feed. This result indicates that there is a baseline level of environmental impurity (e.g., from the metal used to construct the CLSM vessel) for these components that doesn’t change as glass is poured from the CLSM vessel.

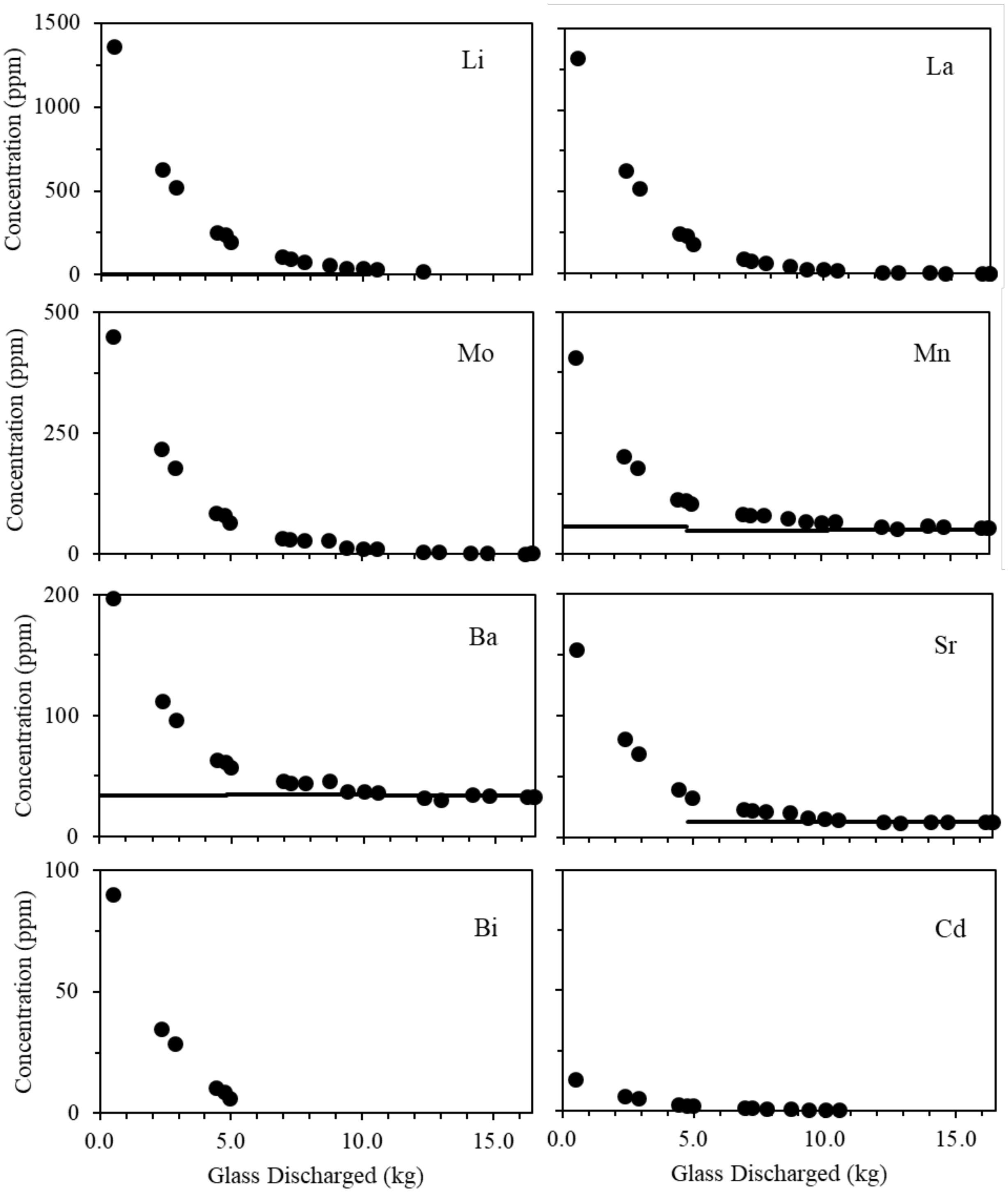

Figure 4.2. Minor components in the glass produced during the LAW runs which were eliminated from the CLSM glass inventory after approximately three turnovers. Baseline levels for each component in the analyzed melter feed are marked with a line.

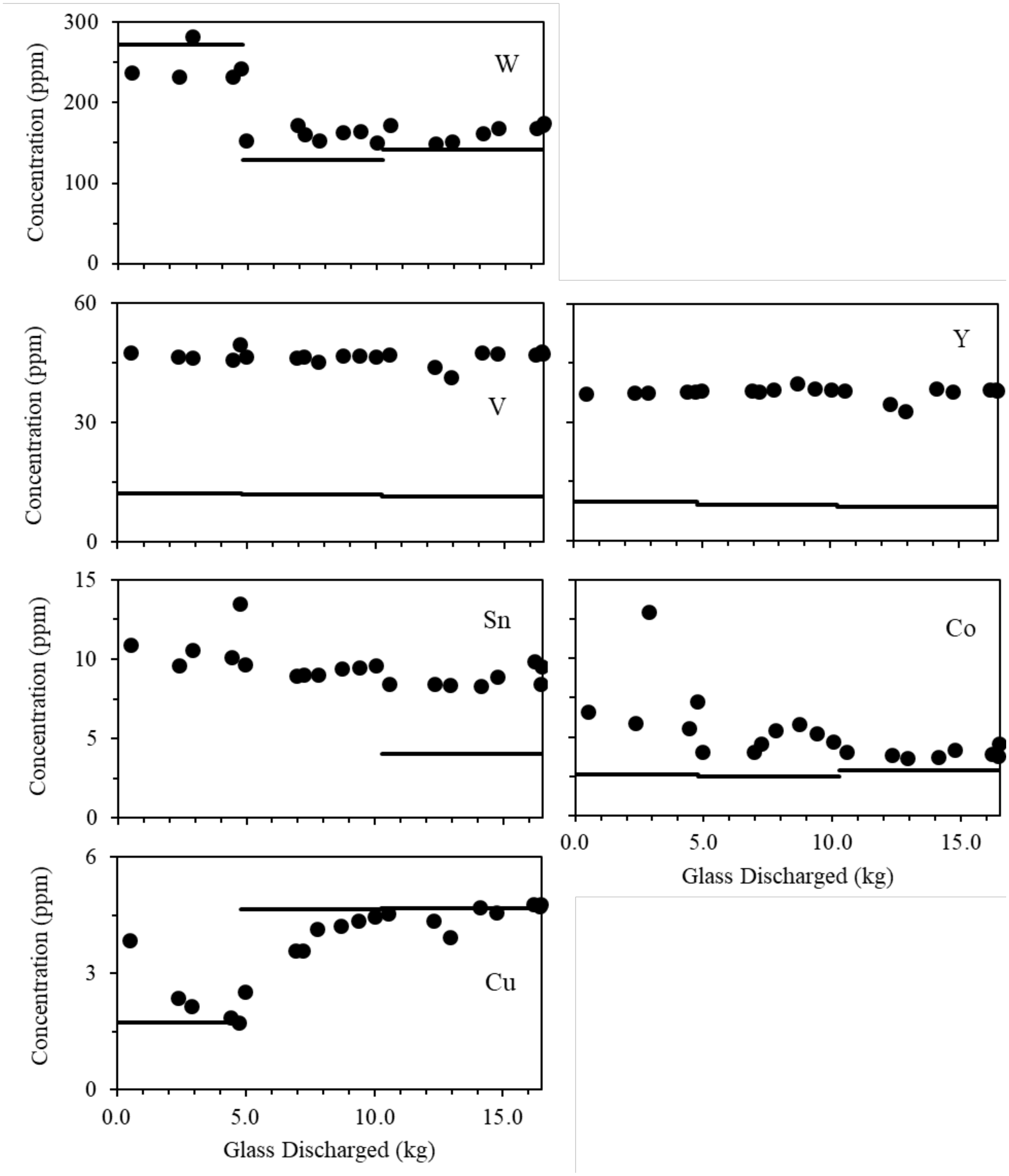

Figure 4.3. Minor components in the glass produced during the LAW runs, which remained at consistent levels based on the baseline from the analyzed melter feed (marked with a line).

4.3 DF, *R*, and Rec Calculations

For each component of the target glass composition captured in the CLSM glass product (Table 4.1 and Table 4.2), and the additive Re where applicable, the following mass flow rates were calculated:

- Input into the CLSM vessel from the melter feed; $\dot{m}_{i,feed}$. Calculated during each run by dividing the total mass of each component (given the melter feed component concentrations listed in Table A.1, Table A.2, and Table A.3 in Appendix A, and Table B.1 in Appendix B and the total mass fed of 9.08 kg for LAW Run 1, 10.88 kg for LAW Run 2, 12.80 kg for LAW Run 3, and 6.85 kg for the AlF2-05 run) by the total runtime (6.23 h for LAW Run 1, 7.62 h for LAW Run 2, 7.56 h for LAW Run 3, and 5.38 h for the AlF2-05 run).
- Output from the CLSM vessel in the glass product; $\dot{m}_{i,glass}$. Calculated from the glass component concentrations and the total glass produced masses of 4.74 kg for LAW Run 1, 5.27 kg for LAW Run 2, 6.45 kg for LAW Run 3, and 2.21 kg for the AlF2-05 run with the amount of each component present in the initial glass subtracted from the total mass.
- Output from the CLSM vessel in the captured offgas; $\dot{m}_{i,offgas}$. Calculated from the summation from all the offgas units, primarily the collected condensate of 3.38 kg during LAW Run 1, 6.62 kg during LAW Run 2, 4.93 kg during LAW Run 3, and 5.24 kg during the AlF2-05 run, and the HEPA filters, with the amount of every component in the appropriate number of blank HEPA filters subtracted from the total mass.

The mass flow rate data for the entire runtimes of LAW Run 1, LAW Run 2, LAW Run 3, and the AlF2-05 run are given in Table D.1, Table D.2, Table D.3, and Table D.4 in Appendix D, respectively, denoted in the “Sample Duration” row as “Run”. In addition, the mass flow tables contain the components mass flow rates calculated exclusively during each offgas sample time period, denoted in the “Sample Duration” row as 1, 2, or 3 as related to the sample number, while the summation of each components mass flow rates listed as the “Total”.

The total mass flow rate in the glass during the sampling time periods compared with the total mass flow rate in the glass during the total runtime can indicate the difference between the glass production rate when the system was believed to be at a steady cold-cap size and coverage and when the cold cap behavior included unsteady characteristics. During LAW Run 1, the percent difference between the total mass flow rate in the glass during the sampling time and the total runtime was -5.9% during sample 1 and -6.8% during sample 2. During LAW Run 2, the percent difference between the total mass flow rate in the glass during the sampling time and the total runtime was -6.4% during sample 1 and -11.4% during sample 2. During LAW Run 3, the percent difference between the total mass flow rate in the glass during the sampling time and the total runtime was -2.2% during sample 1, +1.9% during sample 2, and +2.0% during sample 3. During the AlF2-05 run, the percent difference between the total mass flow rate in the glass during the sampling time and the total runtime was +22.0%. The only time the mass flow rate during a sample varied by greater than 10% from the total runtime was during the second sample of LAW Run 2, when the rate was known to have decreased due to inconsistencies with the feed pump and during the ALF2-05 sample, which was expected given the difference in the average glass production rate during operational segment 2, when the offgas sample was taken, and the total runtime, as described in Section 3.2.

From these mass flow rates, the DF_i, R_i, and Rec_i values, the latter two reported as percentages, were calculated as shown in Eqs. (4.1), (4.2), and (4.3), respectively. The values were calculated for the entire runtimes (denoted in the “Sample Duration” row as “Run”) and exclusively during each offgas sample time period (denoted in the “Sample Duration” row as 1, 2, or 3) for LAW Run 1, displayed in Table 4.3, LAW Run 2, displayed in Table 4.4, LAW Run 3, displayed in Table 4.5, and the AlF2-05 run, displayed in Table 4.6. In addition, for each run, the average (and standard deviation) recoveries of each component during the sampling times were calculated along with the percent difference between the sampling time average and the total runtime recoveries.

Rec_i values of ~90% to 100%, as typically observed in scaled melter systems (Zamecnik et al. 2002; Matlack et al. 2012b), are reported for all the primary glass components in the LAW runs. Several minor components Rec_i values are reported to be outside of the 90% to 100% range. In all the runs, the recovery of Cr and Ni were greater than 100% due to leaching from of the CLSM vessel, as discussed in Section 4.2.2, while the recovery of Re was below 90% for reasons to be discussed in Section 4.5.

The recovery of P and S were below 90% only during LAW Run 3. The concentration of P in the melter feed during Run 3 was below the desired target value due to a batching error, resulting in a P_2O_5 concentration in the glass that was near the analytical detection limit, causing the matrix spike criteria during the analysis to not be met. As such, the recovery value for P during LAW Run 3 had an increased chance of analytical error. Sulfur has been calculated to be highly volatile in other scaled melter systems (Zamecnik et al. 2002; Matlack et al. 2012b) and thus its recovery has a greater potential to fall outside the desired recovery target. The S behavior in the CLSM offgas system is discussed in greater detail in Section 0.

Rec_i values of several of the primary glass components from the AlF2-05 run fell below the 90% to 100% range observed in the LAW runs; thus, it is hypothesized that an incomplete portion of the AlF2-05 melter feed was sampled, resulting in deficiencies in the calculated mass flow rates for several components. The sampling method was changed and improved for sampling the melter feed during the LAW runs.

Table 4.3. Component DF, Percent Emitted, Retention, and Recovery During LAW Run 1

Component	Melter DF	Melter DF	Melter DF	% Emitted	% Emitted	% Emitted	*R*	*R*	*R*	Rec	Rec	Rec	Rec Avg.	Rec St. Dev.	% Diff
Sample Duration:	Run	1	2	Run	1	2	Run	1	2	Run	1	2	1&2	1&2	
Units:				%	%	%	%	%	%	%	%	%	%	%	%
Re	1.5	1.6	1.5	68	65	66	32	35	34	63	79	81	80	1	26
Al	17	64	30	6	2	3	94	98	97	94	98	97	98	1	3
B	21	21	15	5	5	7	95	95	93	96	95	94	95	1	-1
Ca	28	110	37	4	1	3	96	99	97	97	99	97	98	1	2
Cr	--	--	--	--	--	--	126	146	132	127	146	133	140	10	10
Fe	24	23	27	4	4	4	96	96	96	96	96	96	96	1	0
K	16	13	15	6	8	7	94	92	93	94	93	93	93	0	-1
Mg	20	37	20	5	3	5	95	97	95	95	97	95	96	2	1
Na	17	15	16	6	7	6	94	93	94	95	93	94	94	0	-1
Ni	--	--	--	--	--	--	141	240	177	141	240	177	209	45	48
P	--	--	--	--	--	--	105	115	112	105	115	112	113	2	8
Pb	12	7.0	8.6	9	14	12	91	86	88	91	86	88	87	2	-5
S	9.0	8.0	8.7	11	13	11	89	87	89	91	89	91	90	1	-1
Si	33	28	25	3	4	4	97	96	96	97	97	96	96	0	-1
Ti	20	21	21	5	5	5	95	95	95	95	95	95	95	0	0
Zn	23	15	15	4	7	7	96	93	93	96	93	93	93	0	-3
Zr	21	16	21	5	6	5	95	94	95	95	94	95	94	1	-1
Total	23	21	21	4	5	5	96	95	95	96	96	95	95	0	0

Values marked with ‘--’ denote that the component mass flow rate in the glass was greater than in the melter feed.

Table 4.4. Component DF, Percent Emitted, Retention, and Recovery During LAW Run 2

Component	Melter DF	Melter DF	Melter DF	% Emitted	% Emitted	% Emitted	*R*	*R*	*R*	Rec	Rec	Rec	Rec Avg.	Rec St. Dev.	% Diff
Sample Duration:	Run	1	2	Run	1	2	Run	1	2	Run	1	2	1&2	1&2	
Units				%	%	%	%	%	%	%	%	%	%	%	%
Re	1.6	1.6	1.5	62	63	66	38	37	34	79	74	69	71	4	-10
Al	15	21	13	7	5	7	93	95	93	94	96	93	94	2	0
B	8.8	12.0	7.1	11	8	14	89	92	86	90	93	87	90	5	0
Ca	39	55	357	3	2	0	97	98	100	98	98	100	99	1	2
Cr	--	--	--	--	--	--	129	141	145	131	143	148	145	4	11
Fe	55	90	--	2	1	--	98	99	101	98	100	101	100	1	2
K	21	18	23	5	6	4	95	94	96	97	95	98	97	2	0
Mg	--	--	--	--	--	--	112	112	119	112	112	119	115	5	3
Na	28	20	36	4	5	3	96	95	97	97	96	98	97	1	0
Ni	--	--	--	--	--	--	292	283	545	292	284	545	414	185	42
P	12	10	14	8	10	7	92	90	93	92	91	93	92	2	0
Pb	34	39	47	3	3	2	97	97	98	97	98	98	98	0	1
S	11	9	12	9	11	8	91	89	92	94	93	93	93	0	-1
Si	62	--	28	2	--	4	98	100	96	98	100	96	98	3	0
Ti	--	--	--	--	--	--	102	102	101	102	102	101	102	1	0
Zn	20	18	20	5	5	5	95	95	95	96	95	95	95	0	0
Zr	--	--	--	--	--	--	101	102	100	101	102	100	101	1	0
Total	31	38	27	3	3	4	97	98	97	98	98	97	98	1	0

Values marked with ‘--’ denote that the component mass flow rate in the glass was greater than in the melter feed.

Table 4.5. Component DF, Percent Emitted, Retention, and Recovery During LAW Run 3

Component	Melter DF	Melter DF	Melter DF	Melter DF	% Emitted	% Emitted	% Emitted	% Emitted	*R*	*R*	*R*	*R*	Rec	Rec	Rec	Rec	Rec Avg.	Rec St. Dev.	% Diff
Sample Duration:	Run	1	2	3	Run	1	2	3	Run	1	2	3	Run	1	2	3	1,2,3	1,2,3	
Units:					%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Re	1.5	1.4	1.5	1.6	67	70	67	62	33	30	33	38	74	78	75	81	78	3	5
Al	51	102	76	44	2	1	1	2	98	99	99	98	98	99	99	98	98	1	0
B	45	28	34	25	2	4	3	4	98	96	97	96	98	97	97	96	97	0	-2
Ca	19	6.0	37	47	5	17	3	2	95	83	97	98	95	84	97	98	93	8	-2
Cr	--	--	--	--	--	--	--	--	122	147	128	128	123	147	128	128	135	11	10
Fe	516	--	--	228	0	--	--	0	100	102	100	100	100	102	100	100	101	1	0
K	32	13	39	43	3	8	3	2	97	92	97	98	98	94	98	99	97	3	-1
Mg	23	5.4	32	152	4	18	3	1	96	82	97	99	96	82	97	99	93	10	-3
Na	41	13	90	227	2	8	1	0	98	92	99	100	98	92	99	100	97	4	-1
Ni	--	--	--	--	--	--	--	--	151	258	206	210	152	259	207	210	225	29	48
P	3.0	2.3	2.0	2.1	33	43	51	48	67	57	49	52	67	58	50	52	53	4	-20
Pb	18	7.0	34	35	6	14	3	3	94	86	97	97	94	86	97	97	94	7	-1
S	5.7	5.1	4.0	4.0	17	20	25	25	83	80	75	75	85	82	76	76	78	3	-8
Si	39	31	56	31	3	3	2	3	97	97	98	97	97	97	98	97	97	1	0
Ti	50	49	44	44	2	2	2	2	98	98	98	98	98	98	98	98	98	0	0
Zn	32	19	28	30	3	5	4	3	97	95	96	97	97	95	96	97	96	1	-1
Zr	38	15	95	64	3	7	1	2	97	93	99	98	97	93	99	98	97	3	0
Total	40	20	57	45	3	5	2	2	98	95	98	98	98	95	98	98	97	2	-1

Values marked with ‘--’ denote that the component mass flow rate in the glass was greater than in the melter feed.

Table 4.6. Component DF, Percent Emitted, Retention, and Recovery During the AlF2-05 Run

Component	Melter DF	Melter DF	% Emitted	% Emitted	*R*	*R*	Rec	Rec	% Diff
Sample Duration:	Run	1	Run	1	Run	1	Run	1	
Units:			%	%	%	%	%	%	%
Al	11	10	9	10	91	90	91	90	-1
B	13	16	8	6	92	94	93	94	1
Bi	9.8	12	10	8	90	92	90	92	2
Ca	5.4	--	19	--	81	103	82	103	25
Cr	5.5	31	18	3	82	97	83	97	18
Fe	6.1	13	16	8	84	92	84	92	10
K	12	--	8	--	92	102	92	102	11
Li	42	25	2	4	98	96	98	96	-2
Mn	9.9	9.5	10	11	90	89	90	90	0
Na	13	20	8	5	92	95	92	95	3
Ni	6.8	12	15	8	85	92	85	92	8
Ru	4.2	11	24	9	76	91	81	98	21
Si	7.6	8.6	13	12	87	88	87	89	3
Sr	5.7	5.9	18	17	82	83	82	83	1
Zr	17	--	6	--	94	116	94	116	24
Total	11	12	10	9	90	91	91	92	1

Values marked with '--' denote that the component mass flow rate in the glass was greater than in the melter feed.

4.4 Offgas Analysis

Only three components were regularly discovered to have greater than 1.0% of their recovered inventories in the CLSM offgas system: Re, S, and K. Re and S were similarly detected in appreciable quantities in the DM10 offgas system (Matlack et al. 2012b), while K was present in higher than expected levels in the offgas system of the Large C melter (Zamecnik et al. 2002). In addition, the halides, Cl and F, which were not detected in the CLSM glass product due to the analysis method used, were also detected in significant quantities in the offgas system compared to the amount in the melter feed. The locations/units in the offgas system (see Figure 2.1 for unit arrangement) where these components were recovered were the wash of the offgas piping from the CLSM vessel through the sampling loop (including the sampling HEPA filters), the primary SBS sump, the condensate (accumulated over the course of each run), and the primary HEPA filters.

For each CLSM run, the amount and percent of each volatile component (Re, S, K, Cl, and F) recovered in the glass versus the offgas system and the location of those components in the offgas system units are listed in Table D.5 of Appendix D. The trends of the percent offgas recoveries for each component in the offgas units are displayed in Figure 4.4. In the AlF2-05 run, only S, Cl, and F were detected in the offgas system, all of which were impurities in the melter feed and not a part of the glass composition; thus, their inventories are ~10% to 50% of those recovered in the LAW runs. It is suspected that a portion of the condensate collected during LAW Run 1 was not weighed (since the mass of condensate collected during LAW Run 1 was ~3.3 kg and the mass collected during LAW Run 3 was ~5 kg and those values should have been equivalent based on operational observation), leading to an artificially low mass of each component in the condensate during that run. To account for this, the mass of each component measured in the condensate during LAW Run 1 was increased by 50%. Additional primary HEPA filters were used during the runs than were sent for analysis; thus, an amount of each component was captured by the remaining, un-analyzed HEPA filters. To account for this, the mass of each component was estimated to have been deposited on the un-analyzed filters at the same rate as those analyzed, and this value was added to the primary HEPA total.

The recovery for all components in the offgas units followed the same pattern, except for the S in the AlF2-05 run, which was an impurity in the melter feed chemicals and not a target component in the glass composition. The similarity in the recovery behavior indicated a similar response for all components within the offgas system. Specifically, given that the halides followed the same pattern as the other volatile components, the credibility of the estimate for the Cl and F masses recovered in the glass product, discussed in Section 4.2.1, is strengthened.

The plenum volume in the CLSM vessel is much smaller than in other melter systems, even compared to the Large C melter, which had a smaller glass surface area. The size of the plenum volumes, and relevant ratios to other plenum characteristics, for the various melter systems along with the CLSM are compared in Table 4.7. While the plenum volume in the CLSM vessel would decrease the residence time for offgas particulate in the plenum compared to the other melters, the percentages of Re, S, and Cl recovered in the offgas piping, SBS sump, and remainder of the offgas units were similar in the CLSM and in the DM10 melter with AN-105 melter feed (Matlack et al. 2012b, 2016, 2017).

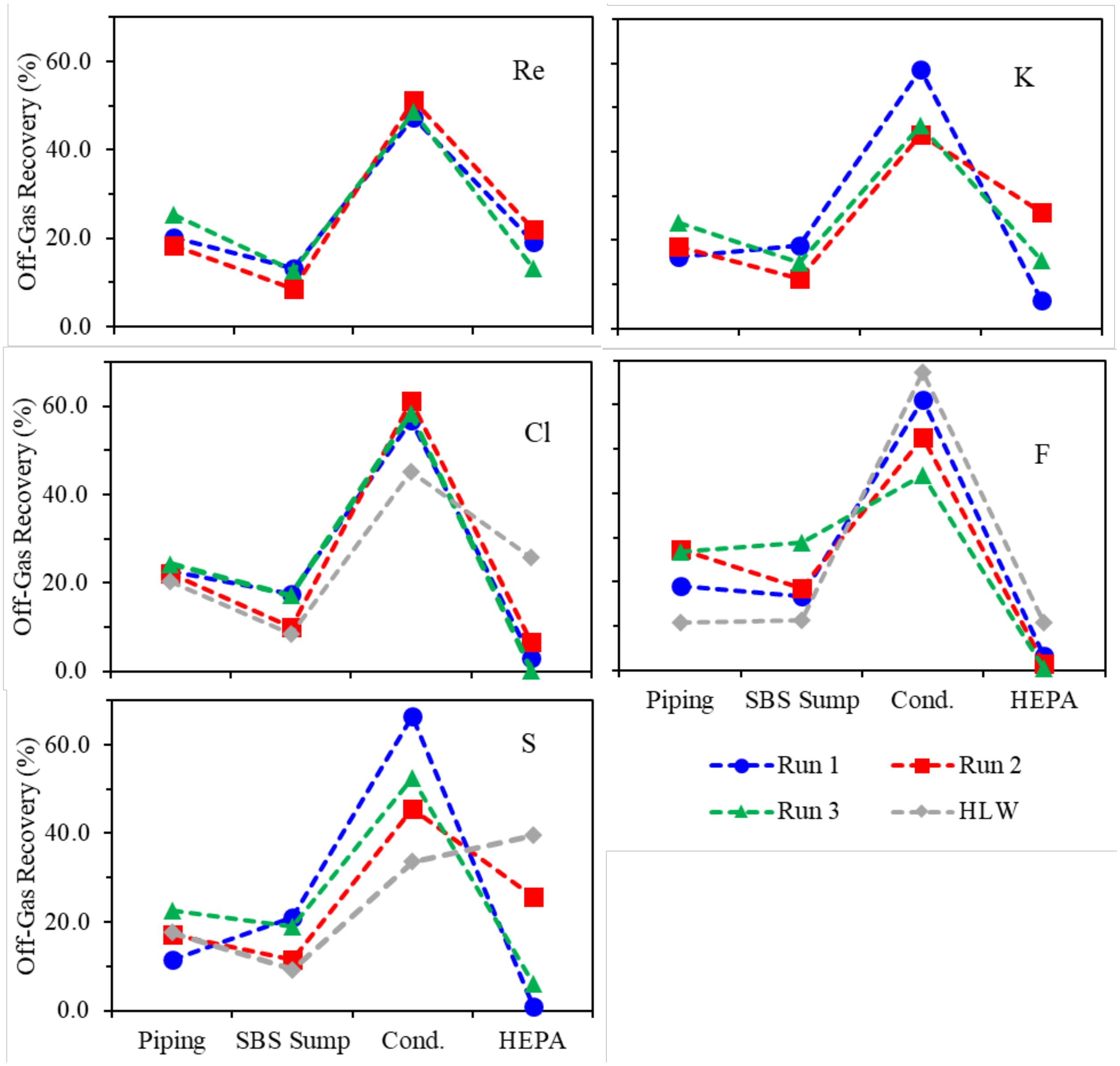

Figure 4.4. Percent of component mass recovered in each offgas unit for each CLSM run.

Table 4.7. Plenum Volume Comparison Between Melters

	CLSM	Large C [(a)]	DM10 [(b)]	DM100 [(b)]	DM1200 [(b)]	WTP LAW [(b)]
Plenum Volume, m^3	0.0018	0.0143	0.0195	0.164	1.25	15.7
Glass Surface Area/ Plenum Volume, m^{-1}	6.427	0.538	1.077	0.659	0.944	0.637
Plenum Volume/ Glass Volume	2.450	17.060	4.570	3.147	1.438	2.060

(a) Zamecnik et al. (2002)
(b) Matlack et al. (2011)

4.5 Re and ^{99}Tc Retention and Analysis

Given the slight increased mass of components estimated to be recovered in the offgas system (described in Section 4.4), the $\mathrm{Rec}_{\mathrm{Re}}$ values for the total runtime of the LAW runs (listed in Table 4.3, Table 4.4, and Table 4.5) were adjusted accordingly and are listed in Table 4.8. These recovery values still fell below the desired 90% to 100% range, but given the low mass flow rates for Re compared to the other glass components (see Table D.1, Table D.2, and Table D.3 in Appendix D), a greater potential for being outside the desired range may be expected. The recovery values for the total runtime of each LAW run, which included periods of unsteady cold-cap characteristics, are displayed in relation to the recovery values during the sampling time periods, when the cold-cap characteristics were assumed to be steady, in Table 4.8.

As described in Section 1.1, AP-105 melter feed with Re was run in the simulant CLSM and both AP-105 and AP-107 melter feeds from samples of real tank wastes with ^{99}Tc were run in the radioactive CLSM. During each of these previous runs with LAW melter feeds, multiple samples were taken and Re or ^{99}Tc analysis was performed during the sampling time periods and during the total runtime, as reported previously (Dixon et al. 2018 for AP-105 and Dixon et al. 2019 for AP-107), the retention and recovery results from which are shown in Table 4.8. Only one primary HEPA filter, used for ~1 hour of the 15.09-hour runtime, was analyzed from the AP-105 run with ^{99}Tc, which contributed to the low recovery of ^{99}Tc during that run. If the total amount of ^{99}Tc recovered in the primary HEPA filter unit during the entire runtime of the AP-105 run were estimated to be at the same rate as recovered from the single analyzed primary HEPA filter, the total runtime recovery of ^{99}Tc would be ~110%. This estimated accumulation on the HEPA filters doesn't account for the variable depositing rate of ^{99}Tc during unsteady cold-cap characteristics or idling periods, so an adjusted value of ~100% is used for the recovery value for ^{99}Tc.

The second offgas sample time period during AN-105 Run 2 was knowingly taken while the cold cap was at less than desired coverage. Thus, the average R_{Re} during all other sampling periods when the cold-cap characteristics were believed to be steady (six total samples), defining the single-pass retention of Re in AN-105 glass while processing AN-105 melter feed in the CLSM was 35% with a standard deviation of 3%. In a similar fashion, during the AP-105 run in the simulant CLSM, both sampling time periods proceeded while the cold-cap characteristics were believed to be steady. Therefore, averaging the R_{Re} values defined the single-pass retention of Re in AP-105 glass while processing AP-105 melter feed in the CLSM was 39% with a standard deviation less than 1%.

As described in Dixon et al. (2018), an issue with the offgas sampling loop during disassembly resulted in an incomplete recovery of Re during the sampling time periods, so the single-pass retention of ^{99}Tc in AP-105 glass while processing AP-105 melter feed in the CLSM has not been fully defined. However, it is instructive that the R_{Re} value increased at each subsequent sampling time period, indicating that the cold-cap conditions were not steady. During the processing of AP-107 melter feed in the CLSM, the recovery of Re during the first sampling time period was ~20% less than during the second and third periods. This may indicate that Re was accumulating in the cold cap and thus its characteristics were not steady. Thus, based on the average $R_{99\mathrm{Tc}}$ during second and third sampling time periods, the single-pass retention of ^{99}Tc in AP-107 glass while processing AP-107 melter feed in the CLSM was 40% with a standard deviation of 1%.

Table 4.8. Re and ^{99}Tc Retention and Recovery During CLSM LAW Runs

Melter Feed	Component	Sample #	*R* (%)	Rec, Sample (%)	Rec, Total (%)
AN-105, Run 1	Re	1	35	79	75[(a)]
	Re	2	34	81	75[(a)]
AN-105, Run 2	Re	1	37	74	87[(a)]
	Re	2	34	69	87[(a)]
AN-105, Run 3	Re	1	30	78	78[(a)]
	Re	2	33	75	78[(a)]
	Re	3	38	81	78[(a)]
AP-105[(b)]	Re	1	39	108	101
	Re	2	38	115	101
AP-105[(b)]	^{99}Tc	1	13	62	~100[(c)]
	^{99}Tc	2	16	28	~100[(c)]
	^{99}Tc	3	24	34	~100[(c)]
AP-107[(d)]	^{99}Tc	1	35	71	91
	^{99}Tc	2	40	108	91
	^{99}Tc	3	39	94	91

(a) Values were adjusted due to an un-measured mass of condensate during AN-105, Run 1, and a portion of the used HEPA filters being un-analyzed.
(b) Dixon et al. (2018)
(c) Values were adjusted due to a portion of the run being performed without primary HEPA filters for recovering ^{99}Tc.
(d) Dixon et al. (2019)

4.6 Run Comparisons

This section compares the production results from the processing of AN-105 and AlF2-05 melter feeds in the CLSM with the results from (1) the processing of AP-105 and AP-107 melter feeds in the CLSM, and (2) the processing of similar compositions of LAW and HLW melter feeds in other scaled-melter systems. These comparisons will elucidate the ways in which the CLSM differs from other scaled melter systems and the data that can be reliably compared between them.

4.6.1 Production Results Comparison Between CLSM Runs with Differing Melter Feed Compositions

The production results from each run with AN-105 melter feed (from Table 3.2) are shown along with the results from the runs with other melter feeds in Table 4.9. Amongst the AN-105 runs, the portion of Run 2 performed on 5/7/2019 was intentionally run with lower-than-desired cold-cap coverage; thus, the average glass production rate and bubbling flux rate were less, and the plenum temperature was greater than for the other AN-105 runs. The results from the remainder of the AN-105 runs show a range for glass production rate from 1500 to 1800 kg m^{-2} d^{-1}, bubbling flux rate from 105 to 125 L m^{-2} min^{-1}, and plenum temperature from 600 to 640 °C. The average glass production and bubbling flux rates during the AP-105 run in the simulant CLSM in APEL were within the ranges of the AN-105 runs, but the plenum temperature was slightly (~20 °C) below the AN-105 range. These results begin to define the typical production ranges for the operation of the simulant CLSM, the consistency of production under the same conditions, and the variability in those conditions while processing different melter feed compositions.

Table 4.9. CLSM Production Values for All LAW Runs

	AN-105, Run 1	AN-105, Run 2	AN-105, Run 2	AN-105, Run 3	AP-105, Simulant	AP-105, Tank Waste	AP-107, Tank Waste
Test Date	12/13/2018	3/28/2019	5/7/2019	7/23/2019	3/14/2018	4/5-12/2018	8/8/2018
Feeding Duration, h	6.23	3.48	4.14	7.56	5.83	15.09	10.07
Low Flow Duration, h	0.00	0.00	2.78	0.00	0.00	0.00	1.71
Downtime, h	0.39	0.00	0.91	0.00	0.68	2.69	0.00
Glass Produced, kg	4.74	2.48	2.79	6.45	4.32	9.45	7.01
Melter Feed Consumed, kg	9.08	5.03	5.85	12.80	10.84	22.2 (a)	15.0 (b)
Average Glass Production Rate, kg m^{-2} d^{-1}	1616	1512	1430	1809	1574	1330	1477
Average Feeding Rate, kg h^{-1}	1.46	1.44	1.41	1.69	1.86	1.47 (a)	1.49 (b)
Average Bubbling Flux Rate, L m^{-2} min^{-1}	110	108	33	122	101	125	149
Average Glass Temperature, °C	1158	1151	1147	1142	1137	1122	1115
Average Plenum Temperature, °C	610	617	716	634	579	673	648

(a) Values could not be measured but were estimated based on the calculated glass yield (g-glass kg-feed^{-1}) of the WDFL1 feed reported by Matlack et al. (2017).

(b) Values could not be measured but were estimated based on the estimated glass yield (g-glass kg-feed^{-1}) of the AP107WDFL feed reported by Matlack et al. (2018).

The runs in the radioactive CLSM with real tank waste have been compared to each other, while their similarities and differences were discussed previously (Dixon et al. 2019). The average glass temperature during the runs in the radioactive CLSM fell below the range of the runs in the simulant CLSM, average of 1147 °C with a standard deviation of 8 °C, due to the increased air flow in a fume hood compared to a fume canopy causing the upper limit of heat supplied by the furnace surrounding the CLSM vessel to be reached. A furnace with greater power capacity was installed for future runs in the radioactive CLSM.

The primary purpose of the runs in the radioactive CLSM was to successfully vitrify the received portions of real tank waste. As such, on average, the cold-cap coverage over the glass melt surface was slightly less in these runs compared to the runs in the simulant CLSM, as indicated by the average plenum temperatures during the two radioactive CLSM runs being greater than the range demonstrated during the simulant CLSM runs. Corresponding to the lower cold-cap coverage and lower glass temperature, the average bubbling flux rate during the two radioactive CLSM runs was greater than the range demonstrated during the simulant CLSM runs, while the average glass production rate was lower than in the simulant CLSM runs.

4.6.2 CLSM LAW Comparison with Literature Melters

AN-105 melter feed has been processed in the DM10 system under many different conditions with many different additives for testing the effect of those conditions and additives on the processability of the feed and retention of components, like rhenium, in the glass product. Initial runs were performed to observe how changes in different processing and feed properties, such as glass temperature, bubbling rate, type of bubbling gas, reductant carbon source, and iron source, affected the volatility of ^{99m}Tc from the glass melt during melter idling (Matlack et al. 2010b). During the processing of these runs, the single-pass R_{Re} value could be calculated for a portion of the runs using AN-105 melter feed, and these values ranged from ~30% to 70% depending on the conditions, with an average plenum temperature of 506 °C and an average bubbling flux rate (bubbling rate in liter per minute scaled by the glass surface area of the DM10) of 142 L m^{-2} min^{-1}. The second set of runs varied additives in the AN-105 melter feed to determine their effect on ^{99m}Tc, Re, and iodine retention in the glass product (Matlack et al. 2011). Among the variety of melter feed conditions, the single-pass R_{Re} value varied from ~30% to 70% while the Re recovery varied from ~75% to >100%.

A recycle system was installed on the DM10 system to add concentrated condensate back to the melter feed to increase retention of the volatile components, like ^{99m}Tc and Re, in the glass product (Matlack et al. 2012b). The third set of runs was performed to test the difference between single-pass retention and recycle retention of ^{99m}Tc, Re, and I. AN-105 melter feed was processed during three runs and difficulties in processing occurred in the first two runs. During the first run, feeding issues occurred and feeding had to be stopped multiple times for the cold cap to be broken up manually, resulting in an average glass production rate of 1765 kg^{-1} m^{-2} d^{-1} with an average bubbling flux rate of 186 L m^{-2} min^{-1} and an average plenum temperature of 445 °C. The target production rate was decreased during the second run, resulting in few interruptions, but an average glass production rate of 1332 kg^{-1} m^{-2} d^{-1} with an average bubbling flux rate of 19 L m^{-2} min^{-1} and an average plenum temperature of 505 °C. The target production rate was thus increased for the third run and no feeding issues were evident, but the cold cap again had to be broken up manually on several occasions, resulting in an average glass production rate of 1850 kg^{-1} m^{-2} d^{-1} with an average bubbling flux rate of 162 L m^{-2} min^{-1} and an average plenum temperature of 480 °C. The Re recovery for all the runs was greater than 100%, while the single-pass R_{Re} could only be calculated during the second and third runs, ranging from ~40% to 70%.

The fourth set of runs was performed to observe the change in iron source, from hematite to iron (II) oxalate, on the recycle retention of ^{99m}Tc, Re, and I (Matlack et al. 2016). The processing of AN-105 melter feed with iron oxalate achieved an average glass production rate of 2257 kg^{-1} m^{-2} d^{-1}, which was slightly greater than the target (2250 kg^{-1} m^{-2} d^{-1}), at a bubbling flux rate of 76 L m^{-2} min^{-1} and an average plenum temperature of 523 °C. Single-pass R_{Re} was not calculated during the run, but the Re recovery was ~90%. The fifth set of runs tested new melter feed and glass compositions, using AN-105 as a performance comparison (Matlack et al. 2017). The processing of AN-105 melter feed achieved an average glass production rate of 2144 kg^{-1} m^{-2} d^{-1}, which was slightly less than the target, at a bubbling flux rate of 143 L m^{-2} min^{-1} and an average plenum temperature of 456 °C. Single-pass R_{Re} was not calculated during the run, but the recycled R_{Re} was similar to the fourth set of runs and Re recovery was ~80%.

The range for the relevant production results when processing AN-105 melter feed in the CLSM, detailed in Section 4.6.1, is compared with the results from processing AN-105 melter feed in the DM10 system in Table 4.10. While the average glass production rate in the CLSM was generally lower than the DM10, a similar pattern emerged of achieving lower production rates on runs with feeding or cold-cap issues. The average bubbling flux rate was also lower in the CLSM compared to the DM10, indicating that an increased bubbling flux rates could potentially produce higher glass production rates in the CLSM. The average plenum temperatures in the CLSM were greater than in the DM10, due to differences related to the construction of the two systems. The CLSM vessel is fabricated as two contiguous pieces of Inconel (the body and lid) sealed tightly together with ceramic-fabric seal, resulting in minimal air leakage from the environment into the vessel, while the DM10 is a refractory-lined vessel with significant air leakage into the vessel cooling the plenum space. The plenum volume was also much larger in the DM10, see Table 4.7, which additionally contributed to the cooler temperatures in the DM10 compared to the CLSM. Despite these differences, S, Cl, and Re behaviors in the offgas systems were similar, as detailed in Section 4.4.

Table 4.10. Production Value Comparison Processing AN-105 in the CLSM and DM10

	CLSM	DM10[(a)]
Average Steady Glass Production Rate Range, kg m^{-2} d^{-1}	1500 – 1800	1850 – 2144
Average Unsteady Glass Production Rate Range, kg m^{-2} d^{-1}	1430	1332 – 1765
Average Steady Bubbling Flux Rate, L m^{-2} min^{-1}	105 – 125	143 – 162
Average Plenum Temperature, °C	600 – 640	456 – 480
R_{Re}	35	41.6

(a) Values from Matlack et al. (2012b, 2017)

The Re recovery during the CLSM runs was 75% to 100%, which is the same as the range observed in the DM10 system. The average single-pass R_{Re} values while processing AN-105 (35%) and AP-105 (39%) melter feeds in the CLSM were slightly less than the average single-pass R_{Re} range calculated in the DM10 with AN-105 melter feed, given in Table 4.10, but within the ~30% to 70% range observed under a variety of conditions.

The Large C Melter system processed AN-102 simulant and real waste melter feeds and the target glass production rate of ~1000 kg m^{-2} d^{-1} was lower than the target during the CLSM run (Zamecnik et al. 2002). As such, the production data wasn't directly comparable between the two systems, but the DFs for ^{99}Tc in the Large C run with real AN-102 waste, DF_{99Tc} = 7 (Zamecnik et al. 2002), and the CLSM run with real AP-107 waste, DF_{99Tc} = 2.1, were the same order of magnitude, indicating similar performance of the systems in relation to the key radioactive component.

4.6.3 CLSM HLW Comparison with Literature Melters

The AlF2-05 glass was an experimental composition designed to push the upper boundary for alumina content (Kroll et al. 2019), and thus no other melter system has been documented to have run a Hanford HLW simulant melter feed with an alumina content as high as 34 wt%. However, the HWI-Al-19 composition, shown in Table 4.2, was comparable in terms of the content of the major glass-forming components of Al_2O_3, B_2O_3, and SiO_2, and this composition was vitrified in the DM10 melter. As a result, the major production results (average glass production rate, bubbling flux rate, glass temperature, and plenum temperature) for the AlF2-05 run are compared with the average values for eight runs processing HWI-Al-19 melter feed in the DM10 system (Matlack et al. 2012a), shown in Table 4.11. The HWI-Al-19 runs in the DM10 were operated to optimize SO_3 content in the glass product; thus, the content of SO_3 in each test varied slightly from the target HWI-Al-19 composition given in Table 4.2. The target glass production rate and glass temperature in those tests were 1300 kg^{-1} m^{-2} d^{-1} and 1150 °C, respectively, and the bubbling flux rate was varied to achieve a cold-cap coverage of 90% to 100% of the glass melt surface.

The feeding duration and amount of glass produced were much greater for the DM10 runs with HWI-Al-19 compared to the AlF2-05 run. In most of the DM10 runs with HWI-Al-19, the amount of glass produced corresponded to three turnovers of the glass inventory (~24 kg), while the amount of glass produced during the AlF2-05 run corresponded to one turnover of the glass inventory (~2 kg), since the purpose of the run was to demonstrate the consistency of glass product given an initial glass inventory and melter feed with the same composition. The differences in system construction between the CLSM and DM10, as detailed in Section 4.6.2, led to the 100 °C difference in average plenum temperature between the runs in the two systems. Accounting for these variances between the systems, the production values are comparable between the two and differences between the average glass production rate and bubbling flux rate may be due to the compositional differences between the AlF2-05 and HWI-Al-19 melter feeds.

Table 4.11. Production Value Comparison Processing AlF2-05 in CLSM and HWI-Al-19 in DM10

	AlF2-05 in CLSM	HWI-Al-19 in DM10[(a)]	
Average Steady Glass Production Rate, kg m^{-2} d^{-1}	1043	1345	± 49
Average Bubbling Flux Rate, L m^{-2} min^{-1}	145	35	± 12
Average Glass Temperature, °C	1152	1157	± 1
Average Plenum Temperature, °C	636	535	± 24
Glass Produced, kg	1.72	23.13	± 4.59
Feeding Duration, h	3.50	19.65	± 4.20

(a) Values from Matlack et al. (2012a)

5.0 Conclusions

The CLSM system was designed to convert obtainable volumes of waste from Hanford tanks to glass while collecting process data and product samples for analysis. This study was performed to assess the performance of the CLSM as a relevant scaled-melter test platform by comparing the results from multiple runs of simulated waste streams with each other and with results from other scaled-melter systems in literature. A LAW simulant, based on the composition of the supernatant in Hanford tank AN-105, was selected for comparison to the same simulant processed in the DM10 melter system operated by VSL of The Catholic University of America. A high-alumina HLW simulant, AlF2-05, with an experimentally high composition of Al_2O_3 in the glass product, 34 wt%, was also vitrified in the CLSM to determine if it was possible for all the Al_2O_3 to be incorporated into the product glass matrix.

Three CLSM runs were performed with simulated AN-105 melter feed. The feeding time during each run ranged from 6 to 8 hours to achieve at least two melter turnovers of the glass inventory in the CLSM vessel. The range of glass production rates during the runs when the cold cap had the desired coverage of 95% to 100% was 1500 to 1800 kg m^{-2} d^{-1} with a bubbling flux rate range from 105 to 125 L m^{-2} min^{-1} and plenum temperatures from 600 to 640 °C. These ranges were similar to previous tests processing AP-105 and AP-107 melter feed in the CLSM. The glass production rate and bubbling flux rate ranges while processing AN-105 in the CLSM were below the ranges achieved while processing AN-105 in the DM10 system, indicating that the bubbling flux rate in the CLSM may be able to be increased to achieve a higher glass production rate. The average plenum temperature range in the CLSM was greater than the DM10 due to the lack of air leakage into the CLSM vessel, the much smaller plenum volume in the CLSM, and other system design differences.

The compositions of the AN-105 glass produced from the CLSM runs were within 10% of the target values for all the major glass components, with the exception of MgO, which was consistently ~15% lower than its target because the mineral source of magnesium, olivine, was less pure than anticipated during melter feed preparation. The recovery of all the major glass components in the CLSM system during each of the AN-105 runs was 90% to 100%, as typically observed in other scaled melter systems and in the previous run with AP-105 melter feed in the CLSM, which establishes that the CLSM may confidently be used to evaluate the partitioning of components into the product streams.

The retention of Re, a non-radioactive surrogate for ^{99}Tc that was added into the AN-105 melter feed, was calculated during specific sampling time frames during each AN-105 run when the cold cap was believed to have steady coverage and thickness over the glass melt surface. During such conditions, the single-pass retention of Re in AN-105 glass while processing AN-105 melter feed in the CLSM was 35% with a standard deviation of 3%. These results in the CLSM aligned with the range of Re retention calculated when processing AN-105 in the DM10 system under a variety of experimental conditions.

The processing of AlF2-05 melter feed in the CLSM produced 2.21 kg of glass over the 5.38-hour runtime, with an average glass production rate at steady cold-cap conditions of 1043 kg^{-1} m^{-2} d^{-1} with a bubbling flux rate of 145 L m^{-2} min^{-1} and a plenum temperature of 636 °C. The composition of Al_2O_3 in the glass product poured during the run was within 1% of the target value, revealing that it was possible to vitrify a waste glass composition with up to 34 wt% of Al_2O_3, leading to the further conclusion that the CLSM system can be used for vitrifying Hanford HLW samples.

In summary, based on these run results in the CLSM and conclusions:

- The CLSM system can be used to vitrify both LAW and HLW melter feeds, either traditional or experimental compositions, at rates that allow for comparisons to other scaled melter systems.

- Performing three CLSM runs with the same melter feed allowed for general production ranges and an average rhenium retention value to be defined.
- While the initial production ranges in the CLSM were below the same melter feed processing in another scaled melter system, the results indicate that the processing in the CLSM may be able to be safely increased and more testing is required to demonstrate this potential.
- A composition spike in the content of a primary glass component (>1.00 wt%) can reach its target value within one turnover of the CLSM glass inventory (2 kg), while a spike in a minor impurity component (<1500 ppm) can reach 10% of its initial level within three turnovers.
- Volatile components in the glass composition (Re, S, K, Cl, and F) accumulated in the custom-designed, CLSM offgas system in a similar fashion to a prototypic offgas system, while all other glass components had less than 1% of their recovered inventories in the offgas system.

The purpose of this study was to assess the performance of the CLSM as a relevant scaled-melter test platform. Based on the consistency of the production data ranges defined during the processing of three diverse LAW melter feed compositions, spanning both simulants and real wastes, in the CLSM and the similarity of those ranges and results to other melter systems from literature, it is concluded that the CLSM system is a viable option for testing Hanford waste vitrification.

6.0 References

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Appendix A – LAW Runs Results Data

The figures and tables in this section display the various processing values (temperatures, effective glass production rates, bubbling flux rates, and melter vacuum measurements) collected during low-activity waste (LAW) continuous laboratory-scale melter (CLSM) Run 1, Run 2, and Run 3, the rhenium concentration in the glass pours, and the complete chemical analytical results.

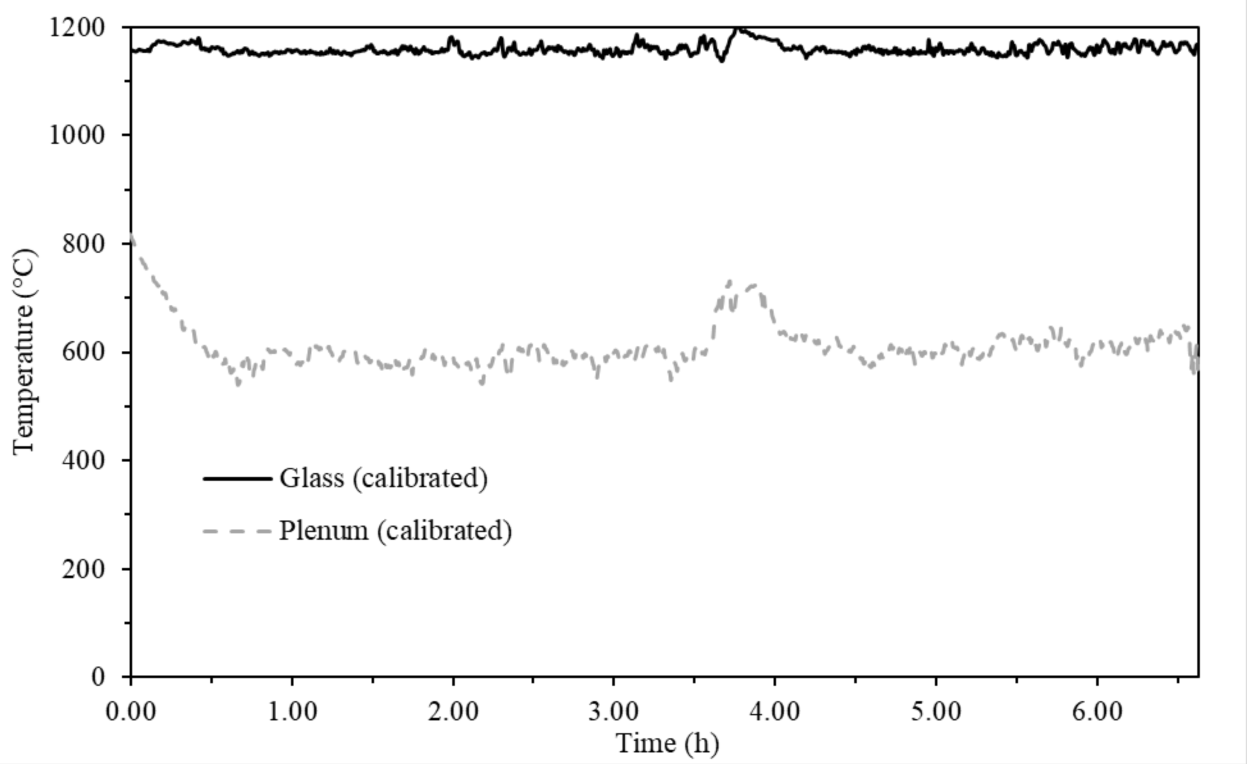

Figure A.1. Glass and plenum temperatures recorded by a calibrated data logger for Run 1.

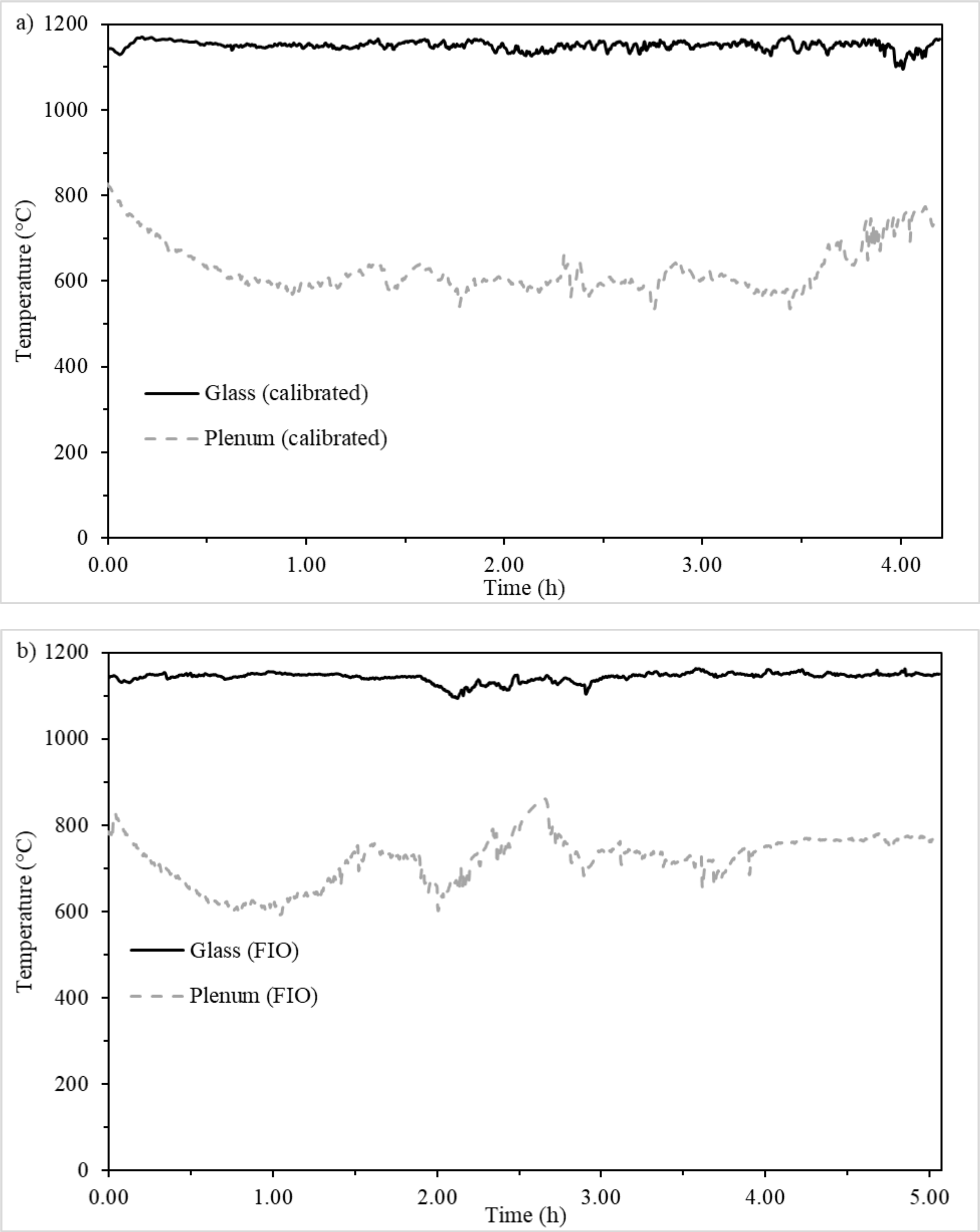

Figure A.2. Glass and plenum temperatures recorded by a calibrated data logger during the portion of Run 2 on a) 3/28/2019 and by an FIO device during the portion of Run 2 on b) 5/7/2019.

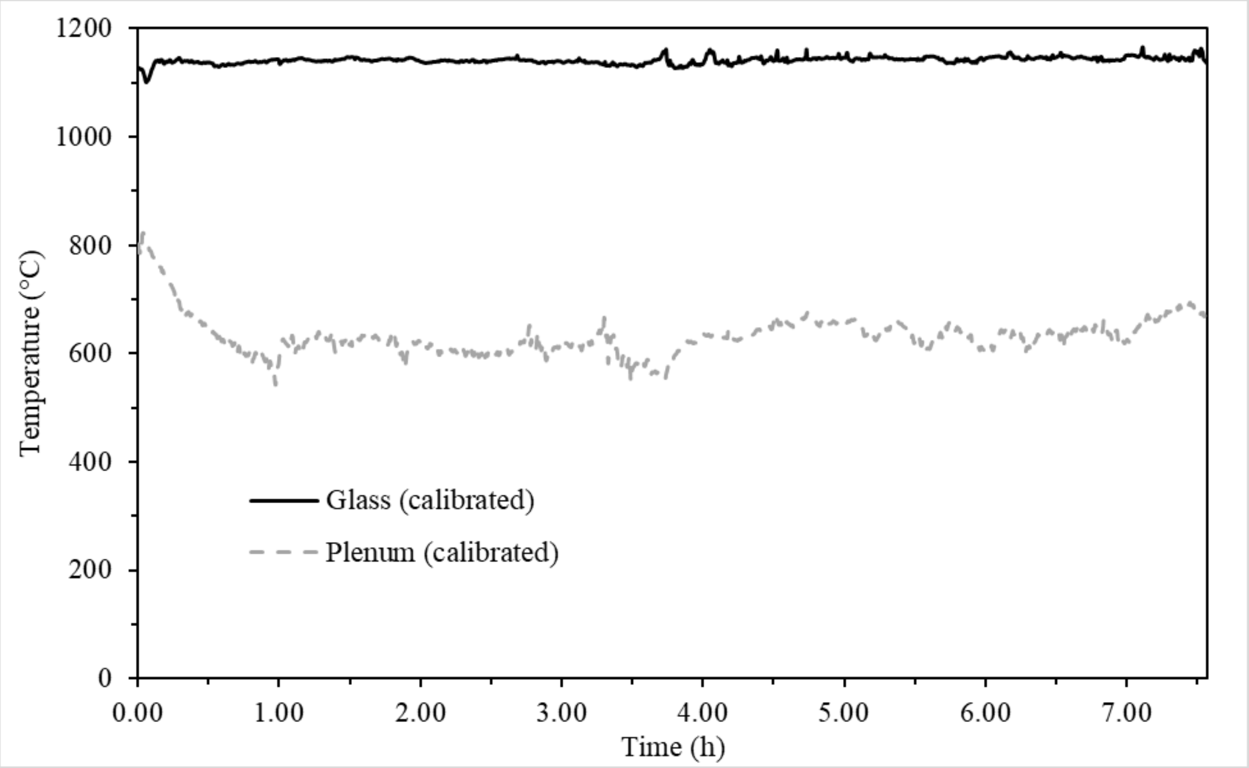

Figure A.3. Glass and plenum temperatures recorded by a calibrated data logger for Run 3.

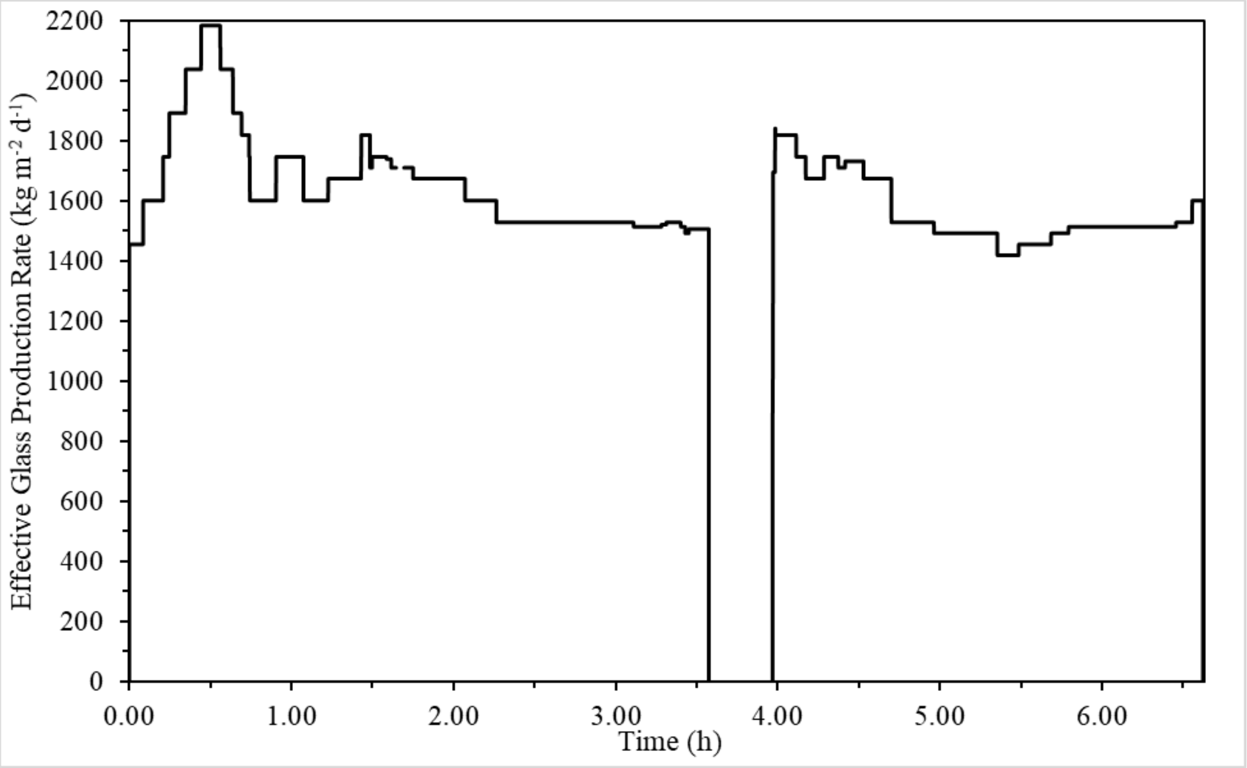

Figure A.4. Effective glass production rate for Run 1.

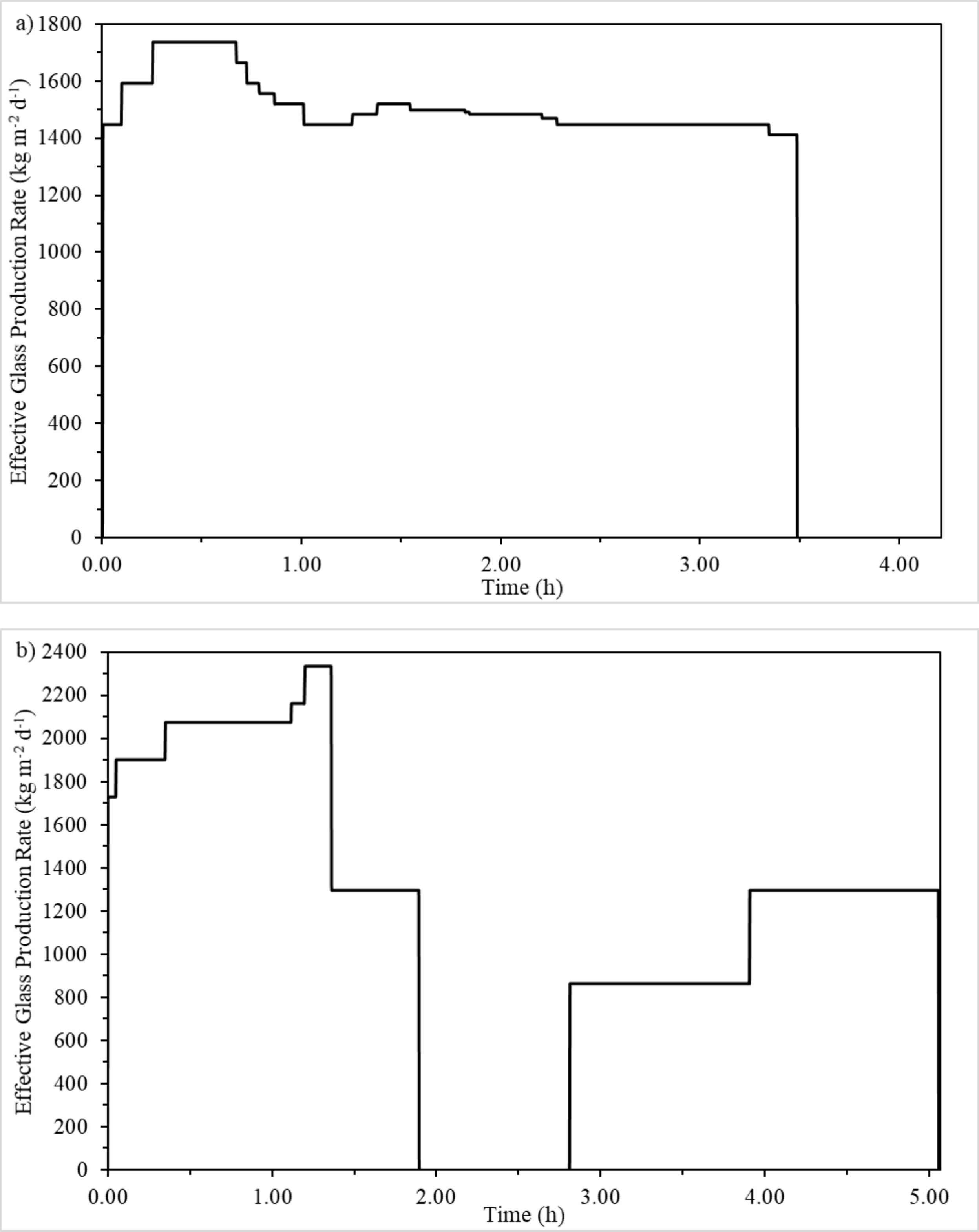

Figure A.5. Effective glass production rate for the portion of Run 2 on a) 3/28/2019 and b) 5/7/2019. Due to the feeding inconsistencies, the feeding pump rate had to be estimated for the portion of the run from hour 3.49 to 3.96 on 3/28/2019 and from hour 1.36 to 5.06 on 5/7/2019 based on observations of cold-cap coverage and drip rate made by the operational team on those days.

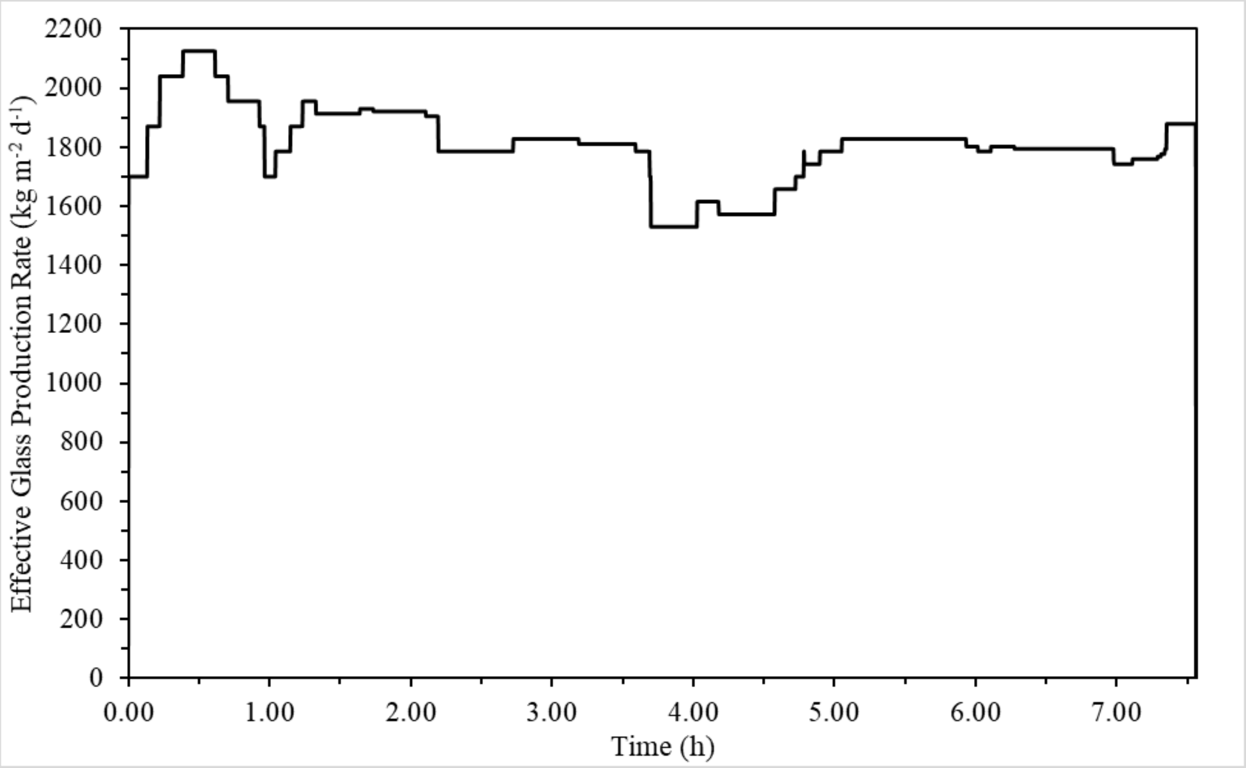

Figure A.6. Effective glass production rate for Run 3.

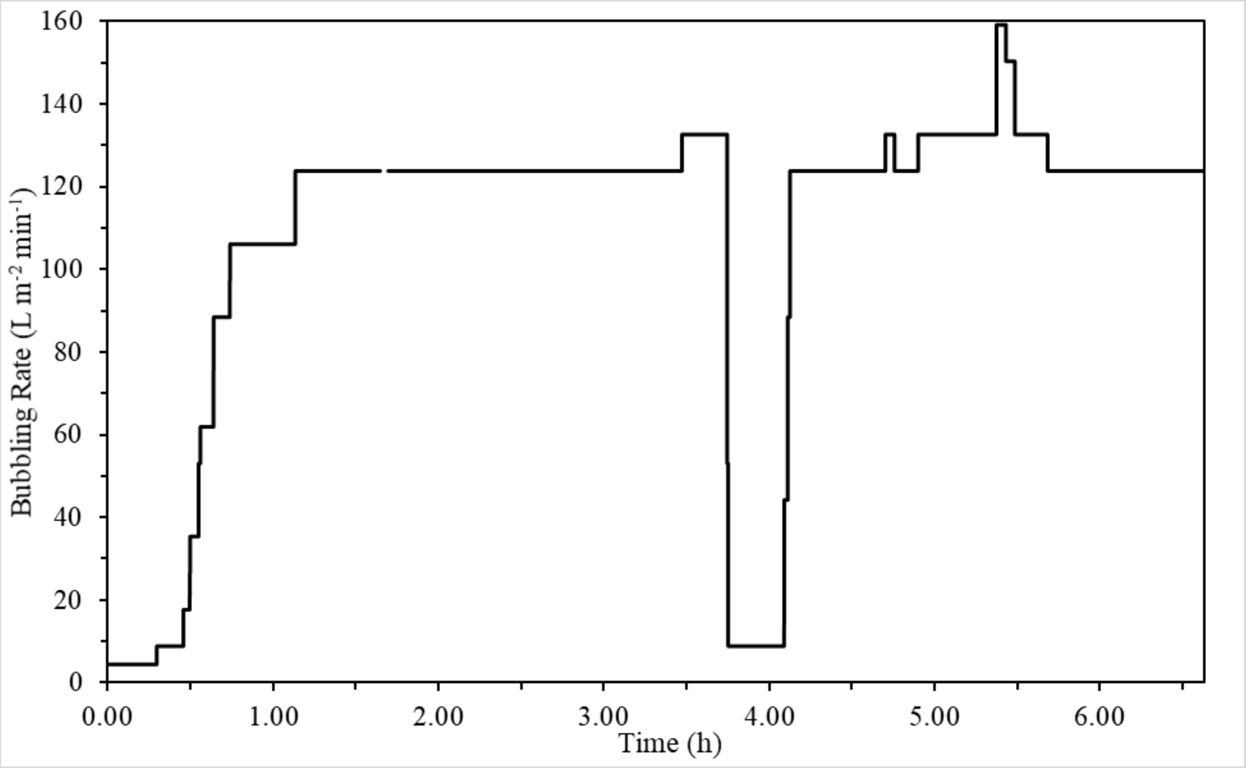

Figure A.7. Bubbling flux rate for Run 1.

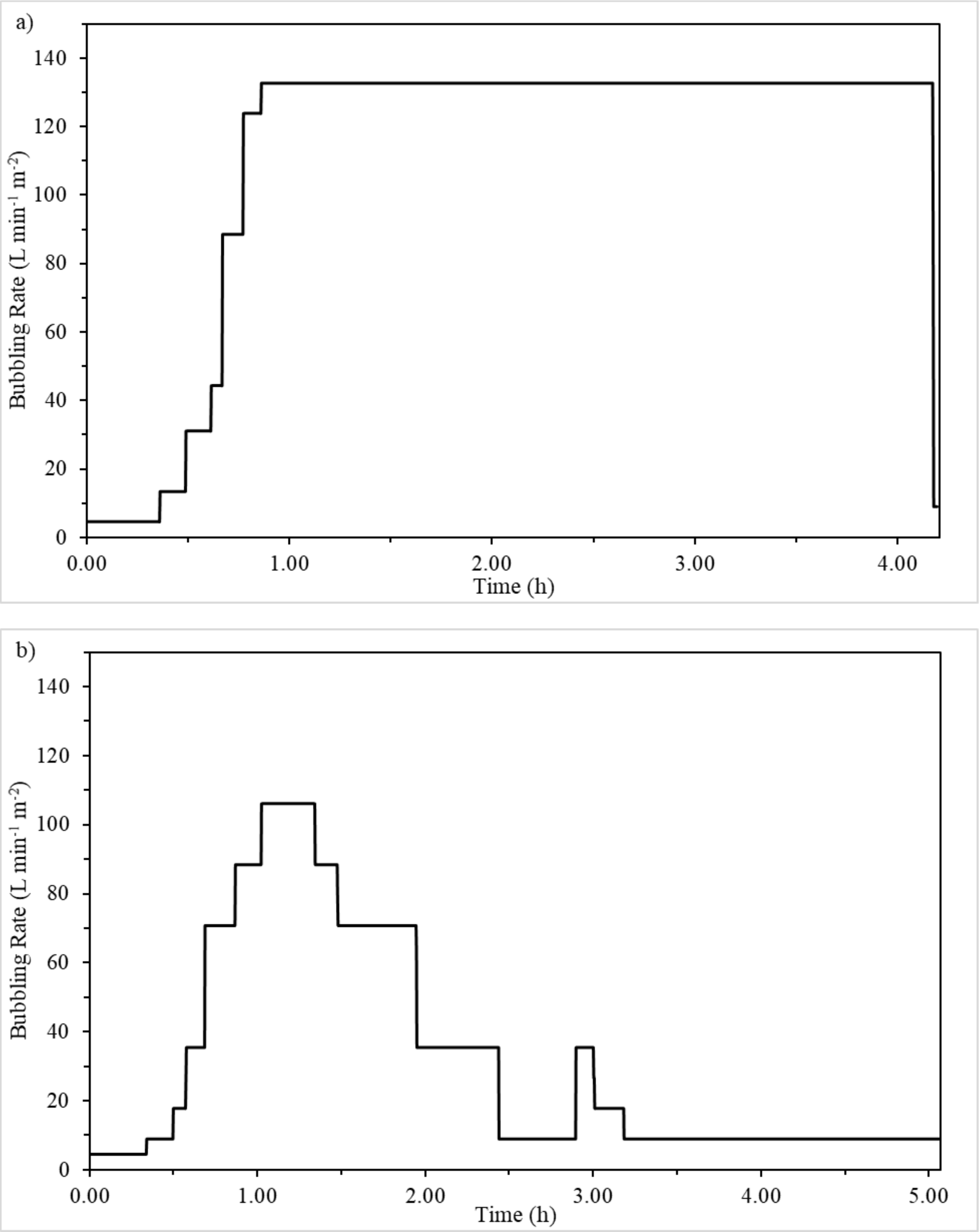

Figure A.8. Bubbling flux rate for the portion of Run 2 on a) 3/28/2019 and b) 5/7/2019.

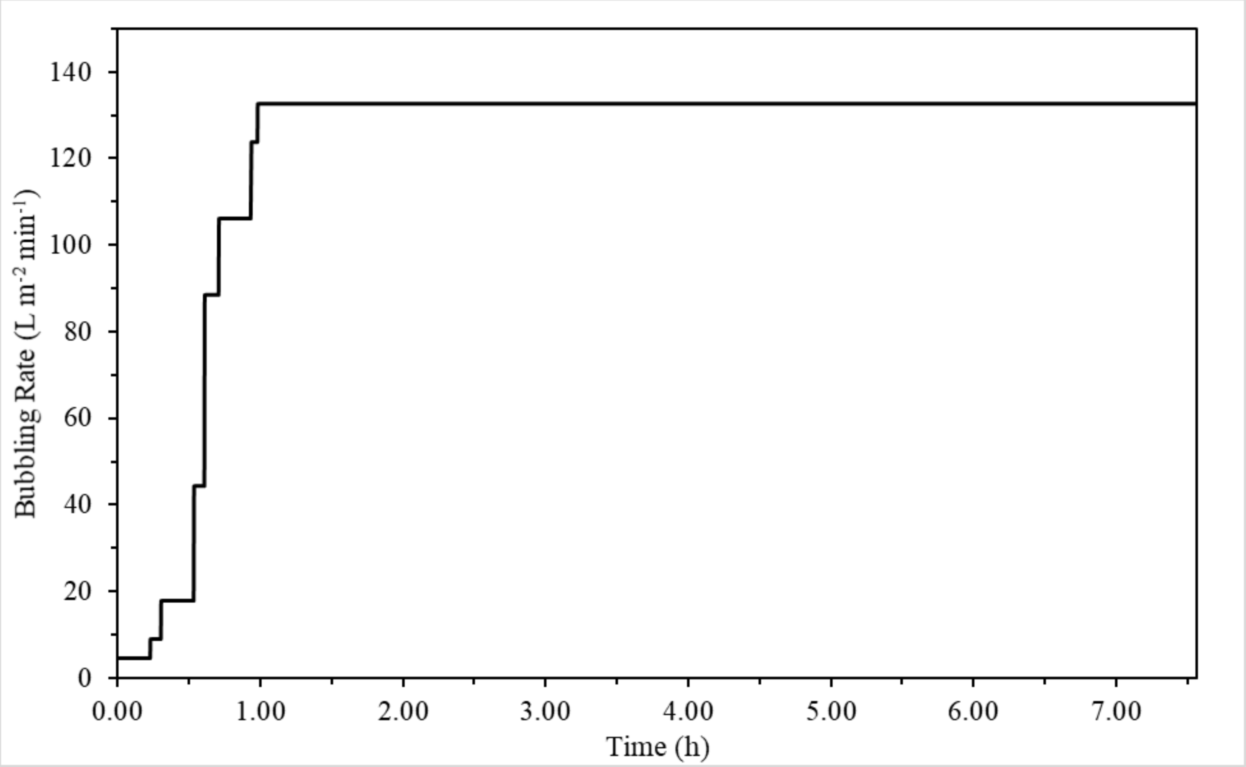

Figure A.9. Bubbling flux rate for Run 3.

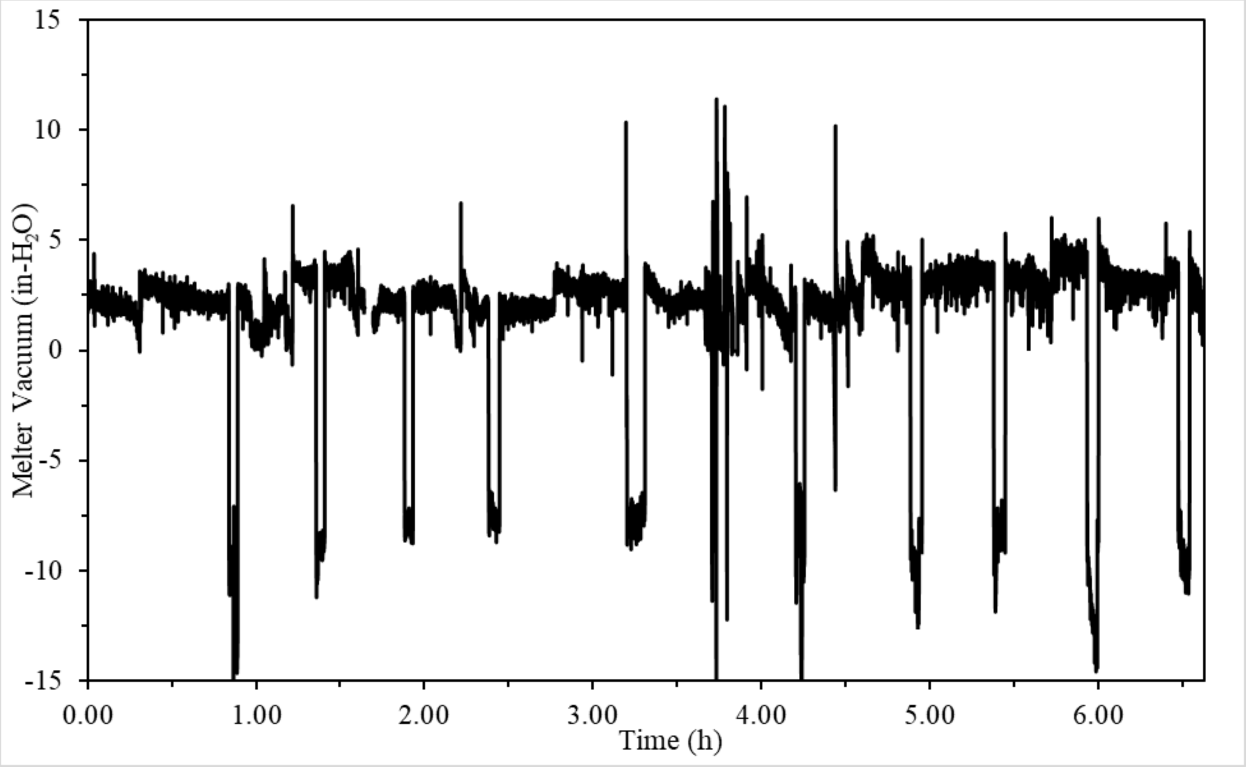

Figure A.10. Melter vacuum measurement for Run 1.

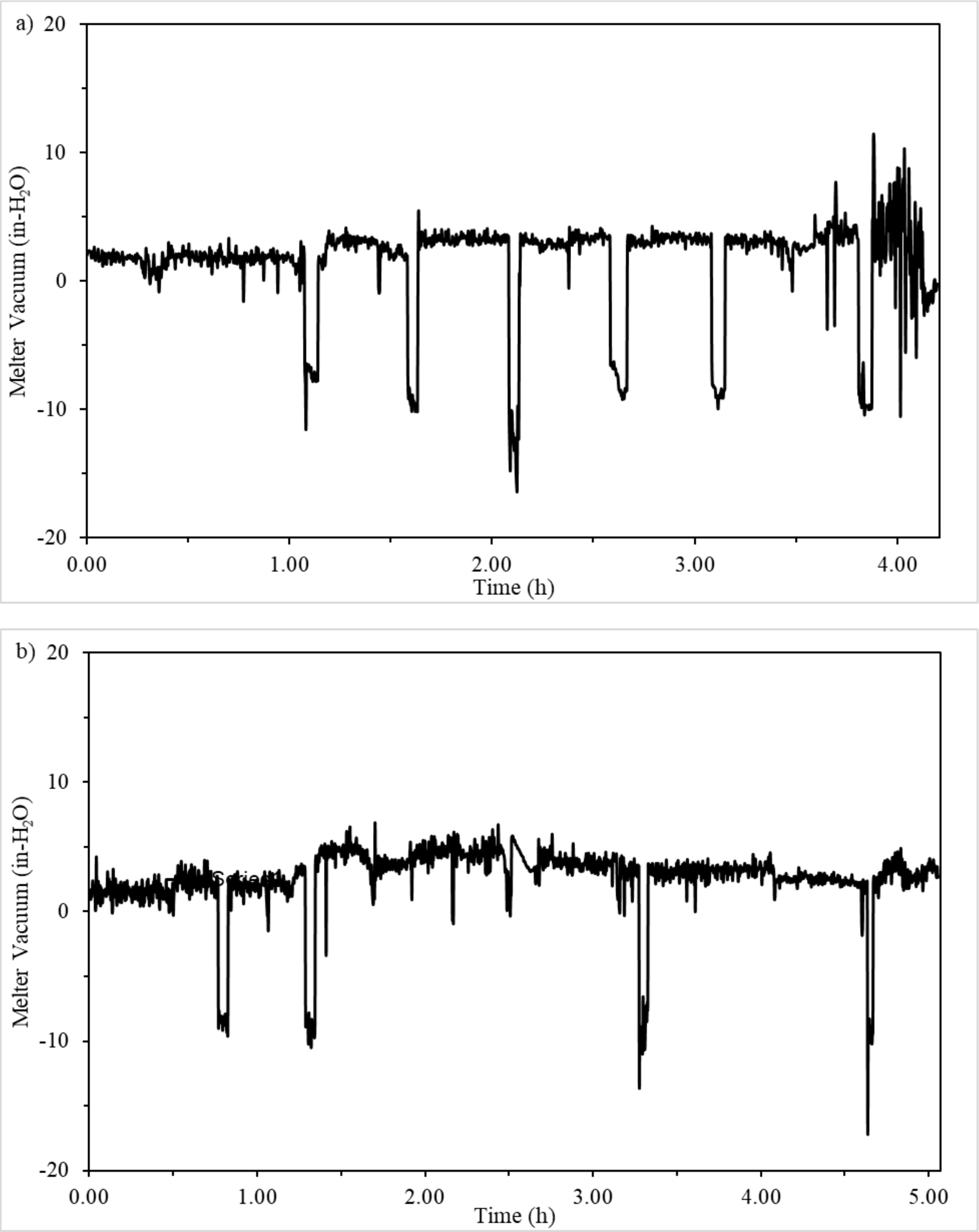

Figure A.11. Melter vacuum measurement for the portion of Run 2 on a) 3/28/2019 and b) 5/7/2019.

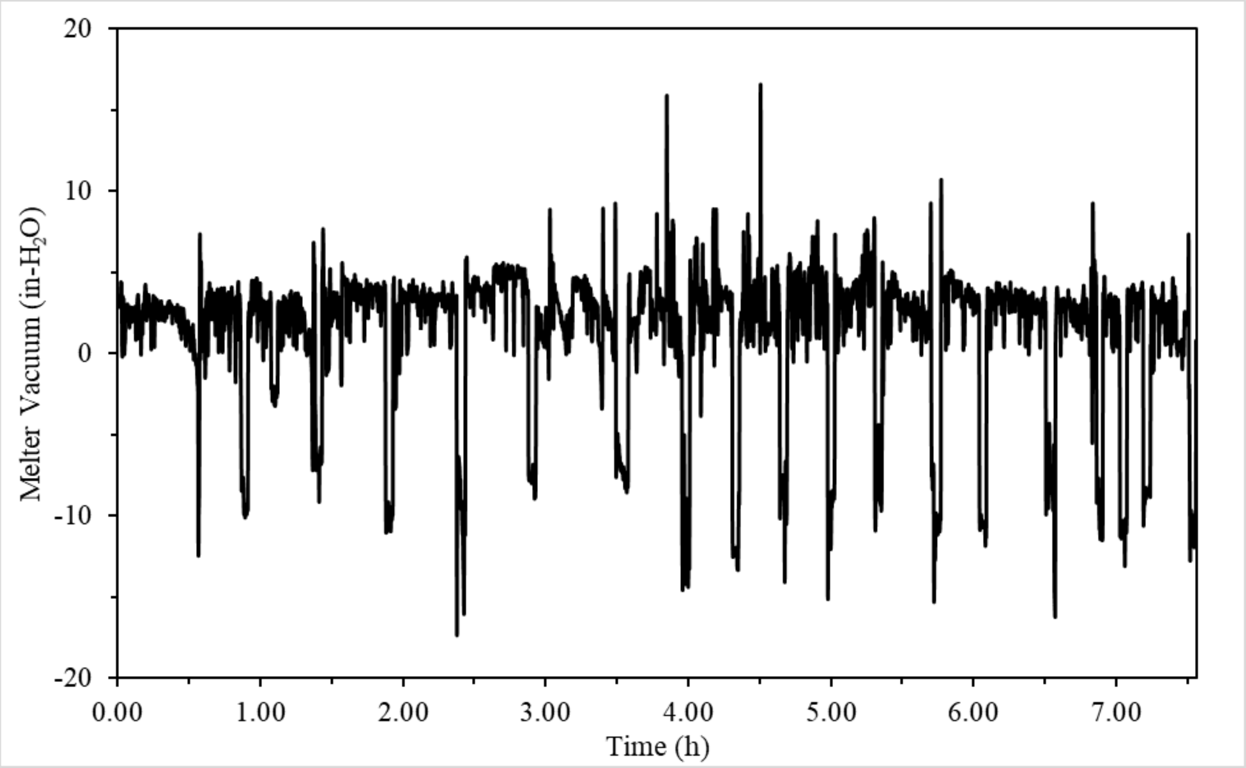

Figure A.12. Melter vacuum measurement for Run 3.

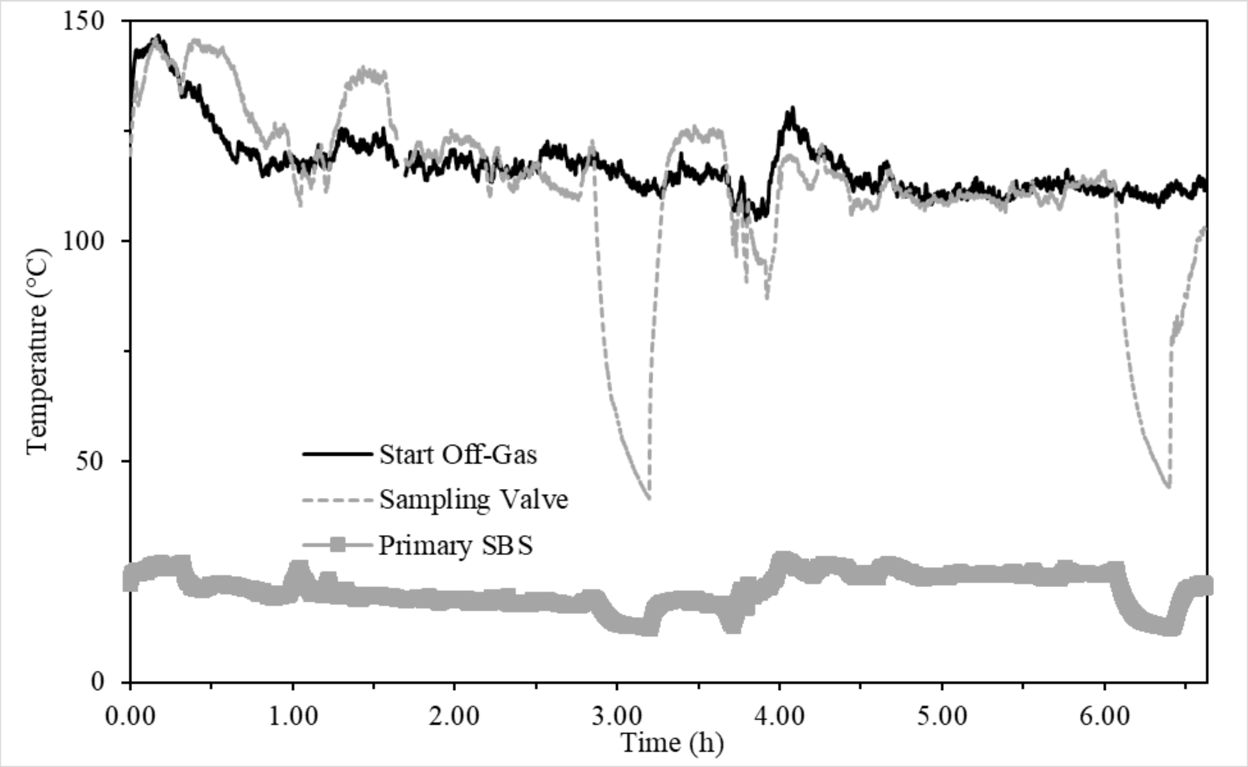

Figure A.13. Start of offgas system, sampling valve, and primary submerged bed scrubber (SBS) temperatures for Run 1.

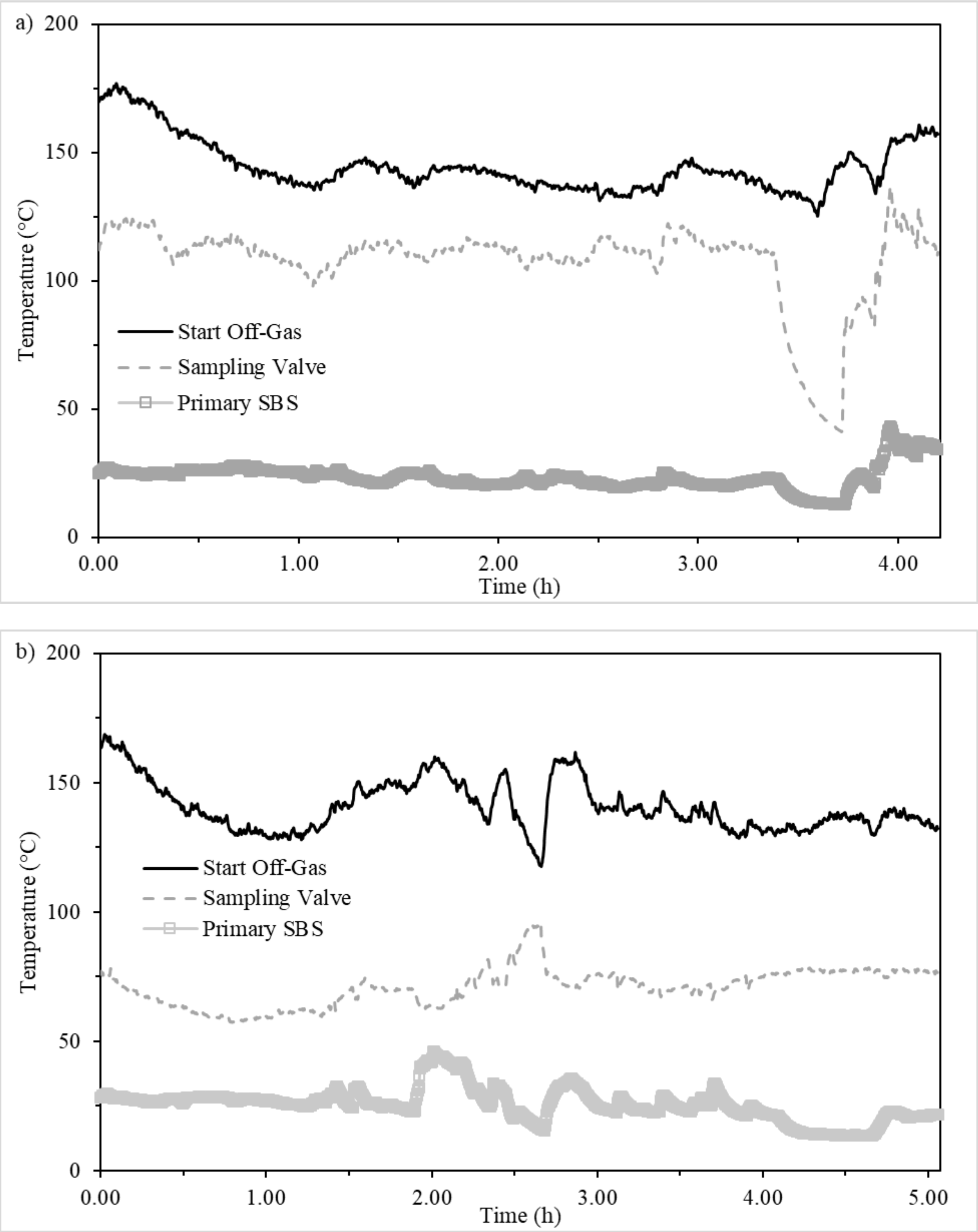

Figure A.14. Start of offgas system, sampling valve, and primary SBS temperatures for the portion of Run 2 on a) 3/28/2019 and b) 5/7/2019.

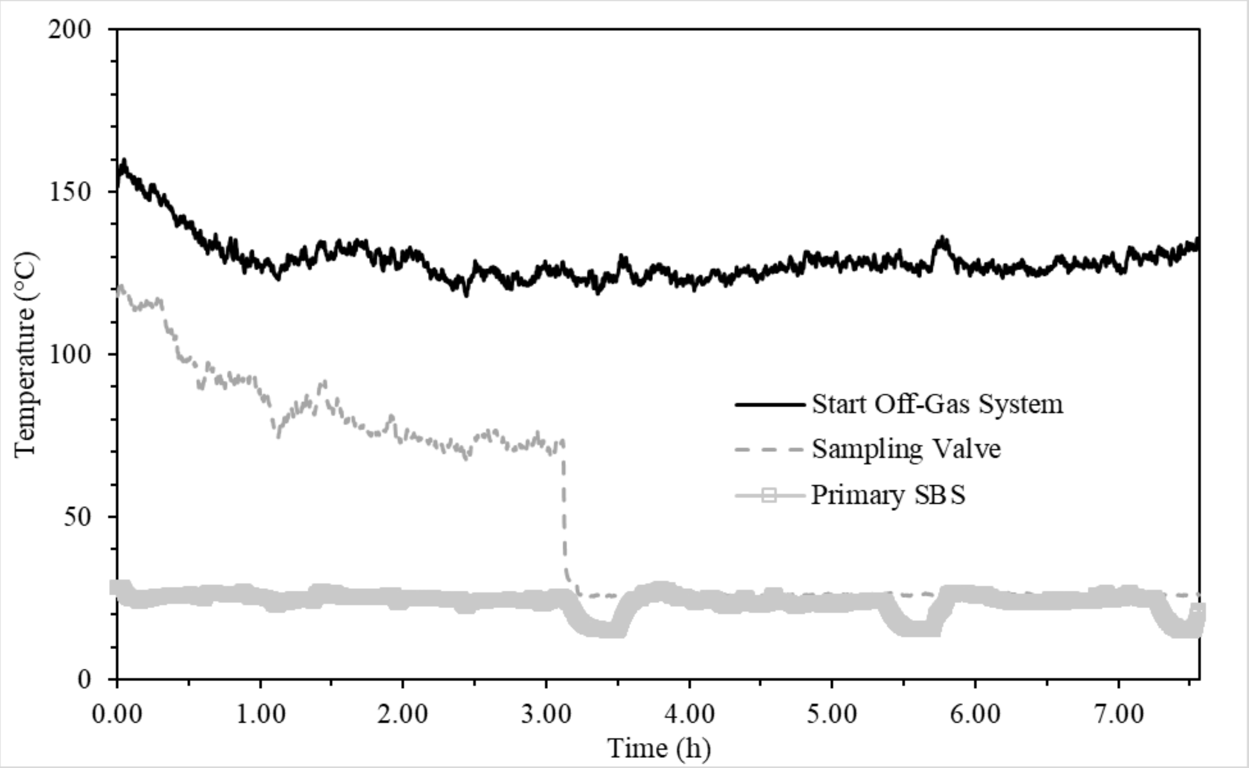

Figure A.15. Start of offgas system, sampling valve, and primary SBS temperatures for Run 3. Around hour 3.30, the thermocouple that was taped to the sampling valve detached from the valve and read a room temperature value for the remainder of the run.

Table A.1. Chemical Analysis of Selected Samples for Run 1

Sample Name	Sample Type	Sample Mass (g)	Rhenium (mg kg^{-1})	Aluminum (mg kg^{-1})	Arsenic (mg kg^{-1})	Barium (mg kg^{-1})	Bismuth (mg kg^{-1})	Boron (mg kg^{-1})	Cadmium (mg kg^{-1})	Calcium (mg kg^{-1})	Chromium (mg kg^{-1})	Cobalt (mg kg^{-1})	Copper (mg kg^{-1})	Iron (mg kg^{-1})
Glass Pour 0.83	Solid	489.07	2.88	34700	--	197	90.0	29500	13.3	17300	1150	6.63	3.86	39600
Glass Pour 3.20	Solid	1866.80	2.76	32500	--	112	34.7	28500	6.44	16700	981	5.86	2.36	39800
Glass Pour 4.20	Solid	521.08	2.56	32100	--	96.7	28.5	28900	5.36	16600	975	13.0	2.14	39500
Glass Pour 6.46	Solid	1558.13	2.64	31900	--	63.1	10.4	28000	2.61	16400	889	5.59	1.87	40100
Glass Pour 6.62	Solid	2309.08	2.42	31600	--	62.0	8.78	29400	2.53	16400	881	7.27	1.74	39700
AN-105 Melter Feed	Feed	9080.00	4.02	17200	--	17.8	--	15700	--	8680	354	1.36	0.896	21500
AN-105 Melter Feed (Duplicate)	Feed	9080.00	4.11	17300	--	17.6	--	15600	--	8930	349	1.37	--	22000
Primary HEPA 1	HEPA	5.31	11.5	11100	--	15900	--	9910	--	4270	51.2	--	0.833	167
Primary HEPA 3	HEPA	5.74	135	10500	--	14800	--	11000	--	4000	119	--	0.756	162
Primary HEPA 7	HEPA	5.61	57.3	10700	--	15200	--	10000	--	4180	69.6	--	0.593	160
Sampling HEPA 1	HEPA	10.76	70.6	10750	--	15500	--	10200	--	4240	89.4	--	0.646	168
Sampling HEPA 2	HEPA	10.55	77.3	10900	--	15500	--	9735	--	4310	70.3	--	0.843	178
Sampling HEPA 3	HEPA	26.07	--	5190	--	7340	--	5100	--	2090	--	--	--	62.7
Condensate	Aqueous	3379.86	1.51	35.3	--	--	--	106	--	8.63	3.17	--	--	19.1
Condensate (Duplicate)	Aqueous	3379.86	1.48	35.1	--	--	--	105	--	8.17	3.14	--	--	18.7
Sampling SBS Sump	Aqueous	1078.49	--	--	--	--	--	29.4	--	--	--	--	--	--
Primary SBS Sump	Aqueous	919.72	2.28	--	--	--	--	160	--	4.83	4.58	--	--	--
Demister Liquid	Aqueous	42.37	1.10	108	--	--	2.39	123	--	16.8	7.72	--	--	77.8
Primary Offgas Piping Wash	Aqueous	130.82	11.5	108	--	--	--	144	--	43.2	14.1	--	--	102
Sampling Offgas Piping Wash	Aqueous	118.44	1.36	22.4	--	--	--	44.8	--	6.98	1.50	--	--	19.1

Values marked with ‘—’ denote that the metal concentration was below the analysis detection limit.

Table A.1. Chemical Analysis of Selected Samples for Run 1 (cont.)

Sample Name	Lanthanum (mg kg^{-1})	Lead (mg kg^{-1})	Lithium (mg kg^{-1})	Magnesium (mg kg^{-1})	Manganese (mg kg^{-1})	Molybdenum (mg kg^{-1})	Nickel (mg kg^{-1})	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})	Silicon (mg kg^{-1})	Silver (mg kg^{-1})	Sodium (mg kg^{-1})	Strontium (mg kg^{-1})	Sulfur (mg kg^{-1})
Glass Pour 0.83	1320	60.2	1360	7810	406	451	633	817	3640	210000	--	146000	154	1590
Glass Pour 3.20	629	65.0	630	7730	202	217	394	707	3740	216000	--	149000	80.5	1670
Glass Pour 4.20	521	66.8	522	7710	178	178	363	708	3750	216000	--	149000	68.4	1660
Glass Pour 6.46	249	67.0	251	7550	114	84.9	290	688	3770	215000	--	150000	39.3	1690
Glass Pour 6.62	235	69.0	240	7540	111	80.4	292	671	3770	215000	--	150000	--	1660
AN-105 Melter Feed	--	38.7	1.13	4160	29.4	--	82.5	322	2120	115000	--	83300	--	999
AN-105 Melter Feed (Duplicate)	--	40.5	1.01	4140	29.6	--	88.9	322	2110	119000	--	83800	--	996
Primary HEPA 1	--	2.33	5.79	669	3.75	18.4	5.14	--	7570	393000	--	23400	157	--
Primary HEPA 3	--	3.94	26.1	619	3.99	27.3	5.91	13.9	8040	368000	--	31200	149	1920
Primary HEPA 7	--	2.60	6.67	651	3.68	17	5.83	12.9	7620	381000	--	25000	153	780
Sampling HEPA 1	--	3.73	12.2	666	4.85	19.4	3.17	14.4	8110	386500	--	31600	154	676
Sampling HEPA 2	--	2.95	6.79	649	3.78	16.7	3.93	15.5	8145	383000	--	29900	158	1014
Sampling HEPA 3	--	0.921	1.08	288	5.57	6.55	1.44	--	3260	183000	--	10900	75.4	--
Condensate	--	--	2.43	--	2.25	--	0.260	--	19.7	22.1	--	320	--	29.9
Condensate (Duplicate)	--	--	2.40	--	2.22	--	0.268	--	19.0	21.6	--	319	--	27.6
Sampling SBS Sump	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Primary SBS Sump	--	--	1.52	--	--	--	--	--	34.4	--	--	563	--	50.2
Demister Liquid	--	--	2.33	--	5.64	1.07	3.90	--	15.3	26.9	0.518	247	--	21.3
Primary Offgas Piping Wash	--	--	11.4	6.39	2.24	1.46	0.742	--	137	103	--	1990	--	173
Sampling Offgas Piping Wash	--	--	3.06	--	1.24	0.760	0.540	--	18.0	12.1	--	270	--	24.5

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

Table A.1. Chemical Analysis of Selected Samples for Run 1 (cont.)

Sample Name	Tin (mg kg^{-1})	Titanium (mg kg^{-1})	Tungsten (mg kg^{-1})	Vanadium (mg kg^{-1})	Yttrium (mg kg^{-1})	Zinc (mg kg^{-1})	Zirconium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Chromate (mg kg^{-1})	Fluoride (mg kg^{-1})	Bromide (mg kg^{-1})	N (Nitrate) (mg kg^{-1})	N (Nitrite) (mg kg^{-1})	P (Phosphate) (mg kg^{-1})
Glass Pour 0.83	10.9	8280	238	47.7	37.2	27900	19600	--	--	2.87	--	--	--	--	--
Glass Pour 3.20	9.61	8250	233	46.5	37.5	28000	20000	--	--	2.81	--	--	--	--	--
Glass Pour 4.20	10.6	8260	283	46.4	37.4	28700	20100	--	--	2.96	--	--	--	--	--
Glass Pour 6.46	10.1	8260	233	45.8	37.7	27900	20300	--	--	2.57	--	--	--	--	--
Glass Pour 6.62	13.5	8220	243	49.8	37.8	29200	20200	--	--	3.34	--	--	--	--	--
AN-105 Melter Feed	--	4540	140	6.20	5.16	16100	11000	1030	2660	637	308	--	13100	11400	126
AN-105 Melter Feed (Duplicate)	--	4520	145	6.39	5.15	15200	11300	1040	2750	644	317	--	13200	11500	130
Primary HEPA 1	--	15.6	77.2	--	2.57	11000	125	--	316	--	28.3	--	1260	--	--
Primary HEPA 3	--	14.6	65.2	--	2.33	10000	113	61.4	4350	--	185	--	12900	--	--
Primary HEPA 7	--	15.0	72.5	--	2.45	10800	119	31.5	1550	--	66.6	--	7890	--	--
Sampling HEPA 1	--	16.3	75.7	--	2.54	10900	123	11200	1680	48.6	386	--	134	--	--
Sampling HEPA 2	--	16.6	75.8	--	2.49	10105	119	11700	2070	12.3	421	--	914	--	--
Sampling HEPA 3	--	7.16	28.8	--	1.07	5400	54.2	22.8	54.9	--	--	--	56.3	--	--
Condensate	--	0.537	--	--	--	17.5	0.760	263	173	--	27.3	--	1610	--	--
Condensate (Duplicate)	--	0.500	--	--	--	17.0	0.798	262	172	--	27.0	--	1870	--	--
Sampling SBS Sump	--	--	--	--	--	--	--	--	--	--	--	--	11.9	220	--
Primary SBS Sump	--	--	--	--	--	4.78	--	443	136	10.2	40.5	--	460	1400	--
Demister Liquid	--	2.25	--	--	--	20.3	3.30	622	145	--	32.9	--	3160	15.8	--
Primary Offgas Piping Wash	--	4.32	--	--	--	79.6	4.54	1980	506	16	210	--	41.2	8.65	--
Sampling Offgas Piping Wash	--	0.423	--	--	--	16.8	--	243	63.5	--	54.4	--	22.5	6.40	--

Values marked with ‘—’ denote that the metal concentration was below the analysis detection limit.

Table A.2. Chemical Analysis of Selected Samples for Run 2

Date	Sample Name	Sample Type	Sample Mass (g)	Rhenium (mg kg^{-1})	Aluminum (mg kg^{-1})	Arsenic (mg kg^{-1})	Barium (mg kg^{-1})	Bismuth (mg kg^{-1})	Boron (mg kg^{-1})	Cadmium (mg kg^{-1})	Calcium (mg kg^{-1})	Chromium (mg kg^{-1})	Cobalt (mg kg^{-1})	Copper (mg kg^{-1})	Iron (mg kg^{-1})
3/28/19	Glass Pour 1.06	Solid	213.09	2.96	31800	--	57.0	6.13	29600	2.29	16400	1060	4.04	2.53	39000
3/28/19	Glass Pour 3.81	Solid	1977.37	3.03	31450	--	45.6	--	29800	1.38	16400	895	4.04	3.60	38950
3/28/19	Glass Pour 4.20	Solid	2288.12	2.66	31400	3.09	44.6	--	29800	1.31	16300	868	4.56	3.58	38700
3/28/19	AN-105 Melter Feed	Feed	5025.00	4.00	16300	--	17.6	--	16050	--	8250	313	1.19	2.36	19450
3/28/19	Sampling HEPA 1	HEPA	10.67	52.8	10735	2.77	13150	--	19150	--	4380	82.6	--	1.39	3170
3/28/19	Primary HEPA 2	HEPA	5.34	22.2	11100	--	15000	--	10700	--	4320	302	--	1.63	167
3/28/19	Primary HEPA 8	HEPA	5.37	77.4	10900	--	14200	--	11700	--	4570	692	--	3.58	183
3/28/19	Condensate	Aqueous	2874.62	1.35	65.7	--	--	--	106	--	6.31	3.59	--	--	21.6
3/28/19	Condensate (Duplicate)	Aqueous	2874.62	1.39	30.4	--	--	2.69	111	--	6.28	3.65	--	--	22.6
5/7/19	Glass Pour 0.76	Solid	556.65	2.56	31300	--	44.1	--	29900	1.10	16400	1230	5.42	4.14	39200
5/7/19	Glass Pour 3.24	Solid	928.23	2.84	31700	--	45.6	--	29200	0.988	16100	1170	5.79	4.22	38100
5/7/19	Glass Pour 4.64	Solid	675.06	2.82	31000	--	37.5	--	29500	0.717	16300	966	5.21	4.36	38700
5/7/19	Glass Pour 5.06	Solid	2629.93	3.00	30900	--	37.0	--	29700	0.692	16000	982	4.72	4.46	38000
5/7/19	AN-105 Melter Feed	Feed	5845.00	3.93	16000	--	16.4	--	16400	--	7810	318	1.19	2.17	18300
5/7/19	Sampling HEPA 1	HEPA	11.89	64.0	12400	--	15000	--	12400	--	4610	416	--	1.00	517
5/7/19	Primary HEPA 5	HEPA	5.28	26.7	11300	3.56	15300	--	11200	--	4620	160	--	1.11	191
5/7/19	Primary HEPA 6	HEPA	9.96	49.6	6670	--	8460	--	8110	--	2640	363	--	1.60	126
5/7/19	Condensate	Aqueous	3752.09	2.01	118	--	--	--	236	--	15.7	8.71	--	--	32.6
5/7/19	Condensate (Duplicate)	Aqueous	3752.09	1.70	93.7	--	--	--	353	--	26.9	8.58	--	--	83.9
5/7/19	Primary SBS Sump	Aqueous	1033.76	1.74	125	--	--	--	410	--	62.7	5.69	--	--	60.0
5/7/19	Primary Offgas Piping Wash	Aqueous	281.33	8.38	326	--	0.318	--	428	--	150	37.7	--	0.265	389
5/7/19	Sampling Offgas Piping Wash	Aqueous	284.68	0.752	145	--	--	--	266	--	53.0	5.55	--	--	186

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

Table A.2. Chemical Analysis of Selected Samples for Run 2 (cont.)

Date	Sample Name	Lanthanum (mg kg^{-1})	Lead (mg kg^{-1})	Lithium (mg kg^{-1})	Magnesium (mg kg^{-1})	Manganese (mg kg^{-1})	Molybdenum (mg kg^{-1})	Nickel (mg kg^{-1})	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})	Silicon (mg kg^{-1})	Sodium (mg kg^{-1})	Strontium (mg kg^{-1})	Sulfur (mg kg^{-1})
3/28/19	Glass Pour 1.06	179	68.8	199	7420	105	65.3	436	627	3750	217000	149000	33.0	1660
3/28/19	Glass Pour 3.81	92.4	68.7	110	7260	82.1	33.9	328	616	3795	214000	151500	23.2	1780
3/28/19	Glass Pour 4.20	81.4	68.4	99.0	7120	80.3	30.7	318	632	3810	214000	152000	22.0	1730
3/28/19	AN-105 Melter Feed	--	34.8	1.31	3200	24.1	--	57.1	339	1985	105500	78700	6.27	992
3/28/19	Sampling HEPA 1	--	11.9	6.02	584	5.00	15.3	8.57	160	8370	378500	54650	180	1625
3/28/19	Primary HEPA 2	--	3.00	8.66	712	5.02	22.7	3.45	14.7	8270	386000	26000	157	601
3/28/19	Primary HEPA 8	--	5.14	39.5	642	4.25	19.0	3.71	16.6	9200	353000	34400	194	1710
3/28/19	Condensate	--	--	0.665	--	0.609	--	0.484	--	15.7	23.1	317	--	18.3
3/28/19	Condensate (Duplicate)	--	--	0.640	--	0.611	--	0.474	--	15.9	23.6	320	--	17.5
5/7/19	Glass Pour 0.76	64.9	65.8	80.9	7170	80.7	28.6	1030	622	3820	213000	152000	21.0	1740
5/7/19	Glass Pour 3.24	45.1	66.1	57.1	7130	74.2	27.9	824	624	3750	217000	151000	20.7	1720
5/7/19	Glass Pour 4.64	30.8	67.2	41.7	7250	67.9	12.9	602	604	3760	216000	152000	16.0	1810
5/7/19	Glass Pour 5.06	27.9	66.3	38.6	7030	66.0	11.4	552	604	3770	217000	151000	15.7	1780
5/7/19	AN-105 Melter Feed	--	32.8	1.09	2920	22.9	--	52.8	310	1880	107000	74700	5.94	945
5/7/19	Sampling HEPA 1	--	3.89	4.39	633	4.59	18.1	3.71	24.1	9080	338000	34300	192	685
5/7/19	Primary HEPA 5	--	3.45	6.03	636	4.08	17.6	3.76	17.2	8800	374000	29400	196	839
5/7/19	Primary HEPA 6	--	3.85	17.6	365	2.70	10.1	3.32	24.0	5360	218000	25100	116	1720
5/7/19	Condensate	--	--	1.00	--	1.19	--	0.474	--	29.1	47.4	683	--	41.3
5/7/19	Condensate (Duplicate)	--	0.424	--	--	0.632	--	0.379	--	38.8	77.2	1200	--	47.4
5/7/19	Primary SBS Sump	--	--	0.609	3.37	1.10	--	0.490	--	43.5	82.4	1400	--	53.9
5/7/19	Primary Offgas Piping Wash	--	0.982	7.09	18.2	3.02	1.14	2.06	--	123	300	2820	0.271	190
5/7/19	Sampling Offgas Piping Wash	--	--	0.851	--	0.952	0.606	0.611	--	30.0	148	1070	--	24.4

Values marked with ‘—’ denote that the metal concentration was below the analysis detection limit.

Table A.2. Chemical Analysis of Selected Samples for Run 2 (cont.)

Date	Sample Name	Tin (mg kg^{-1})	Titanium (mg kg^{-1})	Tungsten (mg kg^{-1})	Vanadium (mg kg^{-1})	Yttrium (mg kg^{-1})	Zinc (mg kg^{-1})	Zirconium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Fluoride (mg kg^{-1})	Bromide (mg kg^{-1})	N (Nitrate) (mg kg^{-1})	N (Nitrite) (mg kg^{-1})	P (Phosphate) (mg kg^{-1})
3/28/19	Glass Pour 1.06	9.69	8270	153	46.5	37.9	27300	20100	--	--	--	--	--	--	--
3/28/19	Glass Pour 3.81	8.98	8210	173	46.3	38.1	27750	19900	--	23.0	--	--	--	--	--
3/28/19	Glass Pour 4.20	9.05	8240	161	46.5	37.8	28000	20000	--	--	--	--	--	--	--
3/28/19	AN-105 Melter Feed	--	3960	58.5	5.99	4.61	14500	9675	976	2760	227	--	13300	11700	142
3/28/19	Sampling HEPA 1	--	106	63.1	0.951	2.37	12950	240	10600	1750	875	--	263	342	--
3/28/19	Primary HEPA 2	--	17.1	44.3	--	2.66	11300	132	39.8	1470	96.5	--	2250	--	--
3/28/19	Primary HEPA 8	--	18.7	51.4	--	2.12	11300	77.5	3260	5160	108	--	4680	--	--
3/28/19	Condensate	--	0.644	--	--	--	27.7	0.983	205	140	29.8	--	1540	--	--
3/28/19	Condensate (Duplicate)	--	0.653	--	--	--	29.1	0.954	208	134	33.5	--	1560	--	--
5/7/19	Glass Pour 0.76	9.02	8110	153	45.3	38.3	27600	19800	--	--	--	--	--	--	--
5/7/19	Glass Pour 3.24	9.44	8360	163	46.8	39.9	27100	20400	--	--	--	--	--	--	--
5/7/19	Glass Pour 4.64	9.51	8180	165	46.8	38.6	27800	20000	--	26.4	--	--	--	--	--
5/7/19	Glass Pour 5.06	9.60	8180	150	46.6	38.2	27600	19900	--	24.6	--	--	--	--	--
5/7/19	AN-105 Melter Feed	--	3860	65.9	5.64	4.35	14000	9540	996	2800	119	--	13500	11900	--
5/7/19	Sampling HEPA 1	--	26.1	55.9	--	2.13	11700	89.4	6810	5000	2920	--	125	1090	--
5/7/19	Primary HEPA 5	--	19.3	57.7	--	2.19	11800	78.3	122	3160	288	--	5370	--	--
5/7/19	Primary HEPA 6	--	11.7	33.8	--	1.19	7050	44.8	2830	12200	--	--	32400	--	--
5/7/19	Condensate	--	1.12	--	--	--	78.5	1.70	322	232	62.6	--	2240	--	--
5/7/19	Condensate (Duplicate)	--	2.64	--	--	--	111	3.78	293	246	84.6	--	2190	--	--
5/7/19	Primary SBS Sump	--	2.16	--	--	--	193	2.42	277	189	124	--	1290	10.1	--
5/7/19	Primary Offgas Piping Wash	--	20.8	--	--	--	312	22.4	1440	563	432	--	59.3	82.2	--
5/7/19	Sampling Offgas Piping Wash	--	8.27	--	--	--	154	11.1	129	66.8	87.9	--	17.7	65.8	--

Values marked with ‘—’ denote that the metal concentration was below the analysis detection limit.

Table A.3. Chemical Analysis of Selected Samples for Run 3

Sample Name	Sample Type	Sample Mass (g)	Rhenium (mg kg^{-1})	Aluminum (mg kg^{-1})	Barium (mg kg^{-1})	Boron (mg kg^{-1})	Cadmium (mg kg^{-1})	Calcium (mg kg^{-1})	Chromium (mg kg^{-1})	Cobalt (mg kg^{-1})	Copper (mg kg^{-1})	Iron (mg kg^{-1})
Glass Pour 0.86	Glass	522.93	2.81	30500	36.2	30700	0.533	16300	1220	4.05	4.55	37400
Glass Pour 2.87	Glass	1761.53	2.59	30400	32.0	30100	--	15150	960	3.82	4.37	36800
Glass Pour 3.49	Glass	620.35	2.33	30600	30.1	29600	--	13900	922	3.64	3.94	37100
Glass Pour 4.98	Glass	1192.13	2.42	30400	34.9	29500	--	16300	875	3.69	4.70	36500
Glass Pour 5.71	Glass	619.39	2.55	30500	33.4	29800	--	16200	804	4.19	4.58	36500
Glass Pour 7.19	Glass	1454.34	2.61	30100	33.1	29900	--	16500	768	3.94	4.79	36300
Glass Pour 7.51	Glass	247.56	2.92	30200	33.1	29500	--	16300	801	3.79	4.74	36300
Glass Pour 7.56	Glass	1968.26	2.83	30300	32.8	31100	--	16300	782	4.56	4.77	36500
AN-105 Melter Feed	Solid/Aqueous	12795.00	3.85	15550	17.2	15250	--	8445	317	1.46	2.33	18450
AN-105 Melter Feed (Duplicate)	Solid/Aqueous	12795.00	3.88	15600	17.1	15700	--	8340	316	1.42	2.38	18300
Sampling HEPA 1	HEPA	10.68	87.8	11250	15150	11150	--	4750	72.5	--	0.810	275
Sampling HEPA 2	HEPA	10.42	78.7	11600	15200	11000	--	4430	69.0	--	0.711	228
Sampling HEPA 3	HEPA	10.45	59.9	11700	15400	11700	--	4790	77.2	--	0.804	326
Primary HEPA 1	HEPA	5.11	44.4	11200	15100	11100	--	4790	172	--	4.19	187
Primary HEPA 2	HEPA	5.45	96.3	11200	15100	10900	--	4650	64.8	--	0.860	200
Primary HEPA 3	HEPA	10.65	47.4	19900	23400	19900	--	16300	91.4	--	0.725	269
Condensate	Aqueous	4933.57	2.19	44.4	--	111	--	13.2	4.74	--	--	54.1
Condensate (Condensate)	Aqueous	4933.57	2.19	45.0	--	114	--	12.9	4.80	--	--	55.3
Primary SBS Sump	Aqueous	969.97	2.87	187	--	194	--	34.6	10.6	--	--	150
Primary Offgas Piping Wash	Aqueous	245.15	12.2	152	--	124	--	74.4	18.9	--	--	203
Sampling Offgas Piping Wash	Aqueous	136.69	1.88	22.1	--	37.3	--	7.92	2.11	--	--	31.6

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

Table A.3. Chemical Analysis of Selected Samples for Run 3 (cont.)

Sample Name	Lanthanum (mg kg^{-1})	Lead (mg kg^{-1})	Lithium (mg kg^{-1})	Magnesium (mg kg^{-1})	Manganese (mg kg^{-1})	Molybdenum (mg kg^{-1})	Nickel (mg kg^{-1})	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})	Silicon (mg kg^{-1})	Sodium (mg kg^{-1})	Strontium (mg kg^{-1})	Sulfur (mg kg^{-1})
Glass Pour 0.86	21.9	69.0	35.6	7170	68.3	10.2	774	63.3	3770	206000	150000	14.9	1450
Glass Pour 2.87	10.1	65.2	20.3	6715	56.4	5.16	411	145	3735	205000	147000	12.6	1505
Glass Pour 3.49	8.00	61.7	--	6170	51.8	3.71	338	136	3560	205000	138000	11.7	1570
Glass Pour 4.98	5.99	69.8	--	7440	58.1	2.77	338	144	3790	206000	149000	13.1	1500
Glass Pour 5.71	4.79	69.8	--	7320	56.5	2.37	270	117	3750	208000	148000	12.7	1470
Glass Pour 7.19	3.15	69.4	--	7610	55.2	1.35	232	145	3750	207000	147000	12.6	1520
Glass Pour 7.51	3.22	69.9	--	7510	55.8	1.54	275	123	3760	205000	149000	12.6	1470
Glass Pour 7.56	3.52	69.7	--	7510	55.4	2.06	235	146	3740	207000	147000	12.6	1800
AN-105 Melter Feed	--	36.3	--	3860	25.9	--	67.1	119	1930	106500	75150	6.35	978
AN-105 Melter Feed (Duplicate)	--	36.2	--	3760	25.7	--	64.7	121	1950	107000	75700	6.36	990
Sampling HEPA 1	--	3.39	--	651	4.29	16.5	4.01	16.7	9110	374000	30900	205	632
Sampling HEPA 2	--	3.30	--	604	4.16	15.0	3.36	21.6	8830	372000	30700	184	641
Sampling HEPA 3	--	3.31	--	650	5.02	16.2	3.86	30.7	8930	375000	30900	202	476
Primary HEPA 1	--	2.91	49.9	660	4.84	18.9	3.56	20.0	9040	380000	27700	209	547
Primary HEPA 2	--	3.44	--	641	8.25	16.6	6.01	19.1	9040	372000	30300	201	626
Primary HEPA 3	1.86	2.29	--	1730	6.62	1.55	1.15	48.7	12800	161000	42700	297	455
Condensate	--	--	--	--	1.20	--	0.275	--	25.7	38.2	401	--	27.4
Condensate (Duplicate)	--	--	--	--	1.22	--	0.269	--	26.0	38.9	400	--	28.4
Primary SBS Sump	--	0.565	0.663	10.0	6.02	--	1.47	--	42.6	97.6	651	--	51.2
Primary Offgas Piping Wash	--	0.590	2.86	9.68	1.68	0.866	2.97	--	130	171	1900	--	172
Sampling Offgas Piping Wash	--	--	--	--	0.525	--	0.965	--	22.6	18.5	390	--	24.0

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

Table A.3. Chemical Analysis of Selected Samples for Run 3 (cont.)

Sample Name	Tin (mg kg^{-1})	Titanium (mg kg^{-1})	Tungsten (mg kg^{-1})	Vanadium (mg kg^{-1})	Yttrium (mg kg^{-1})	Zinc (mg kg^{-1})	Zirconium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Fluoride (mg kg^{-1})	N (Nitrate) (mg kg^{-1})	N (Nitrite) (mg kg^{-1})	P (Phosphate) (mg kg^{-1})
Glass Pour 0.86	8.47	8120	172	47.2	38.0	28900	18300	--	--	--	--	--	--
Glass Pour 2.87	8.43	8075	150	43.9	34.7	28550	18700	--	--	--	--	--	--
Glass Pour 3.49	8.39	8080	152	41.4	32.8	27800	18700	--	--	--	--	--	--
Glass Pour 4.98	8.30	8110	162	47.5	38.4	27600	18500	--	--	--	--	--	--
Glass Pour 5.71	8.89	8060	169	47.4	37.8	28300	19800	--	--	--	--	--	--
Glass Pour 7.19	9.84	8070	169	47.2	38.2	28600	19700	--	--	--	--	--	--
Glass Pour 7.51	8.46	8060	172	47.9	38.2	28400	19700	--	--	--	--	--	--
Glass Pour 7.56	9.54	8130	175	47.4	38.1	29300	19900	--	--	--	--	--	--
AN-105 Melter Feed	2.03	4155	70.3	5.90	4.43	14500	10070	988	2690	338	3220	2870	100
AN-105 Melter Feed (Duplicate)	--	4160	72.8	5.50	4.28	15100	10100	991	2720	330	13100	11600	109
Sampling HEPA 1	--	23.1	55.7	--	2.21	12300	92.5	11700	1690	240	689	--	--
Sampling HEPA 2	--	18.6	55.8	--	1.96	12400	74.2	13400	2310	384	442	--	--
Sampling HEPA 3	--	23.4	61.3	--	2.21	12700	84.5	8150	2450	779	353	--	--
Primary HEPA 1	--	20.0	58.3	--	2.24	12300	81.0	192	2010	36.4	2110	--	--
Primary HEPA 2	2.06	18.7	63.8	--	2.15	12100	78.0	22.1	1830	--	5730	--	--
Primary HEPA 3	--	237	69.5	3.36	1.67	18500	73.4	27.9	1170	36.5	7030	--	--
Condensate	--	2.10	--	--	--	27.5	2.68	405	183	37.6	4825	--	--
Condensate (Duplicate)	--	2.09	--	--	--	28.3	2.70	403	173	37.9	4810	--	--
Primary SBS Sump	--	6.13	--	--	--	90.7	3.92	605	246	126	3050	--	--
Primary Offgas Piping Wash	--	8.67	--	--	--	136	8.29	1790	496	363	88.3	6.25	--
Sampling Offgas Piping Wash	--	0.748	--	--	--	27.2	--	299	65.7	67.2	58.7	5.47	--

Values marked with ‘—’ denote that the metal concentration was below the analysis detection limit.

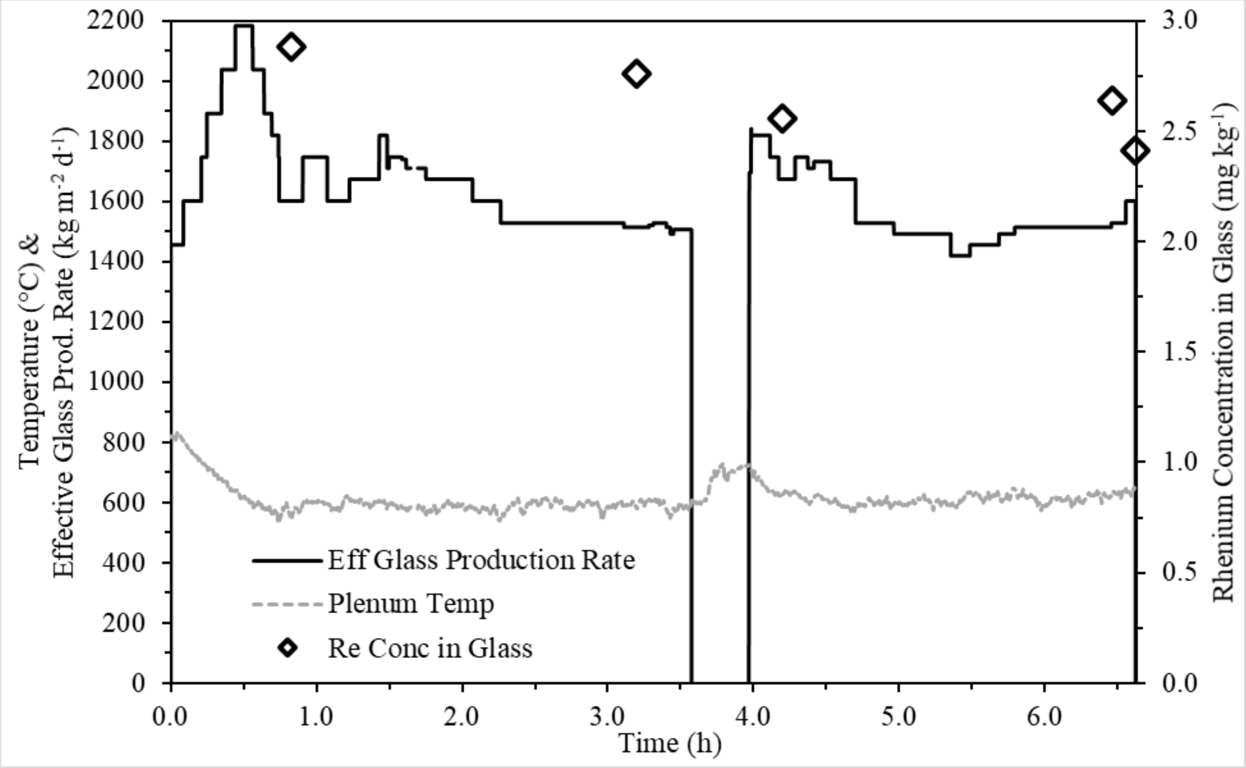

Figure A.16. Effective glass production rate, plenum temperature, and Re concentration in analyzed glass pour samples from Run 1.

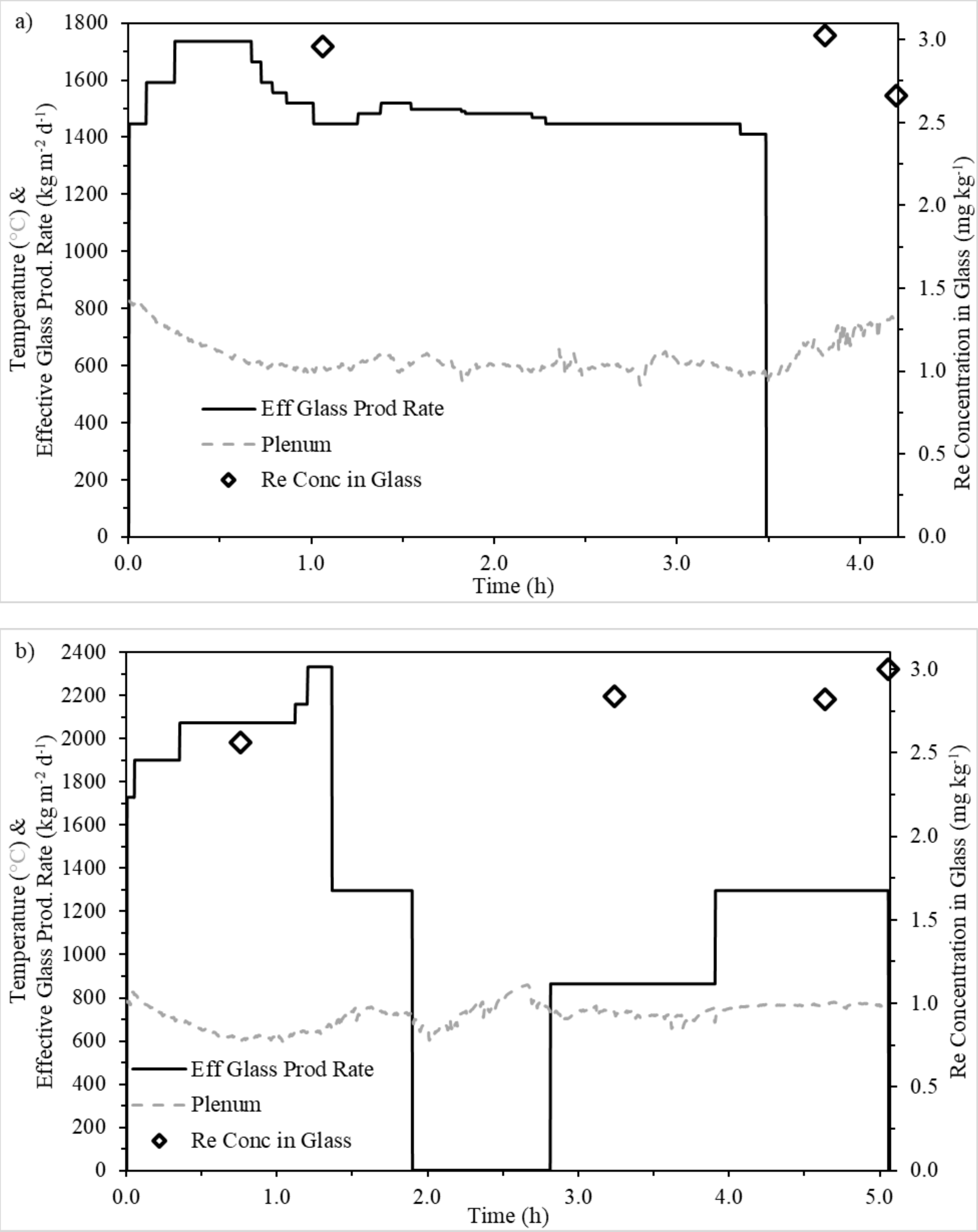

Figure A.17. Effective glass production rate, plenum temperature, and Re concentration in analyzed glass pour samples for the portion of Run 2 on a) 3/28/2019 and b) 5/7/2019.

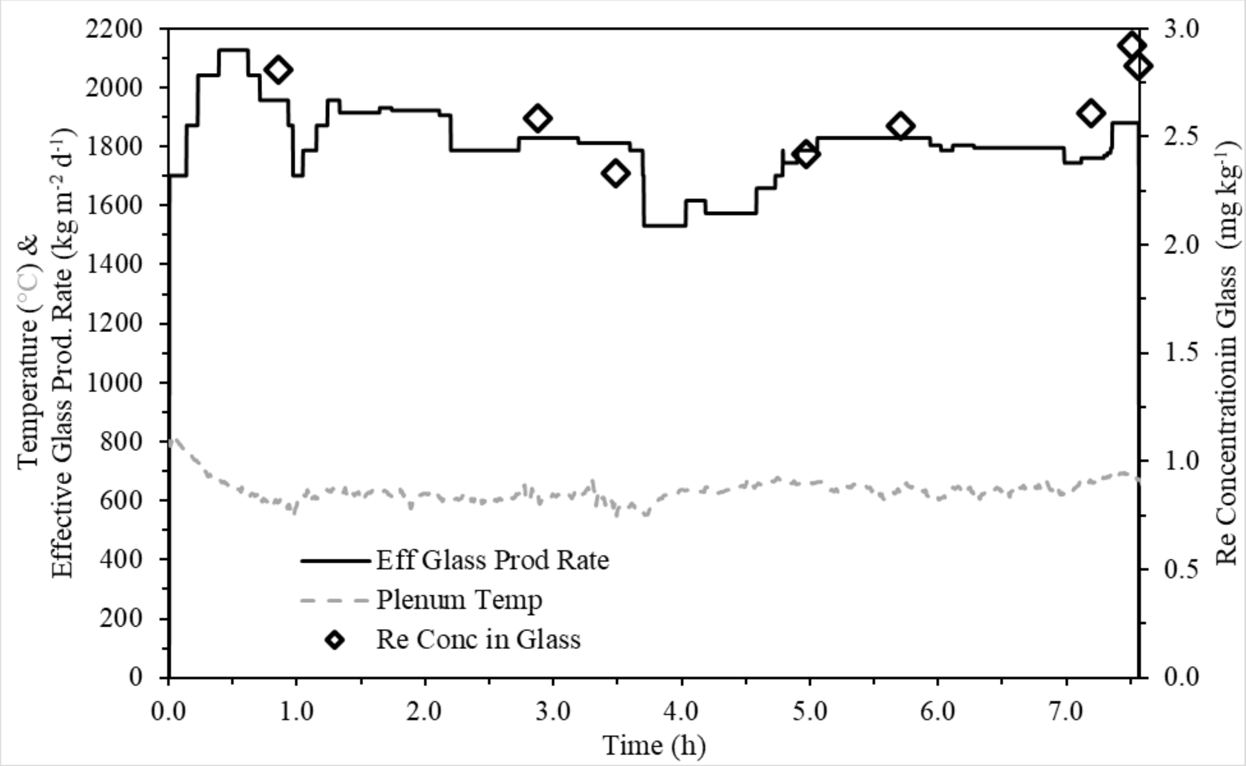

Figure A.18. Effective glass production rate, plenum temperature, and Re concentration in analyzed glass pour samples from Run 3.

Appendix B – HLW Run Results Data

The figures and table in this section display the various processing values (temperatures, effective glass production rates, bubbling flux rates, and melter vacuum measurements) collected during the AlF2-05 run, the ruthenium concentration in the glass pours, and the complete chemical analytical results.

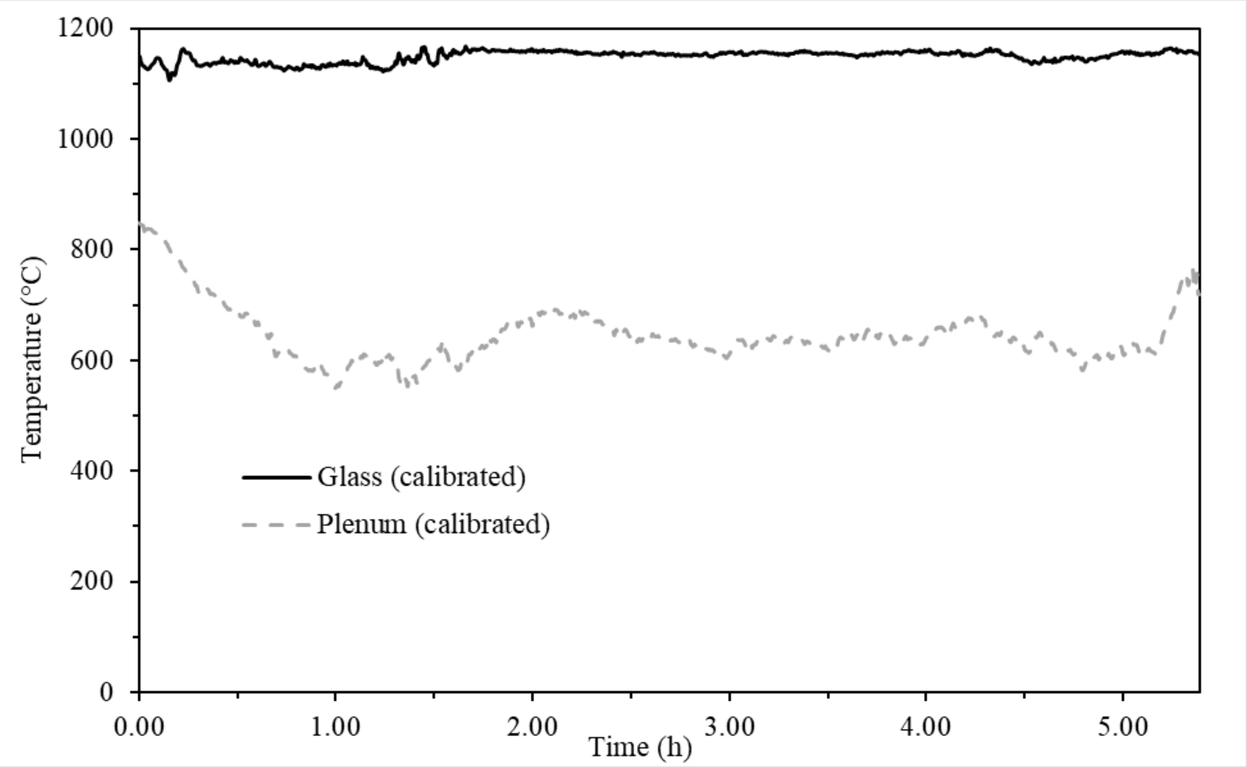

Figure B.1. Glass and plenum temperatures recorded by a calibrated data logger for the AlF2-05 run.

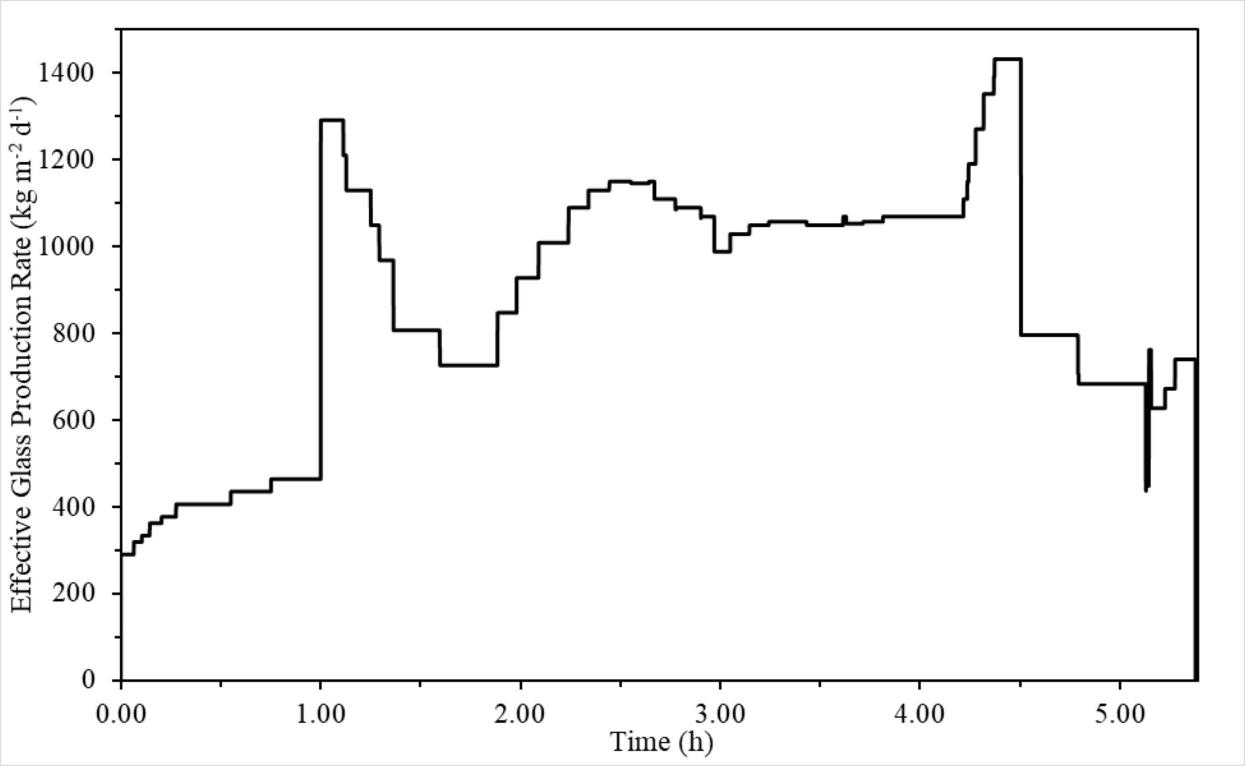

Figure B.2. Effective glass production rate for the AlF2-05 run.

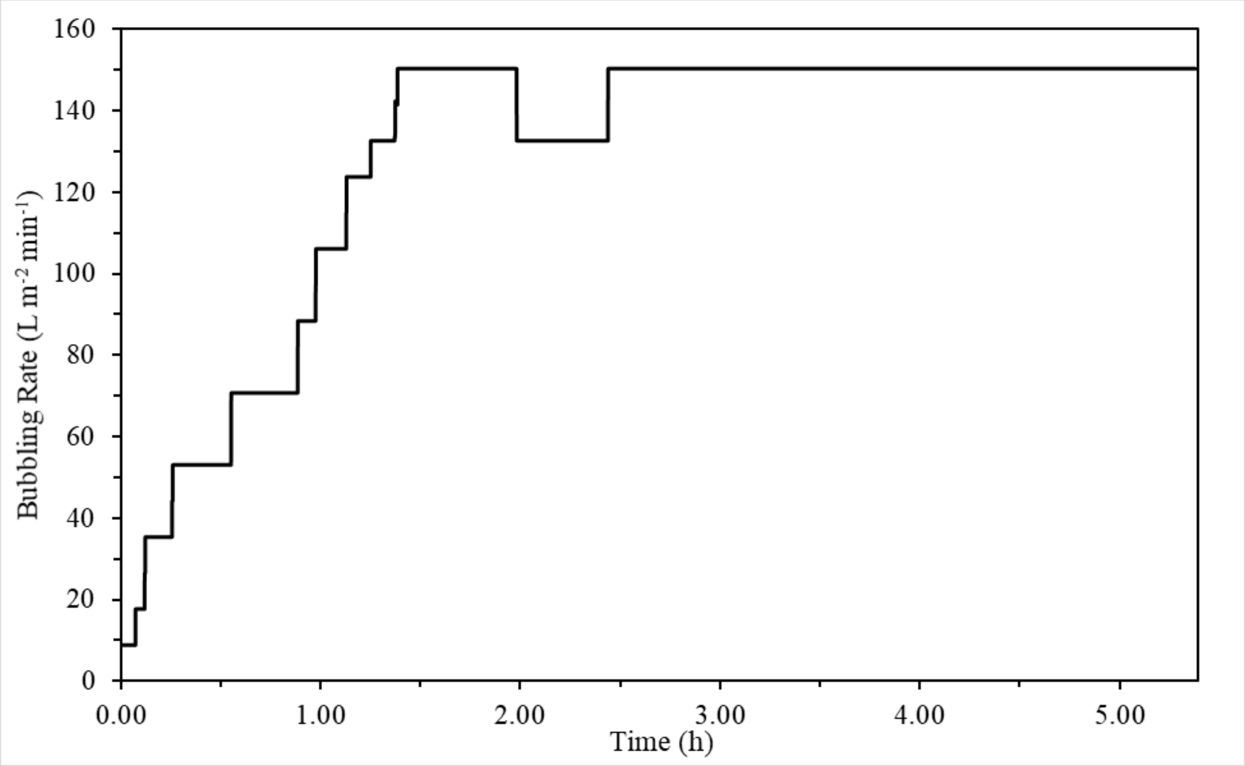

Figure B.3. Bubbling flux rate for the AlF2-05 run.

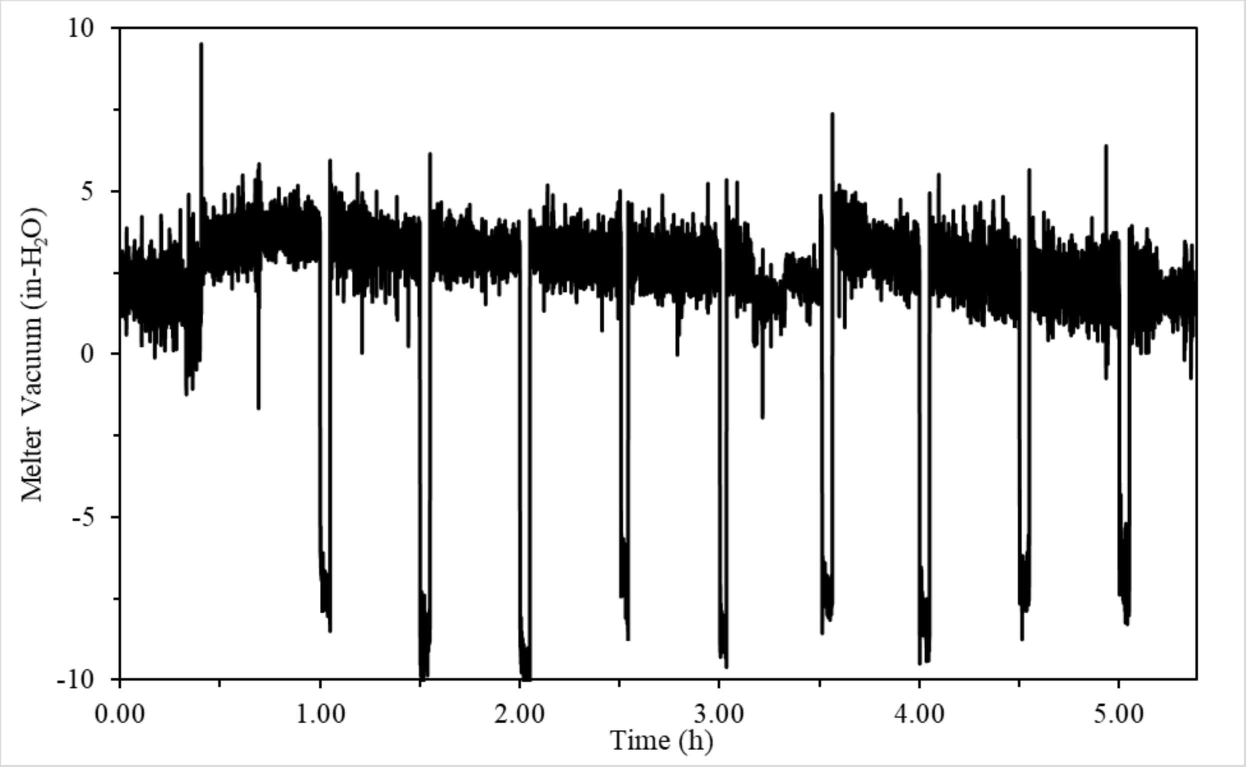

Figure B.4. Melter vacuum measurement for the AlF2-05 run.

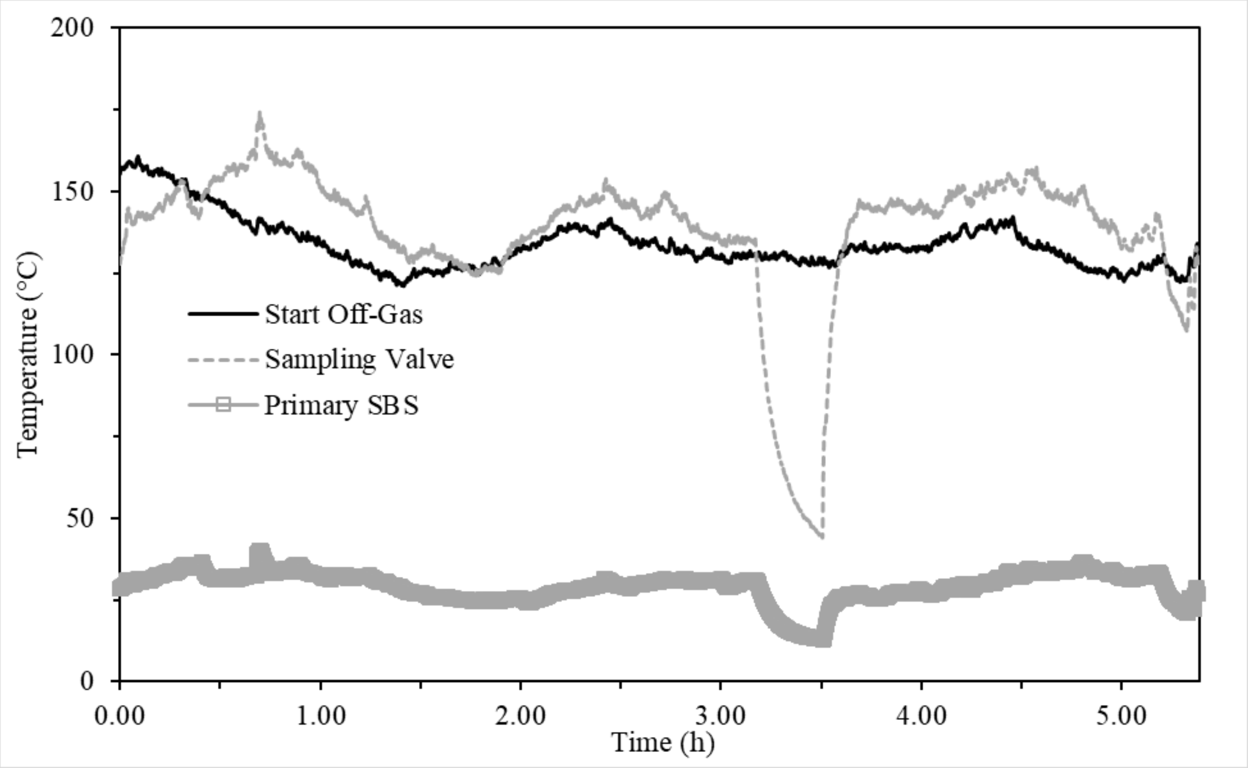

Figure B.5. Start of offgas system, sampling valve, and primary SBS temperatures for the AlF2-05 run.

Table B.1. Chemical Analysis of Selected Samples for the AlF2-05 Run

Sample Name	Sample Type	Sample Mass (g)	Ruthenium (mg kg^{-1})	Aluminum (mg kg^{-1})	Arsenic (mg kg^{-1})	Barium (mg kg^{-1})	Bismuth (mg kg^{-1})	Boron (mg kg^{-1})	Cadmium (mg kg^{-1})	Calcium (mg kg^{-1})	Chromium (mg kg^{-1})	Cobalt (mg kg^{-1})	Copper (mg kg^{-1})	Iron (mg kg^{-1})
Glass Pour 1.00	Solid	192.20	95.8	176000	2.64	16.0	2820	68000	1.04	2010	1450	7.57	2.07	9890
Glass Pour 2.47	Solid	733.74	140	175000	4.43	11.7	2850	68300	0.629	1720	1230	6.56	2.14	9020
Glass Pour 3.51	Solid	476.37	198	177000	4.72	14.5	3120	70200	--	1660	1200	4.78	2.23	8810
Glass Pour 5.01	Solid	727.92	164	176500	6.07	9.47	2950	70100	--	1590	1190	5.14	2.59	8750
Glass Pour 5.38	Solid	1879.15	100	179000	3.62	9.80	2950	68000	--	1550	1190	5.12	2.51	8700
AlF2-05 Melter Feed	Feed	6850.00	70.5	63150	2.60	2.46	1095	24200	--	519	400	--	1.05	3075
Primary HEPA 1	HEPA	5.52	64.3	11000	--	15600	43.8	10900	--	4290	249	--	10.8	158
Primary HEPA 2	HEPA	5.27	1030	10800	2.94	15500	208	14200	--	4140	624	--	1.22	196
Sampling HEPA 1	HEPA	10.57	247	11100	--	15900	25.2	10600	--	4300	90.8	--	0.689	173
Condensate	Aqueous	5238.32	2.01	21.6	--	--	--	175	--	5.97	1.74	--	--	20.5
Condensate (Duplicate)	Aqueous	5238.32	2.07	22.9	--	--	--	174	--	6.17	1.74	--	--	20.9
Sampling SBS Sump	Aqueous	1250.85	--	--	--	--	--	32.0	--	--	--	--	--	--
Primary SBS Sump	Aqueous	964.03	0.972	--	--	--	--	246	--	--	1.94	--	--	--
Demister Liquid	Aqueous	23.09	0.612	71.8	--	--	--	125	--	30.1	24.9	--	0.479	198
Primary Offgas Piping Wash	Aqueous	215.78	16.1	104	--	--	3.31	155	--	6.89	7.05	--	--	15.9
Sampling Offgas Piping Wash	Aqueous	34.23	2.62	38.8	--	--	--	115	--	7.17	1.49	--	--	13.0

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

Table B.1. Chemical Analysis of Selected Samples for the AlF2-05 Run (cont.)

Sample Name	Lanthanum (mg kg^{-1})	Lead (mg kg^{-1})	Lithium (mg kg^{-1})	Magnesium (mg kg^{-1})	Manganese (mg kg^{-1})	Molybdenum (mg kg^{-1})	Nickel (mg kg^{-1})	Phosphorus (mg kg^{-1})	Potassium (mg kg^{-1})	Silicon (mg kg^{-1})	Silver (mg kg^{-1})	Sodium (mg kg^{-1})	Strontium (mg kg^{-1})	Sulfur (mg kg^{-1})
Glass Pour 1.00	7.57	0.890	26400	91.9	9590	38.5	736	32.6	540	120000	--	61000	576	81.8
Glass Pour 2.47	3.41	0.843	26700	62.9	9880	22.9	677	24.0	497	119000	--	59400	579	58.2
Glass Pour 3.51	25.8	--	27700	187	10100	17.4	692	28.6	599	119000	--	60100	573	71.4
Glass Pour 5.01	1.77	--	27000	67.0	9875	12.8	668	19.7	507	117500	--	59150	571	49.9
Glass Pour 5.38	3.50	--	27800	82.3	9890	11.5	686	17.5	552	118000	--	59300	569	42.7
AlF2-05 Melter Feed	--	--	9305	47.9	3640	--	243	--	189	43400	--	20400	223	32.4
Primary HEPA 1	--	2.82	239	649	4.67	33.6	3.38	--	7820	386000	--	27200	157	1020
Primary HEPA 2	--	1.89	1060	669	14.7	31.0	10.6	--	7210	383000	--	24900	155	1530
Sampling HEPA 1	--	1.97	115	682	18.5	16.9	4.19	--	7620	398000	--	22900	158	--
Condensate	--	--	8.43	2.41	--	--	0.270	--	--	12.2	--	54.0	--	5.76
Condensate (Duplicate)	--	--	8.38	2.50	--	--	--	--	--	13.1	--	53.7	--	5.43
Sampling SBS Sump	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Primary SBS Sump	--	--	16.5	--	--	--	--	--	--	--	--	77.8	--	8.38
Demister Liquid	--	--	8.83	--	5.28	2.80	15.2	--	--	63.4	0.593	133	0.265	9.25
Primary Offgas Piping Wash	--	--	37.3	--	7.38	0.999	0.684	--	14.0	16.1	--	362	0.462	69.0
Sampling Offgas Piping Wash	--	--	13.3	--	3.55	--	0.342	--	--	10.9	--	156	--	12.5

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

Table B.1. Chemical Analysis of Selected Samples for the AlF2-05 Run (cont.)

Sample Name	Tin (mg kg^{-1})	Titanium (mg kg^{-1})	Tungsten (mg kg^{-1})	Vanadium (mg kg^{-1})	Yttrium (mg kg^{-1})	Zinc (mg kg^{-1})	Zirconium (mg kg^{-1})	Chloride (mg kg^{-1})	Sulfate (mg kg^{-1})	Chromate (mg kg^{-1})	Fluoride (mg kg^{-1})	Bromide (mg kg^{-1})	N (Nitrate) (mg kg^{-1})	N (Nitrite) (mg kg^{-1})
Glass Pour 1.00	2.51	302	90.0	2.82	--	794	2520	--	--	--	--	--	--	--
Glass Pour 2.47	--	200	70.5	2.07	--	561	2220	--	--	2.68	--	--	--	--
Glass Pour 3.51	--	164	48.8	1.76	--	453	2120	--	--	2.26	--	--	--	--
Glass Pour 5.01	--	136	52.7	1.62	--	340	2010	--	--	2.22	--	--	--	--
Glass Pour 5.38	--	131	47.3	1.58	--	311	1990	--	--	2.35	--	--	--	--
AlF2-05 Melter Feed	--	--	--	--	--	--	589	--	61.6	--	--	--	116	--
Primary HEPA 1	--	15.7	74.6	--	2.45	10900	119	231	1725	187	52.6	--	3505	--
Primary HEPA 2	--	13.0	71.6	--	2.41	10500	120	939	4270	754	115	49.8	2310	--
Sampling HEPA 1	--	16.0	72.8	--	2.58	11200	126	484	580	99.1	50.2	62.9	--	--
Condensate	--	0.410	--	--	--	6.93	--	22.2	17.7	--	7.39	--	24.7	7.11
Condensate (Duplicate)	--	0.429	--	--	--	7.10	--	23.0	18.5	--	7.49	--	24.4	7.03
Sampling SBS Sump	--	--	--	--	--	0.413	--	--	--	--	--	--	--	--
Primary SBS Sump	--	--	--	--	--	0.584	--	23.1	24.9	5.45	6.71	--	--	6.05
Demister Liquid	--	3.77	--	--	--	47.9	4.51	277	104	--	11.0	--	12500	--
Primary Offgas Piping Wash	--	0.325	--	--	--	10.5	--	209	201	10.1	24.3	7.10	7.76	--
Sampling Offgas Piping Wash	--	0.284	--	--	--	10.8	--	86.7	34.2	--	11.6	--	6.35	--

Values marked with '—' denote that the metal concentration was below the analysis detection limit.

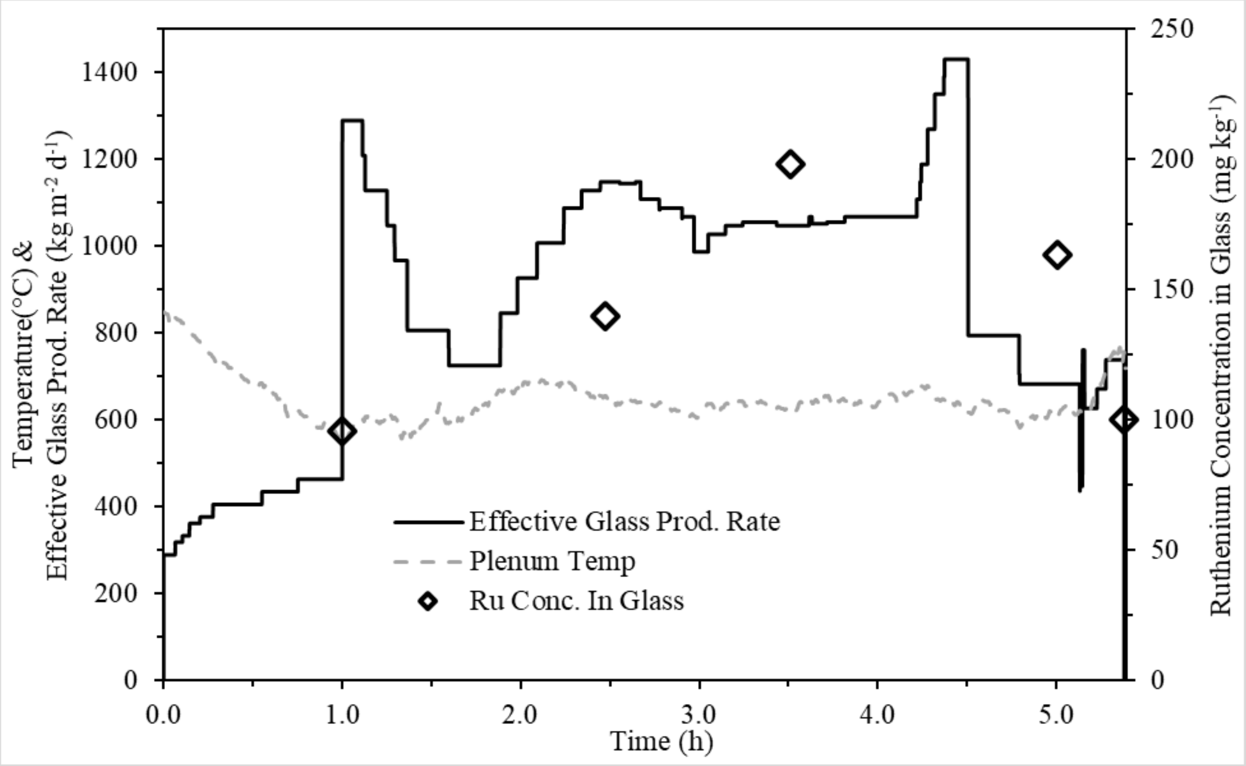

Figure B.6. Effective glass production rate, plenum temperature, and Ru concentration in analyzed glass pour samples for the AlF2-05 run.

Appendix C – Glass Compositional Trends

The figures in this section display the compositional trends for each component oxide in the analyzed glass product from the LAW runs and the AlF2-05 run.

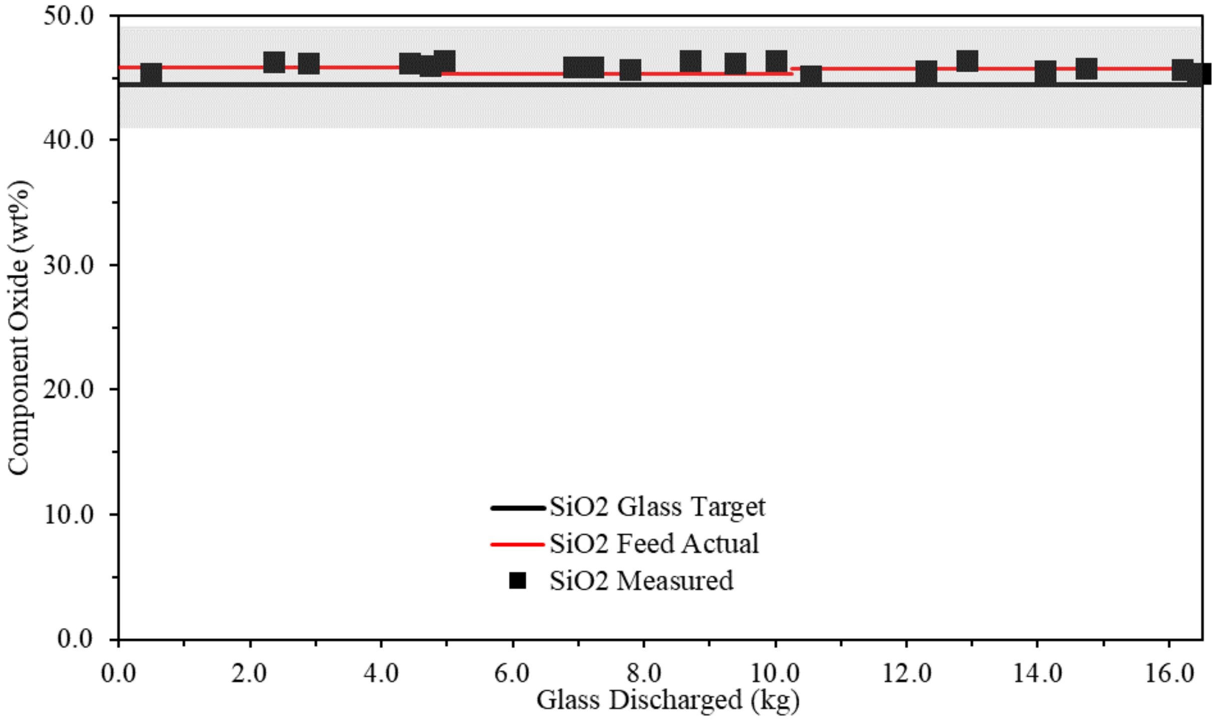

Figure C.1. Measured SiO_2 content in the LAW run glass product and AN-105 melter feed along with the SiO_2 content target from the AN-105 glass composition.

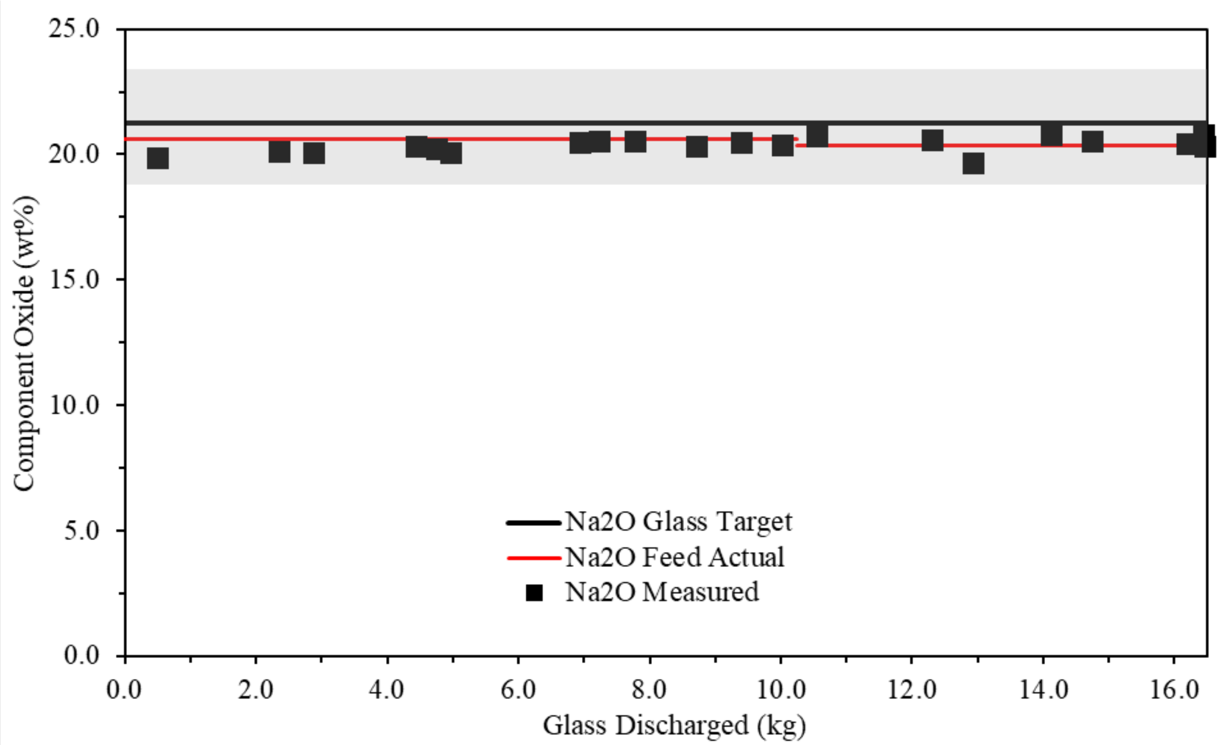

Figure C.2. Measured Na_2O content in the LAW run glass product and AN-105 melter feed along with the Na_2O content target from the AN-105 glass composition.

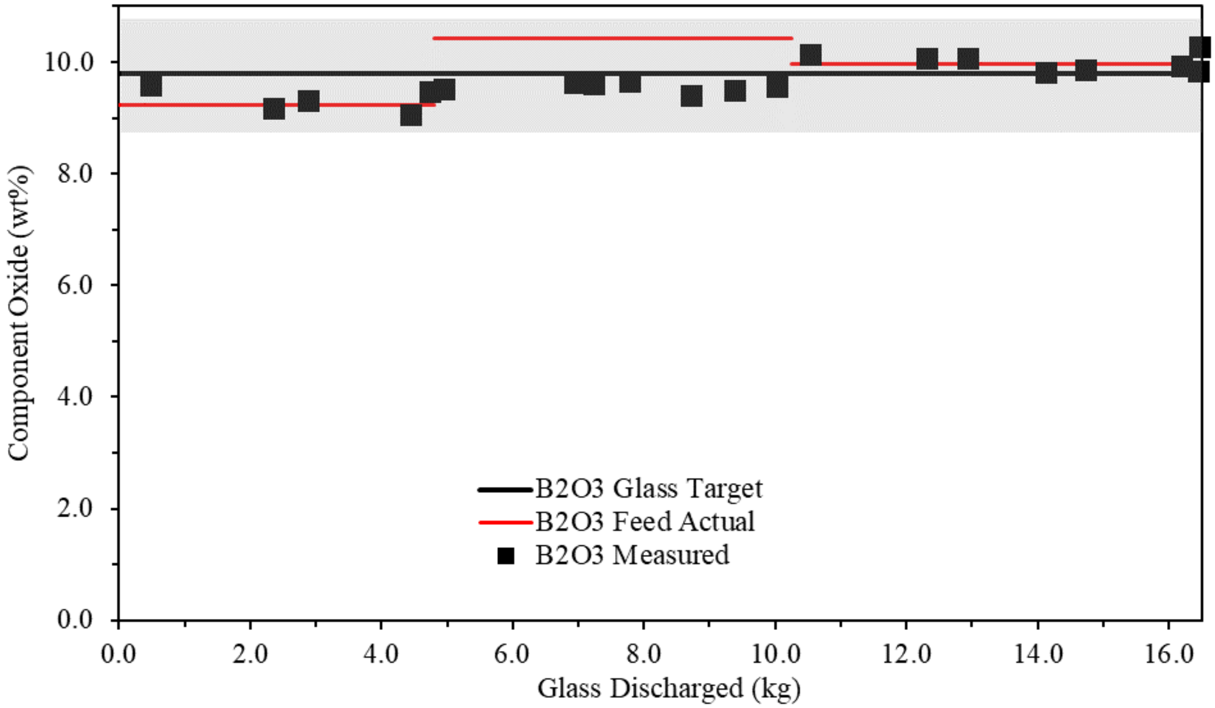

Figure C.3. Measured B_2O_3 content in the LAW run glass product and AN-105 melter feed along with the B_2O_3 content target from the AN-105 glass composition.

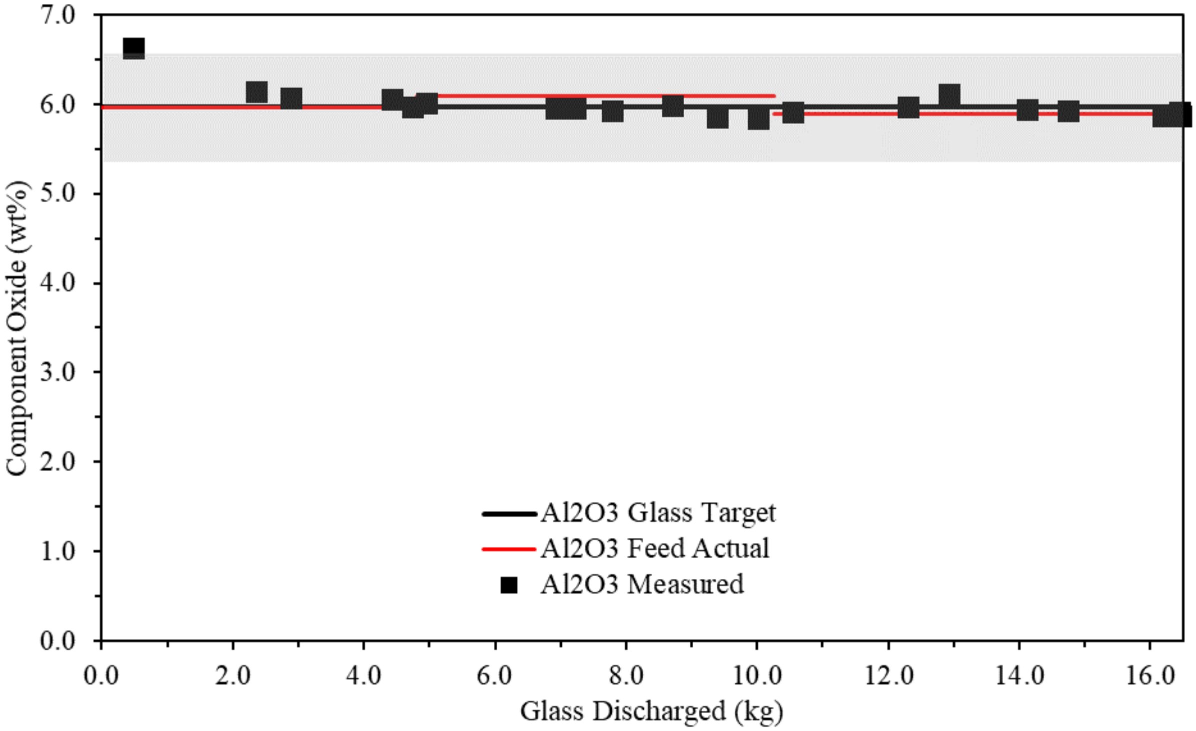

Figure C.4. Measured Al_2O_3 content in the LAW run glass product and AN-105 melter feed along with the Al_2O_3 content target from the AN-105 glass composition.

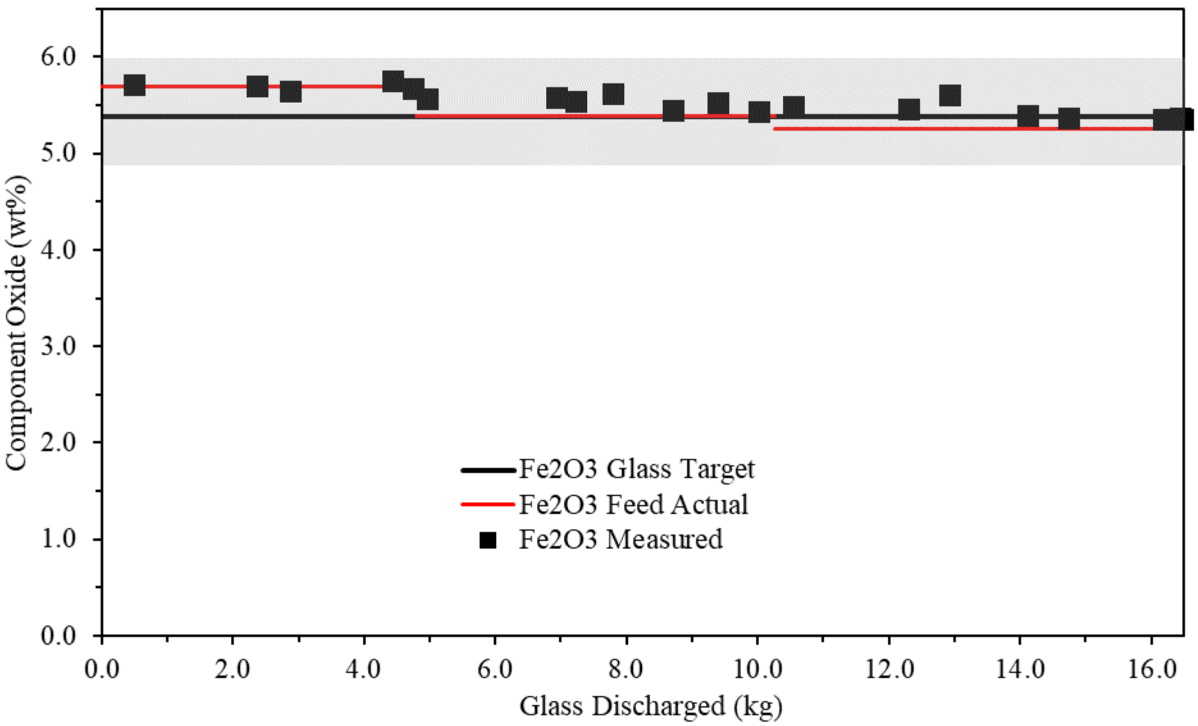

Figure C.5. Measured Fe_2O_3 content in the LAW run glass product and AN-105 melter feed along with the Fe_2O_3 content target from the AN-105 glass composition.

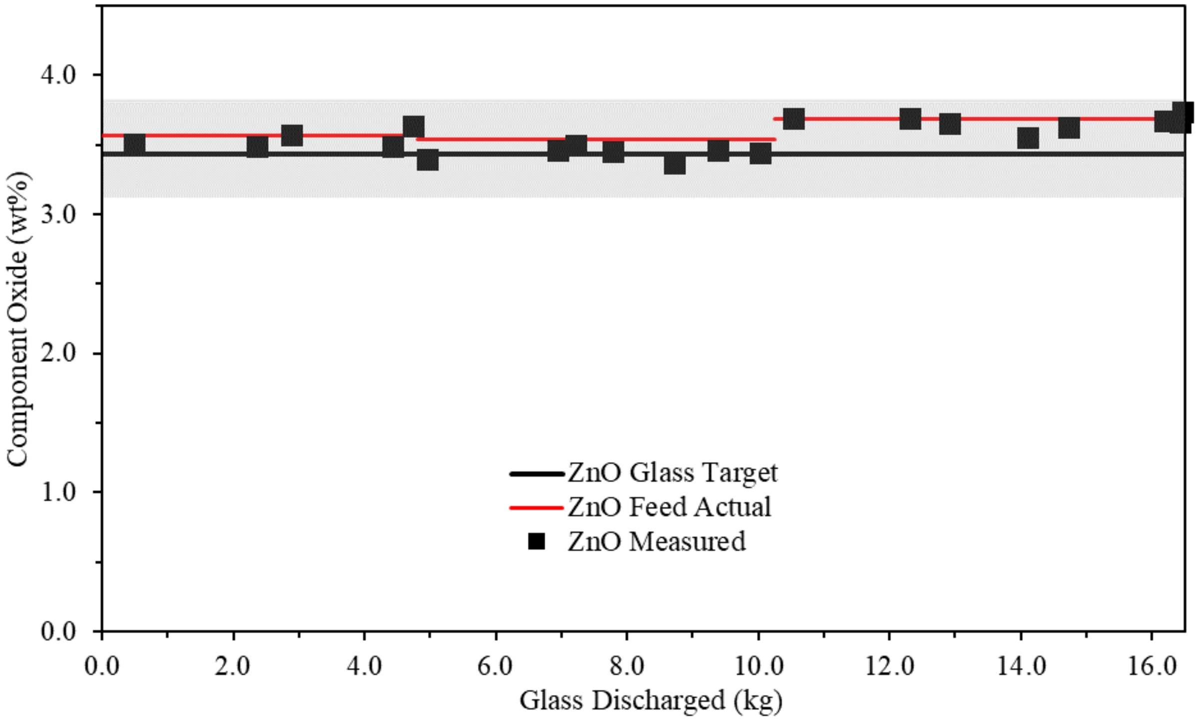

Figure C.6. Measured ZnO content in the LAW run glass product and AN-105 melter feed along with the ZnO content target from the AN-105 glass composition.

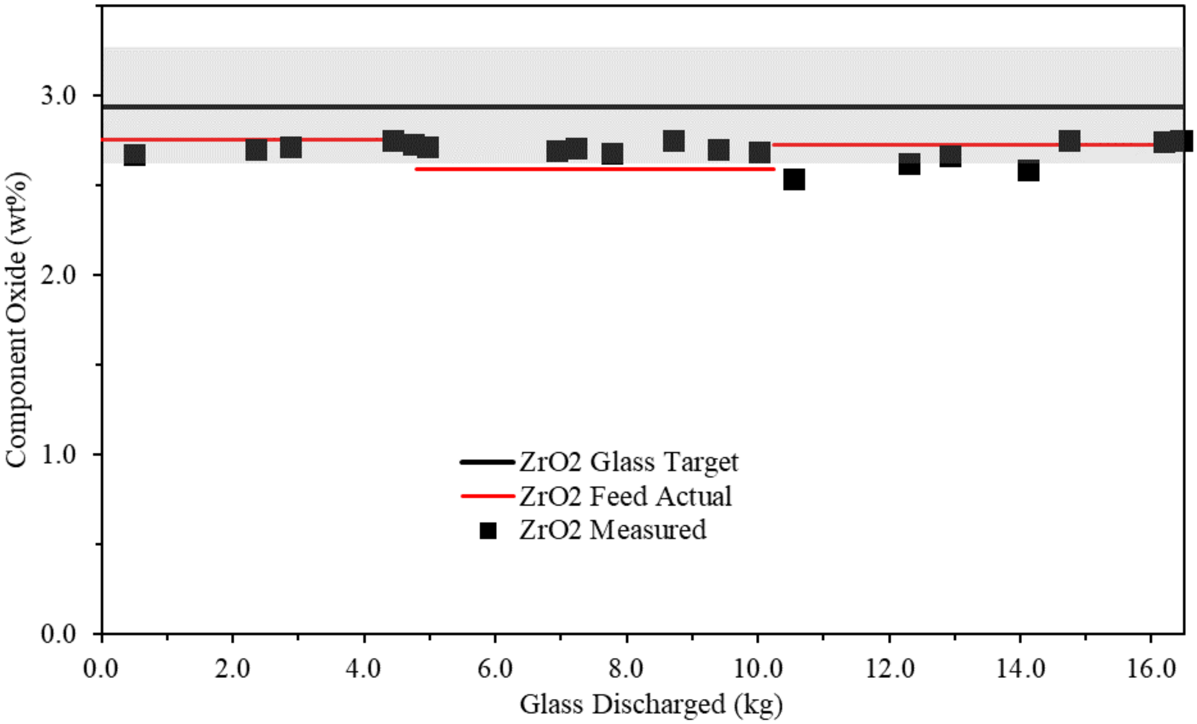

Figure C.7. Measured ZrO_2 content in the LAW run glass product and AN-105 melter feed along with the ZrO_2 content target from the AN-105 glass composition.

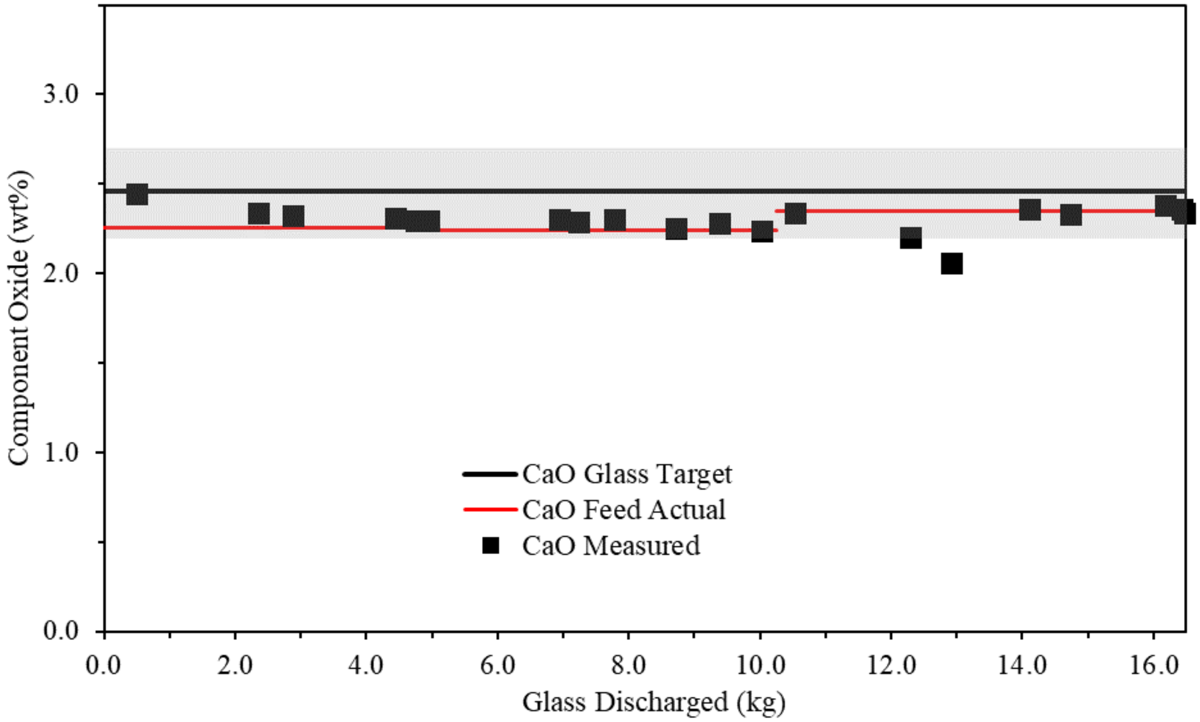

Figure C.8. Measured CaO content in the LAW run glass product and AN-105 melter feed along with the CaO content target from the AN-105 glass composition.

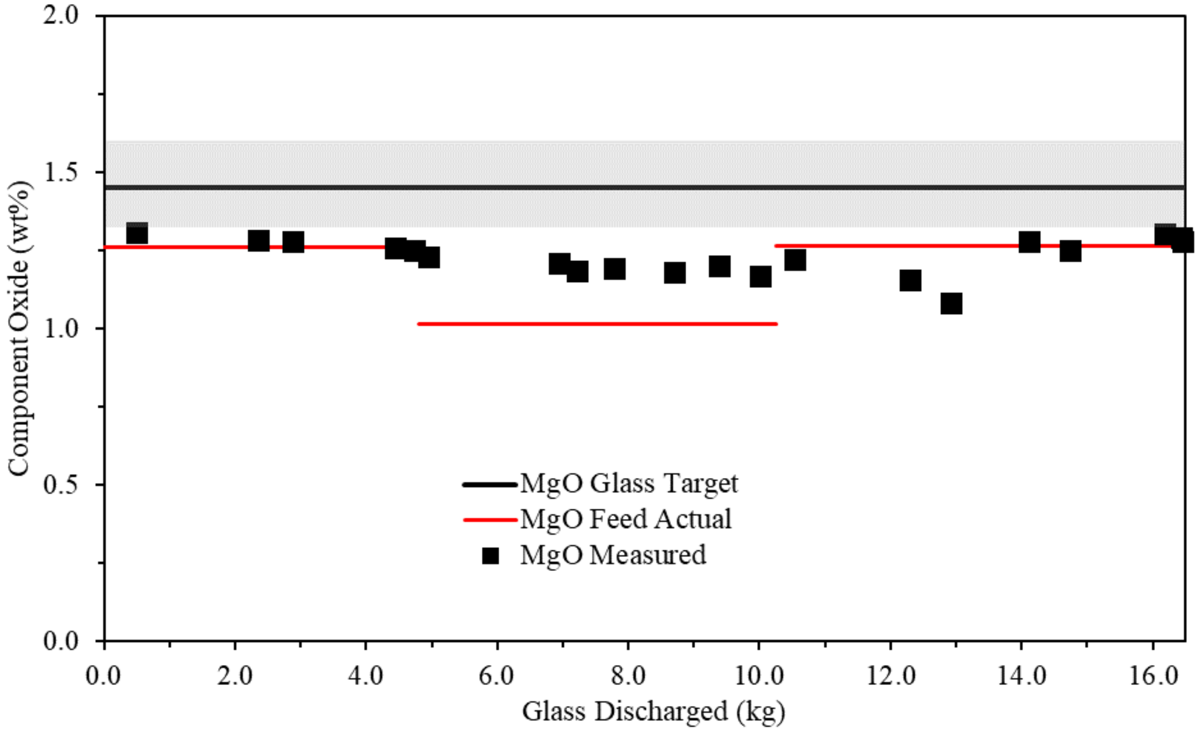

Figure C.9. Measured MgO content in the LAW run glass product and AN-105 melter feed along with the MgO content target from the AN-105 glass composition.

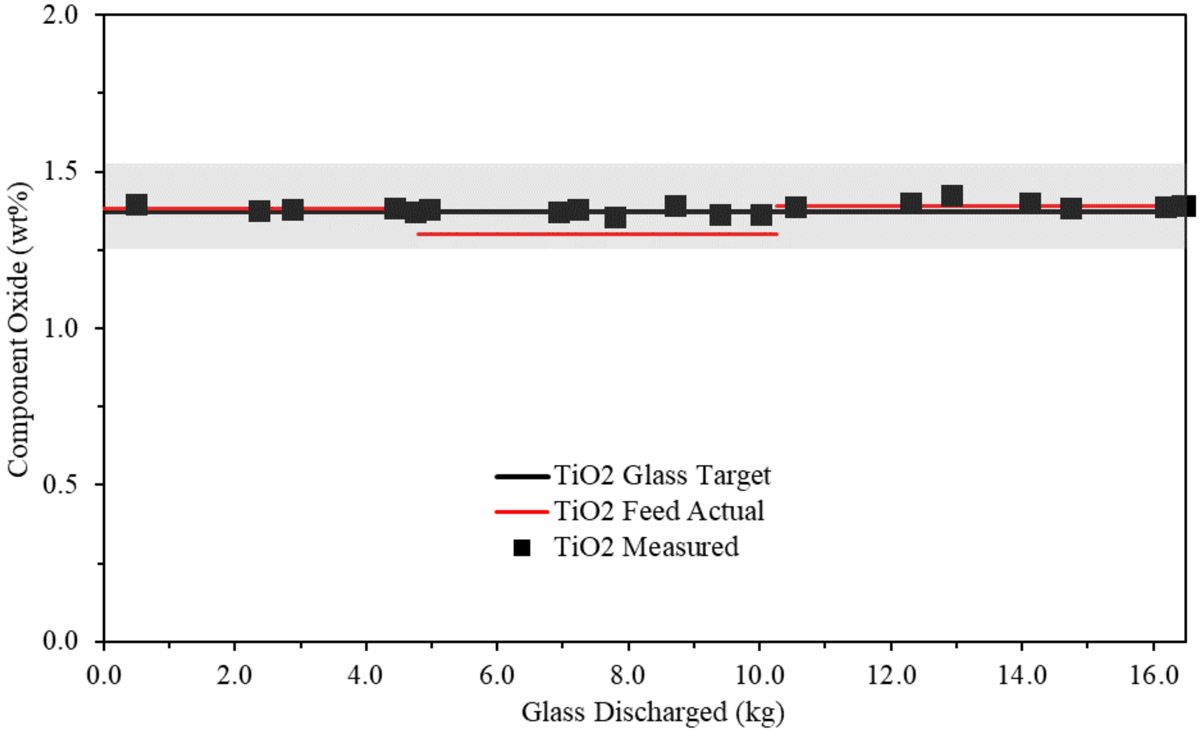

Figure C.10. Measured TiO_2 content in the LAW run glass product and AN-105 melter feed along with the TiO_2 content target from the AN-105 glass composition.

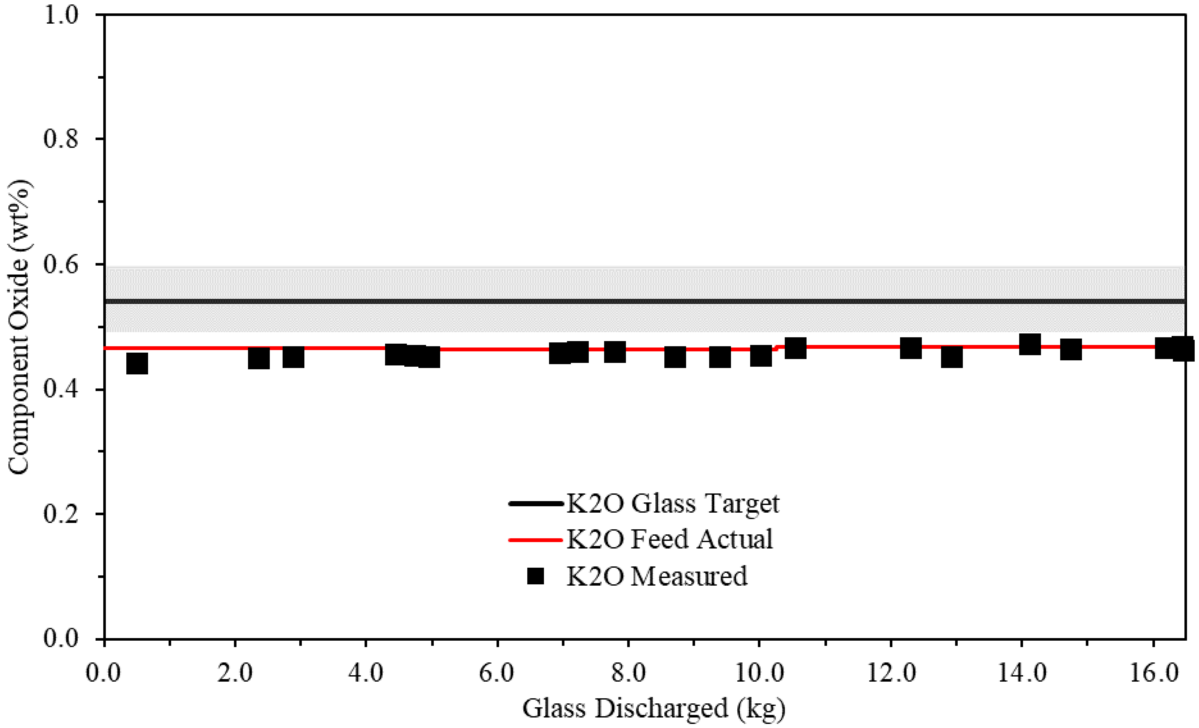

Figure C.11. Measured K_2O content in the LAW run glass product and AN-105 melter feed along with the K_2O content target from the AN-105 glass composition.

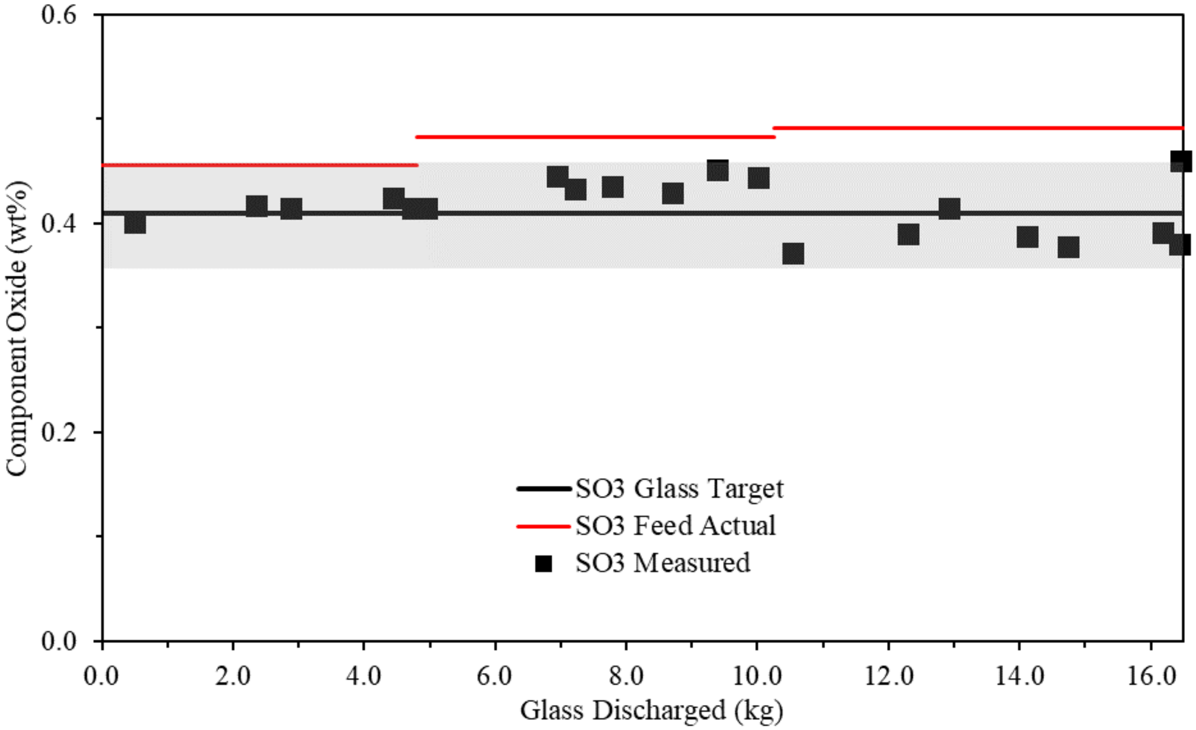

Figure C.12. Measured SO_3 content in the LAW run glass product and AN-105 melter feed along with the SO_3 content target from the AN-105 glass composition.

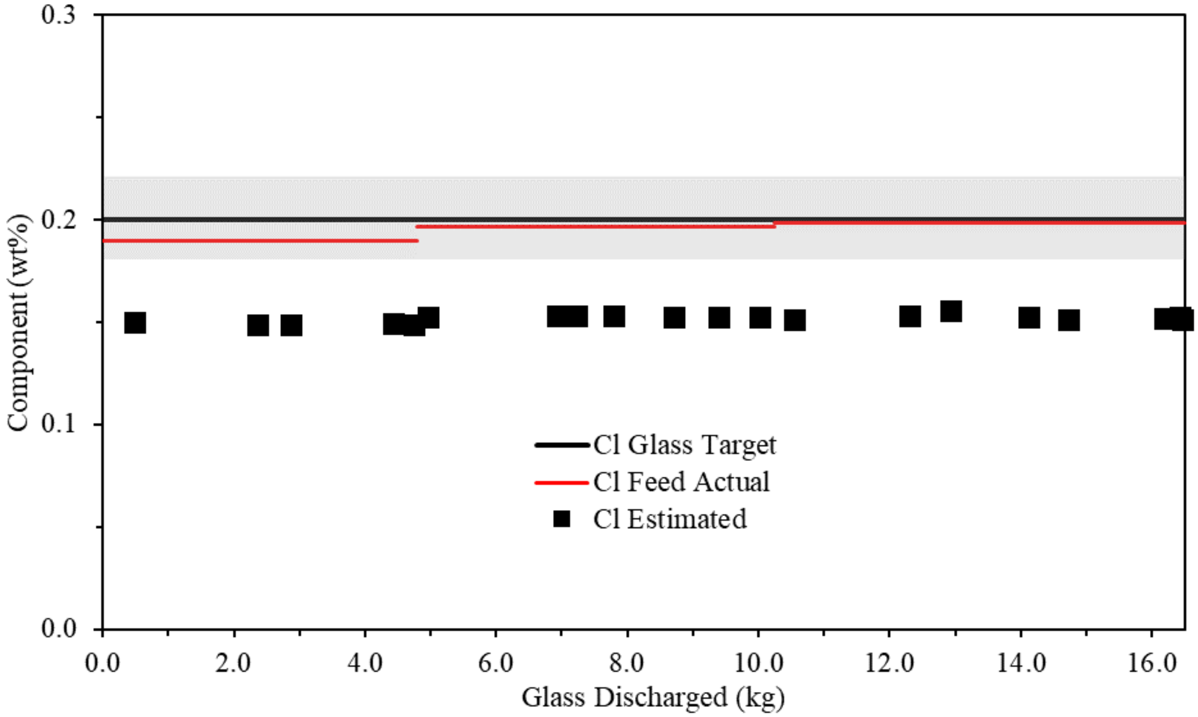

Figure C.13. Measured Cl content in the LAW run glass product and AN-105 melter feed along with the Cl content target from the AN-105 glass composition.

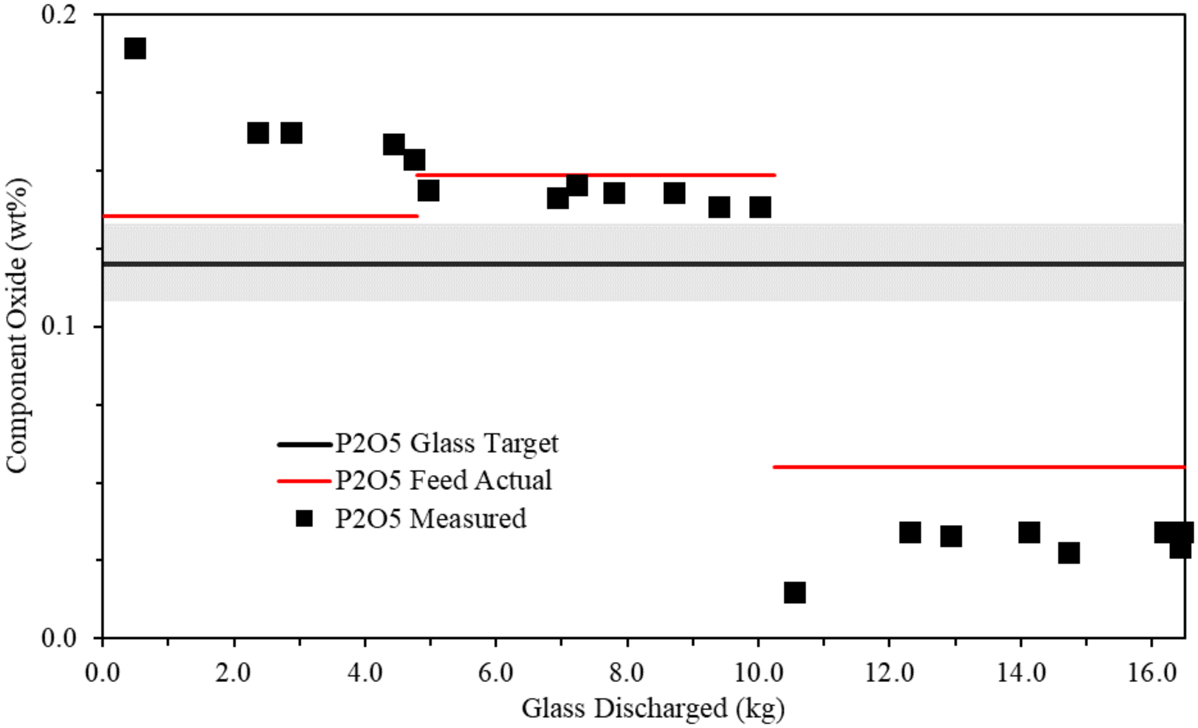

Figure C.14. Measured P_2O_5 content in the LAW run glass product and AN-105 melter feed along with the P_2O_5 content target from the AN-105 glass composition.

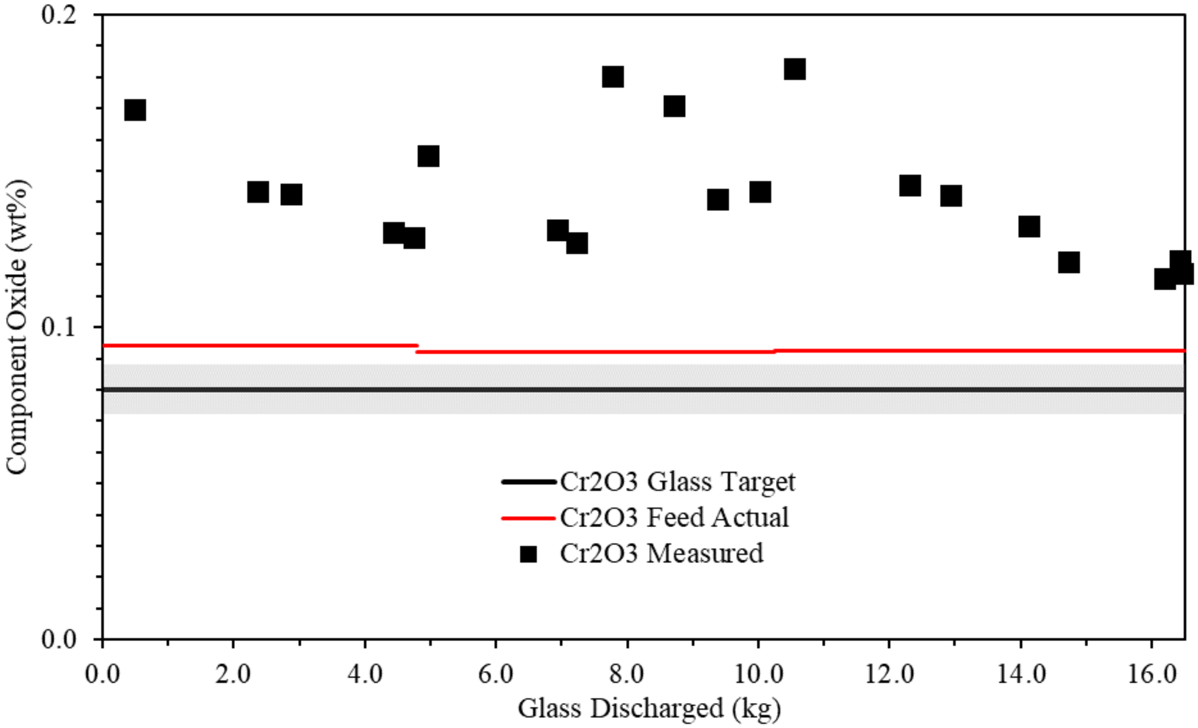

Figure C.15. Measured Cr_2O_3 content in the LAW run glass product and AN-105 melter feed along with the Cr_2O_3 content target from the AN-105 glass composition.

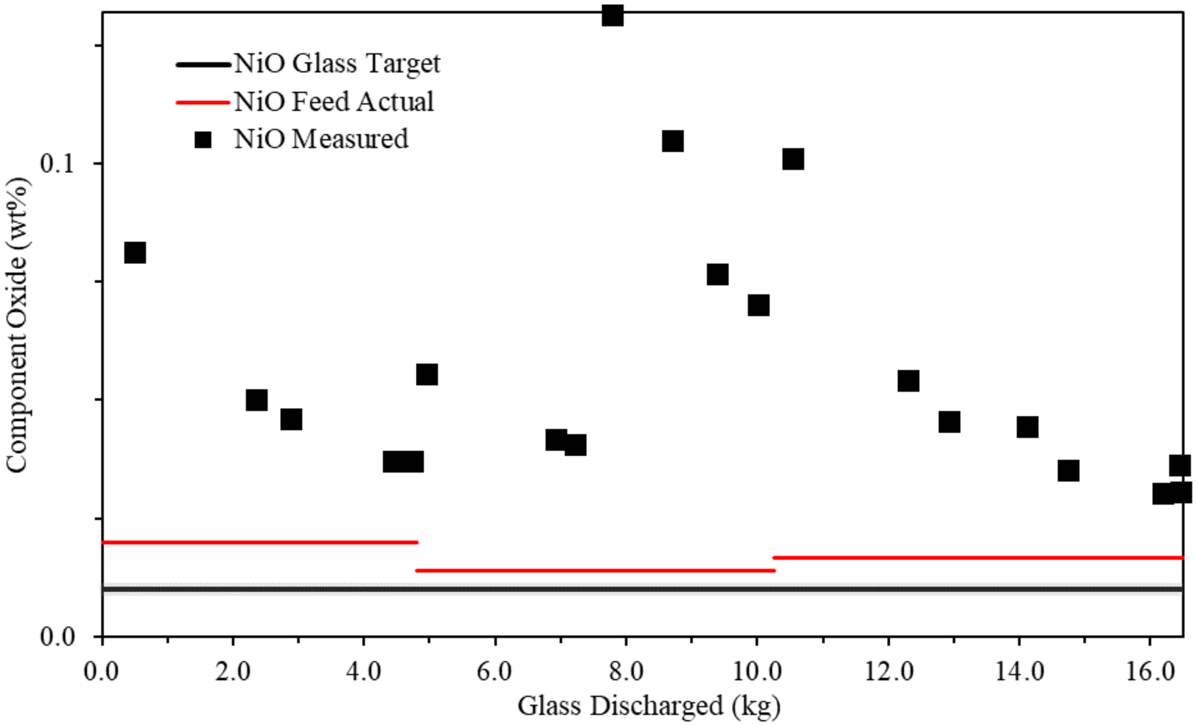

Figure C.16. Measured NiO content in the LAW run glass product and AN-105 melter feed along with the NiO content target from the AN-105 glass composition.

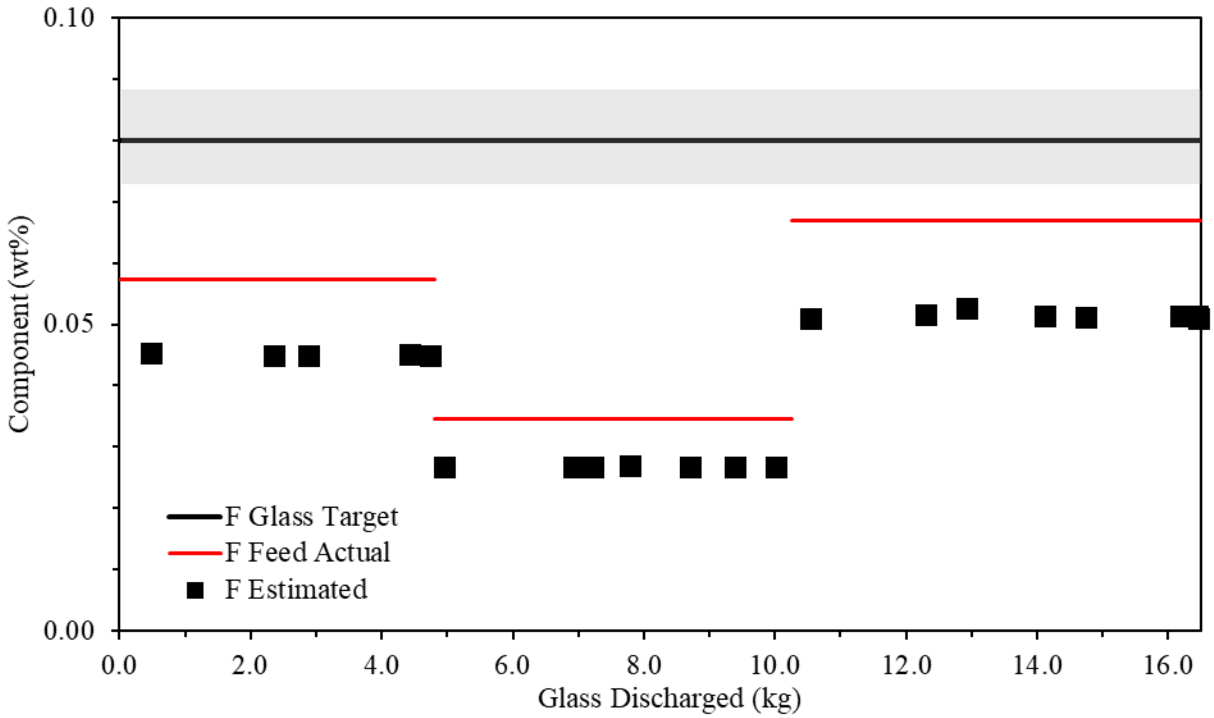

Figure C.17. Measured F content in the LAW run glass product and AN-105 melter feed along with the F content target from the AN-105 glass composition.

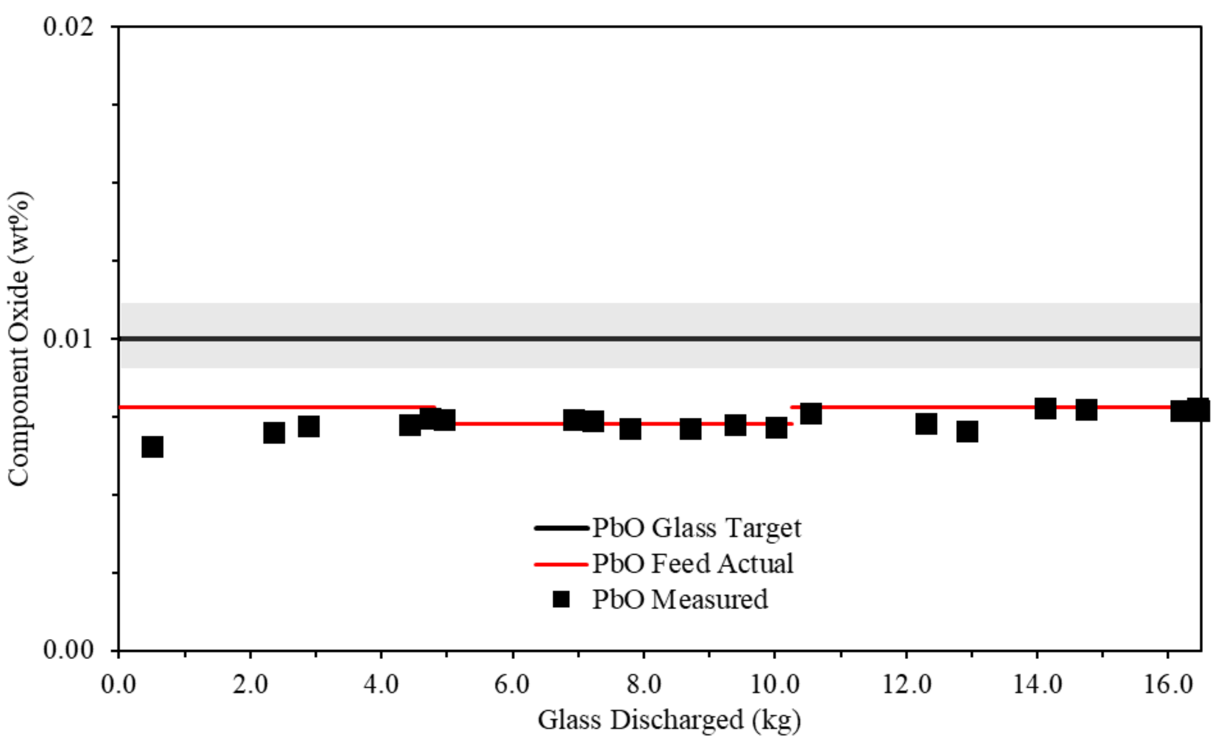

Figure C.18. Measured PbO content in the LAW run glass product and AN-105 melter feed along with the PbO content target from the AN-105 glass composition.

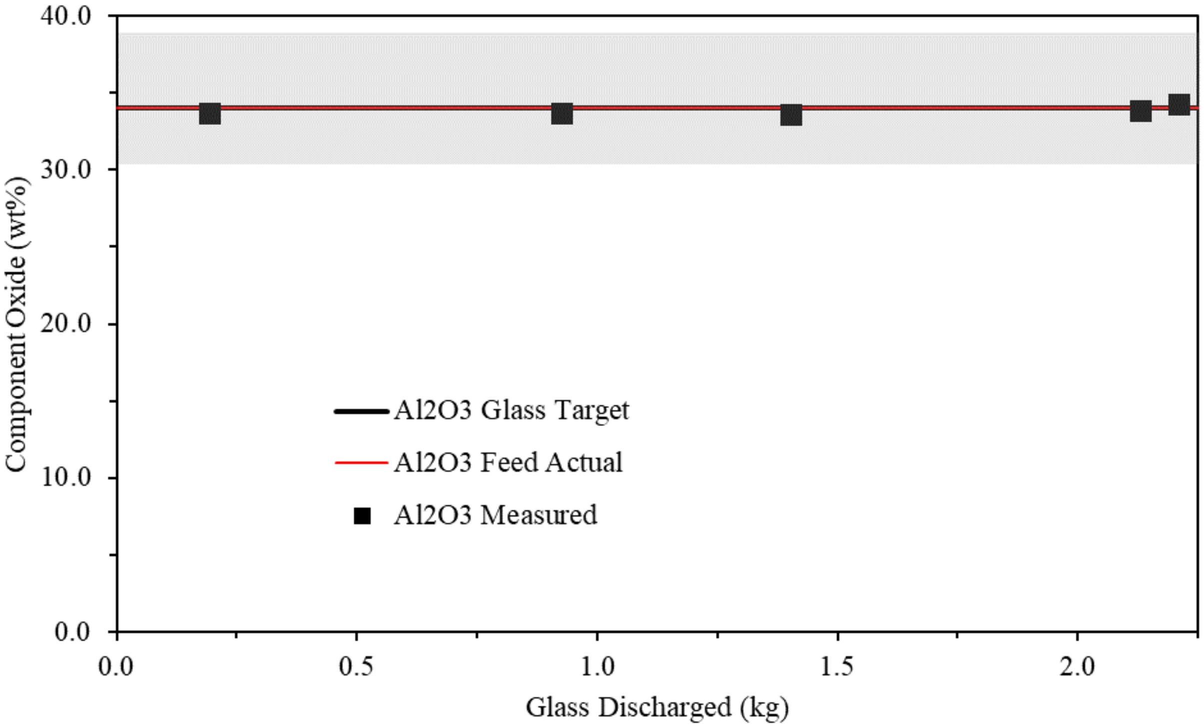

Figure C.19. Measured Al_2O_3 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the Al_2O_3 content target from the AlF2-05 glass composition.

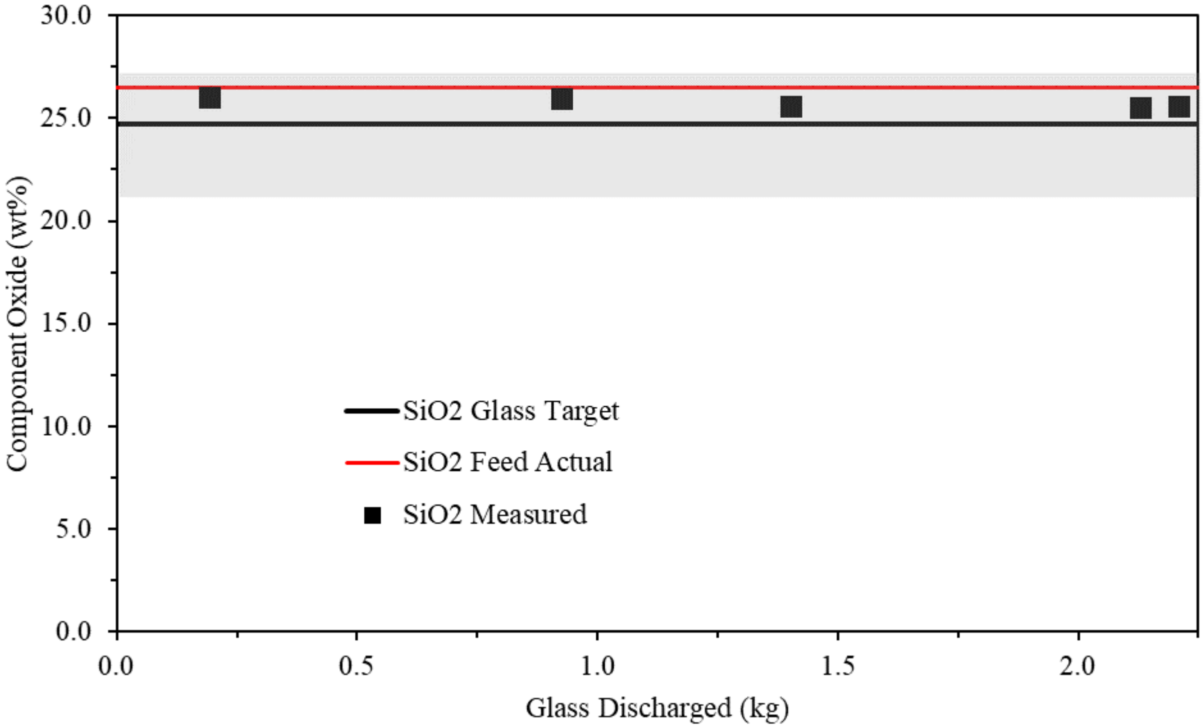

Figure C.20. Measured SiO_2 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the SiO_2 content target from the AlF2-05 glass composition.

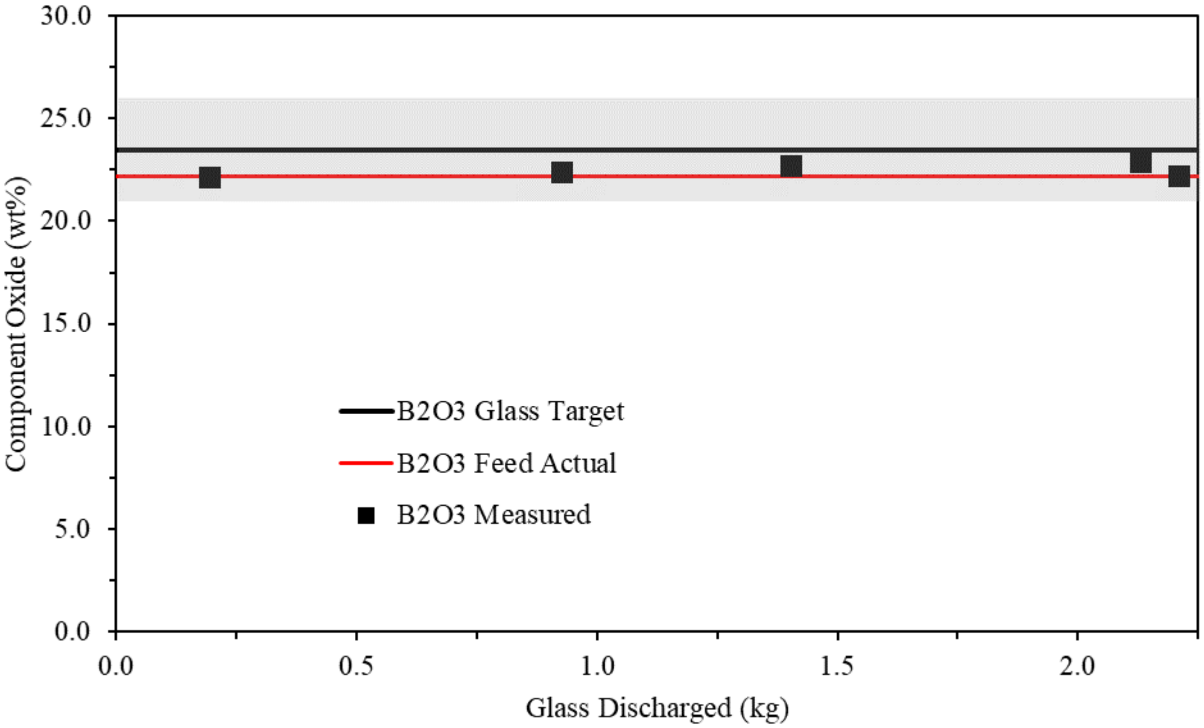

Figure C.21. Measured B_2O_3 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the B_2O_3 content target from the AlF2-05 glass composition.

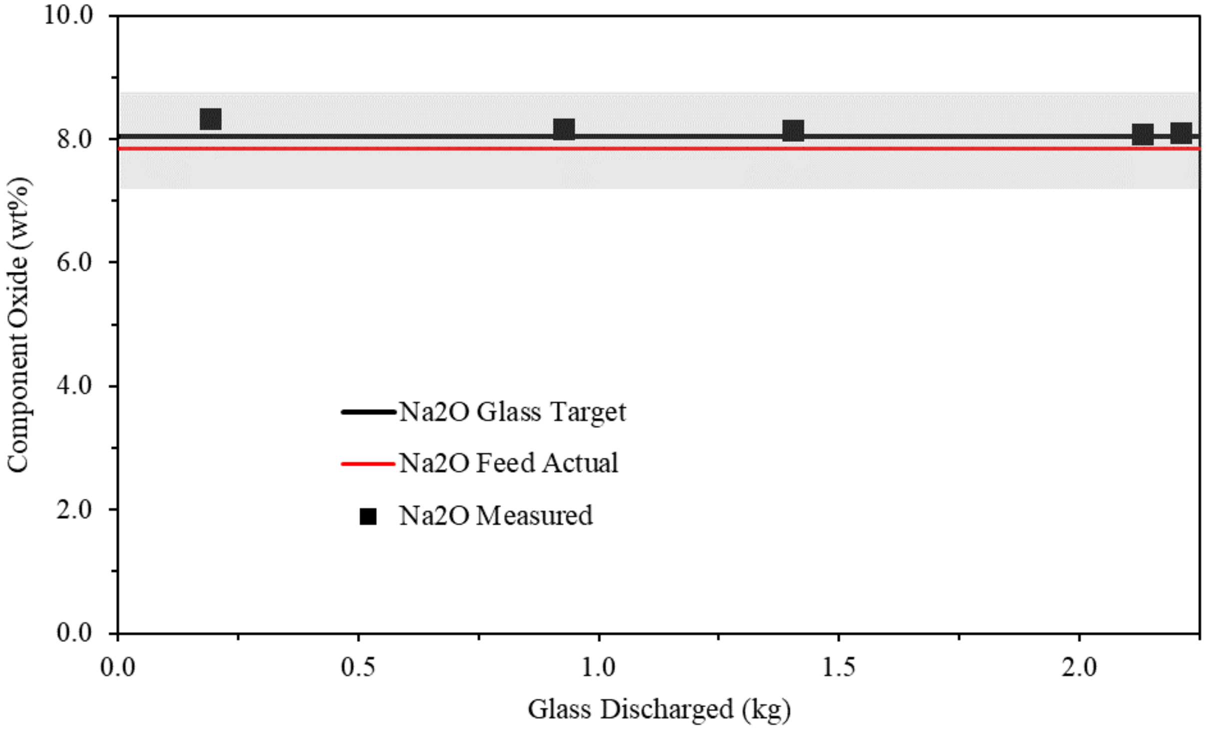

Figure C.22. Measured Na_2O content in the AlF2-05 run glass product and AlF2-05 melter feed along with the Na_2O content target from the AlF2-05 glass composition.

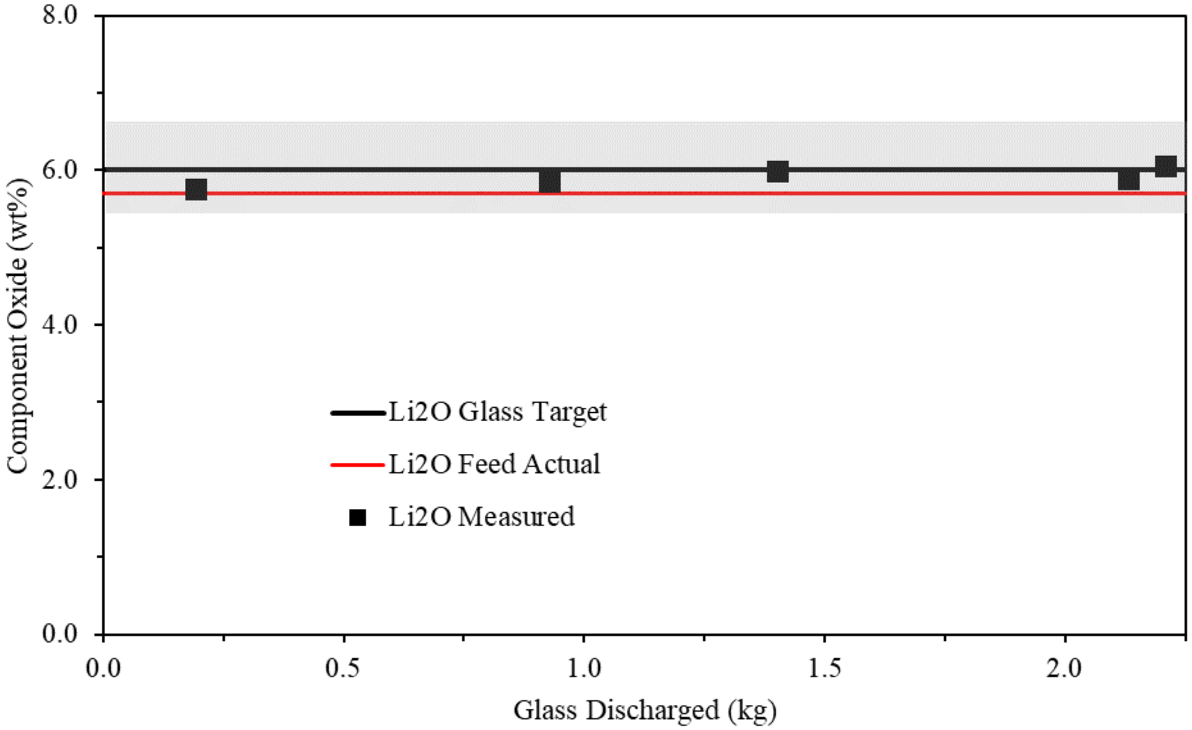

Figure C.23. Measured Li_2O content in the AlF2-05 run glass product and AlF2-05 melter feed along with the Li_2O content target from the AlF2-05 glass composition.

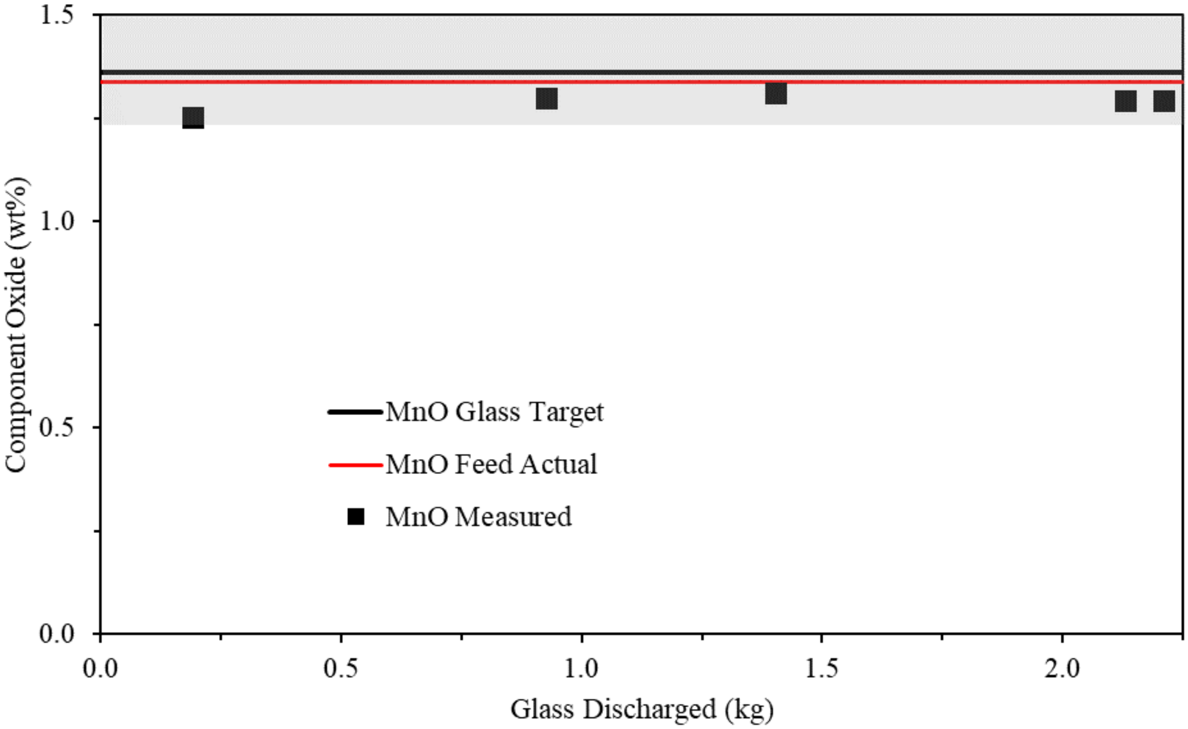

Figure C.24. Measured MnO content in the AlF2-05 run glass product and AlF2-05 melter feed along with the MnO content target from the AlF2-05 glass composition.

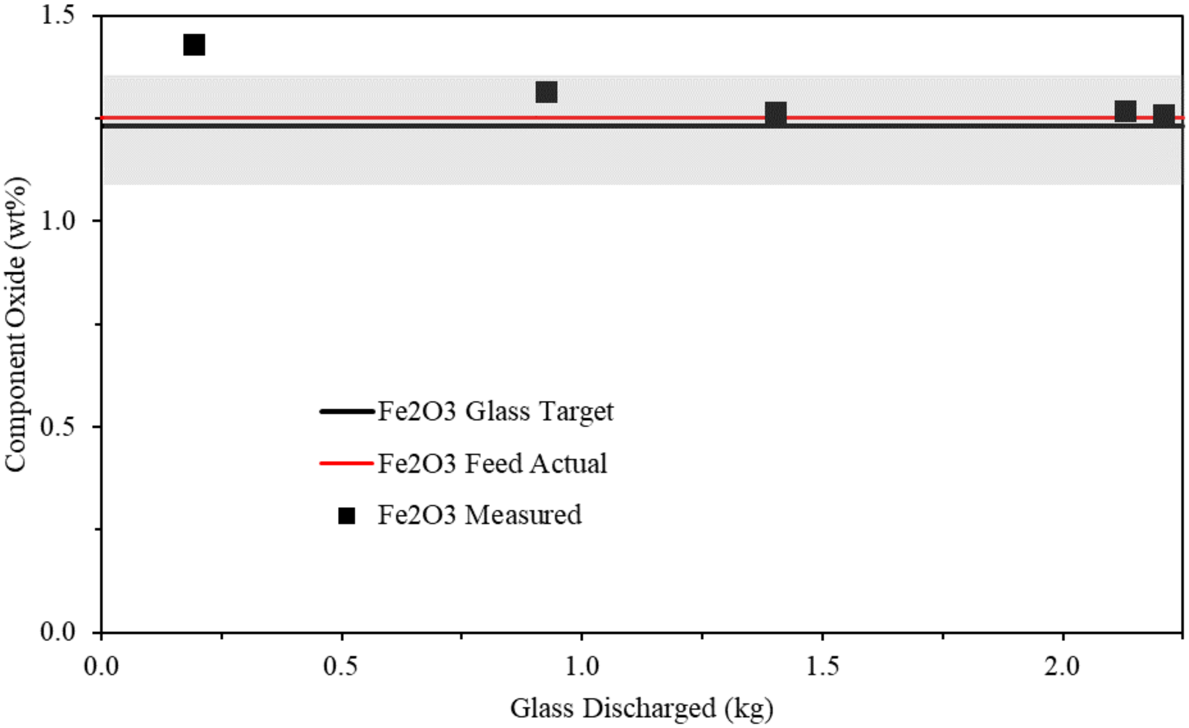

Figure C.25. Measured Fe_2O_3 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the Fe_2O_3 content target from the AlF2-05 glass composition.

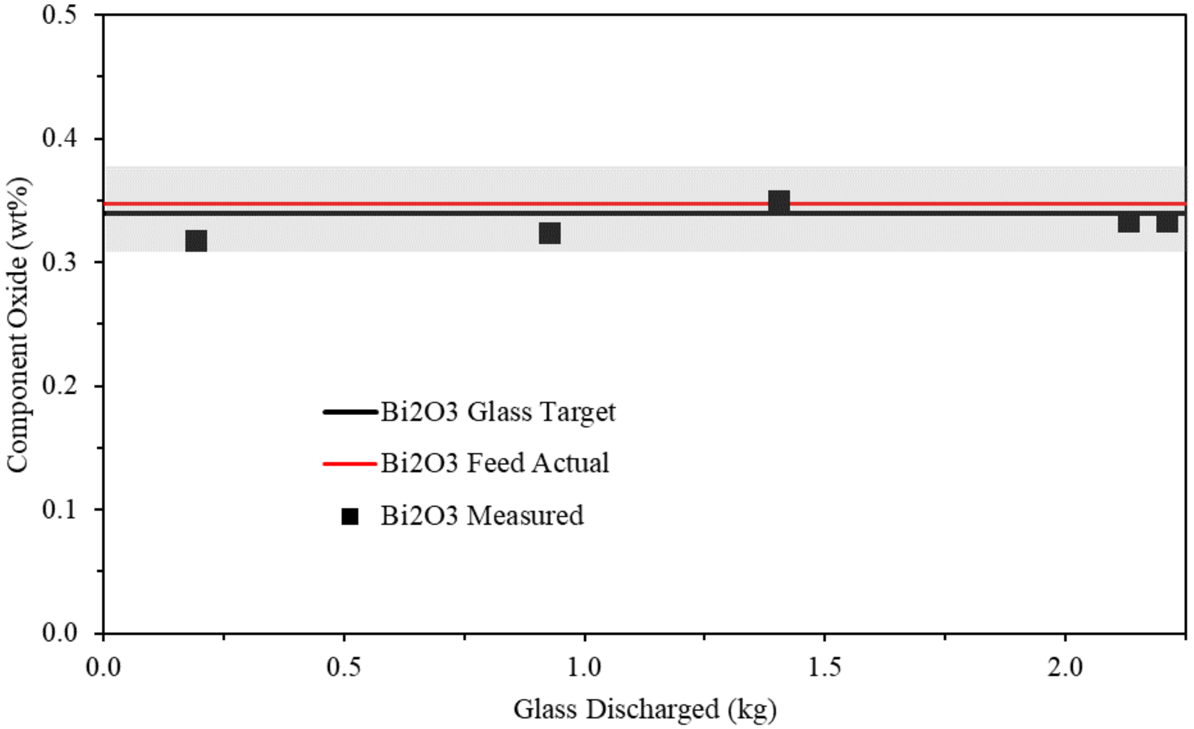

Figure C.26. Measured Bi_2O_3 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the Bi_2O_3 content target from the AlF2-05 glass composition.

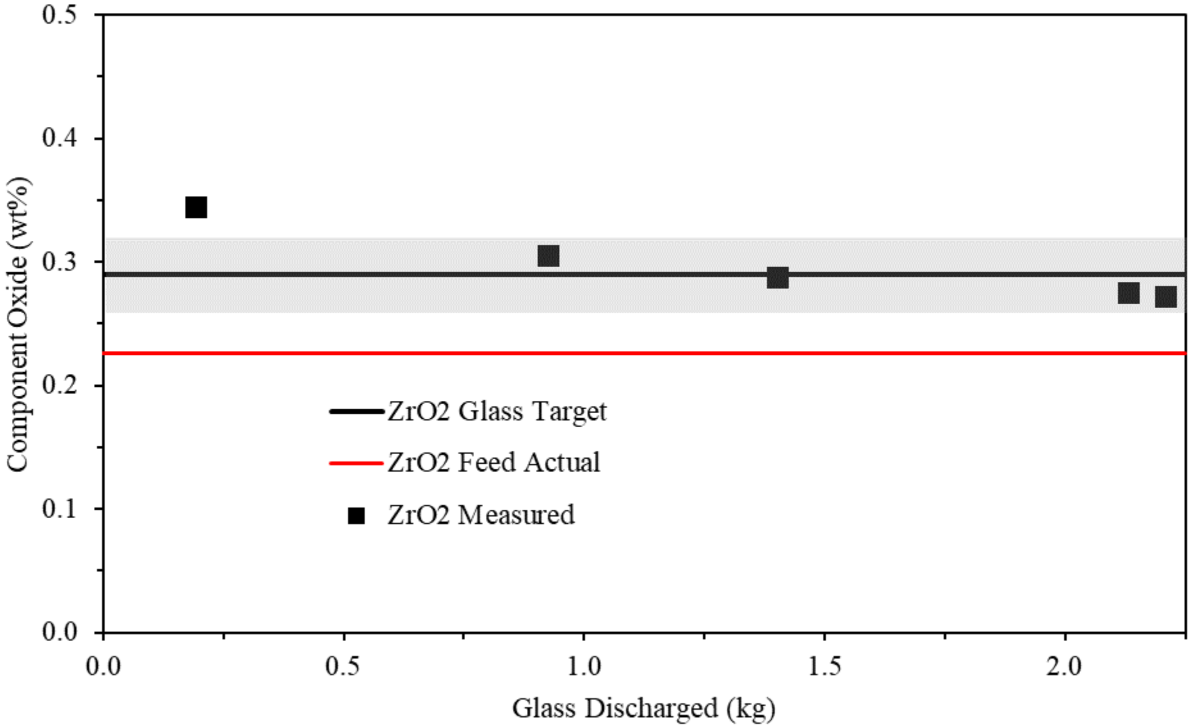

Figure C.27. Measured ZrO_2 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the ZrO_2 content target from the AlF2-05 glass composition.

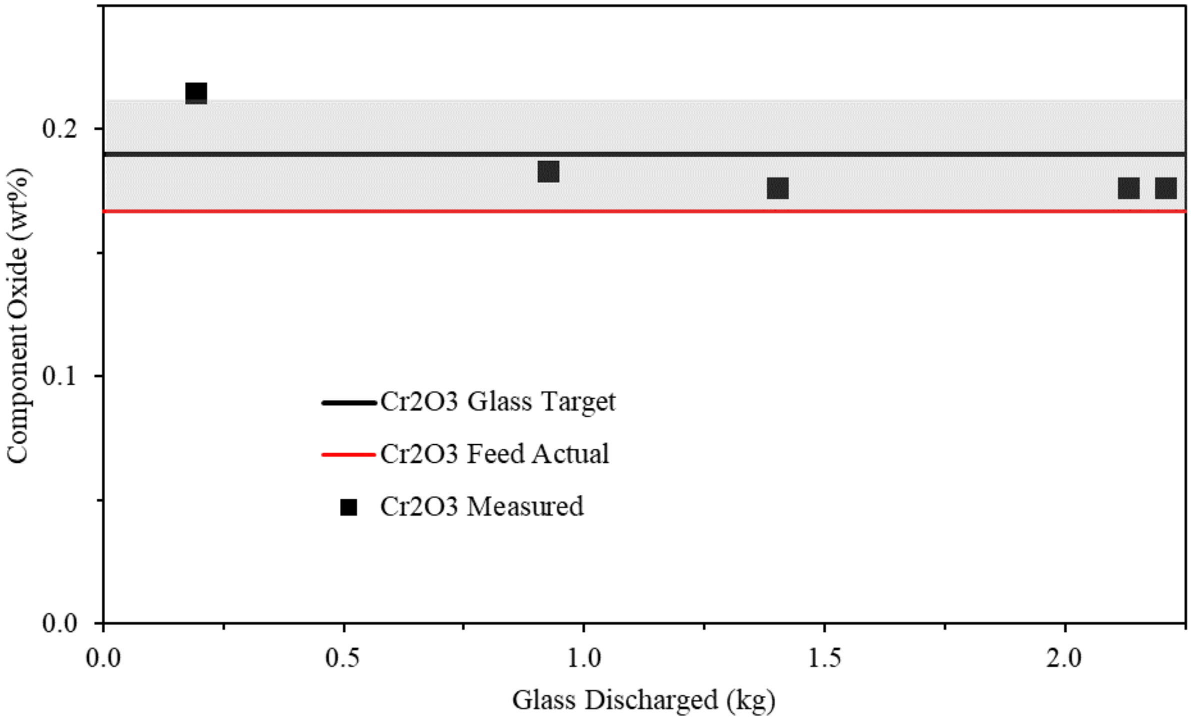

Figure C.28. Measured Cr_2O_3 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the Cr_2O_3 content target from the AlF2-05 glass composition.

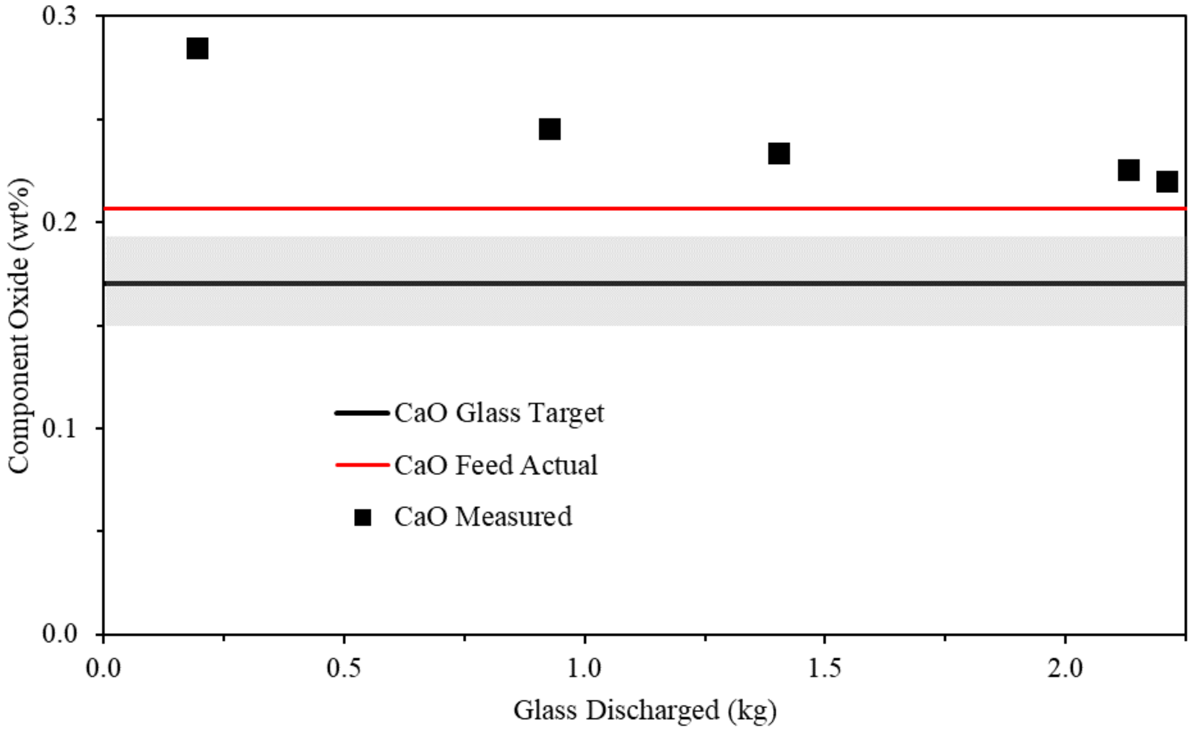

Figure C.29. Measured CaO content in the AlF2-05 run glass product and AlF2-05 melter feed along with the CaO content target from the AlF2-05 glass composition.

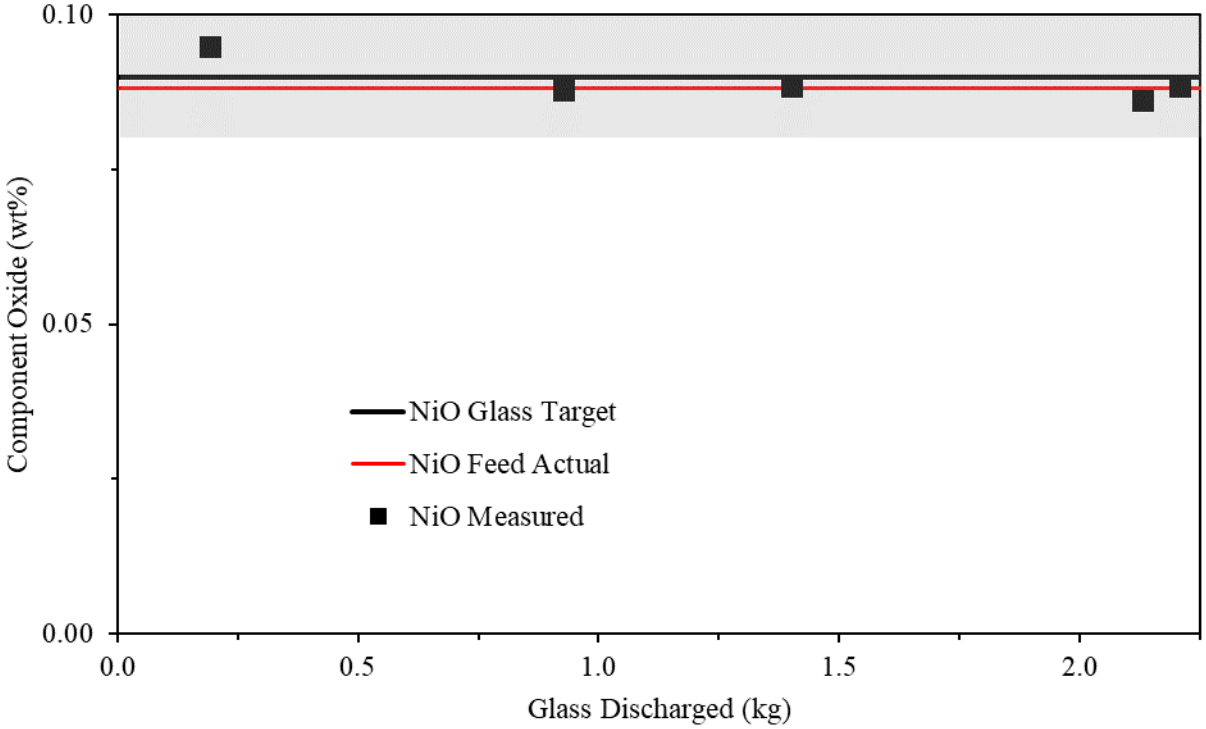

Figure C.30. Measured NiO content in the AlF2-05 run glass product and AlF2-05 melter feed along with the NiO content target from the AlF2-05 glass composition.

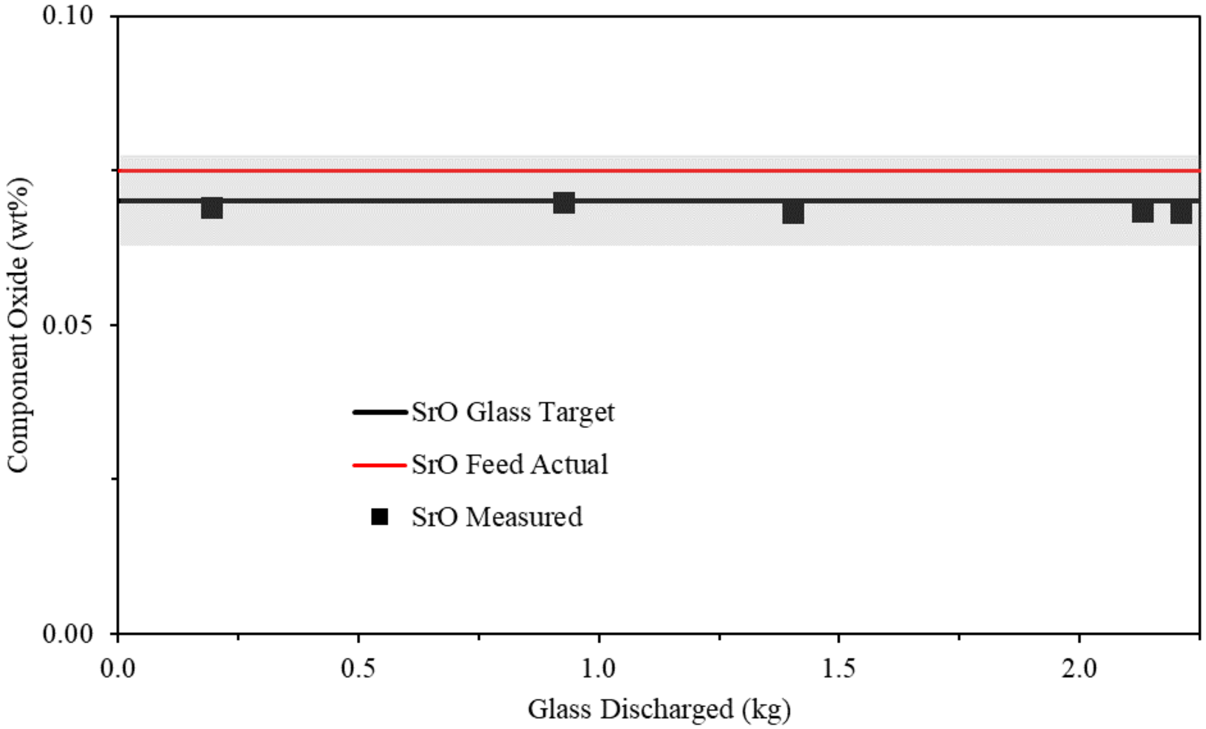

Figure C.31. Measured SrO content in the AlF2-05 run glass product and AlF2-05 melter feed along with the SrO content target from the AlF2-05 glass composition.

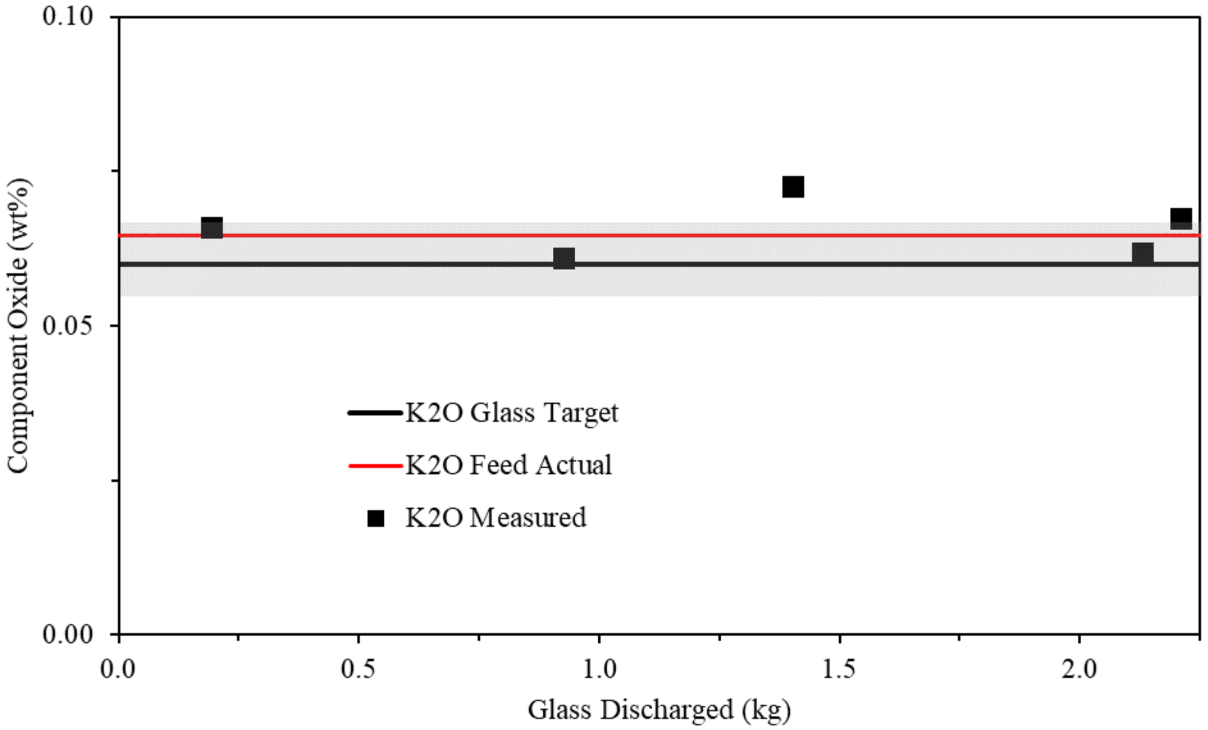

Figure C.32. Measured K_2O content in the AlF2-05 run glass product and AlF2-05 melter feed along with the K_2O content target from the AlF2-05 glass composition.

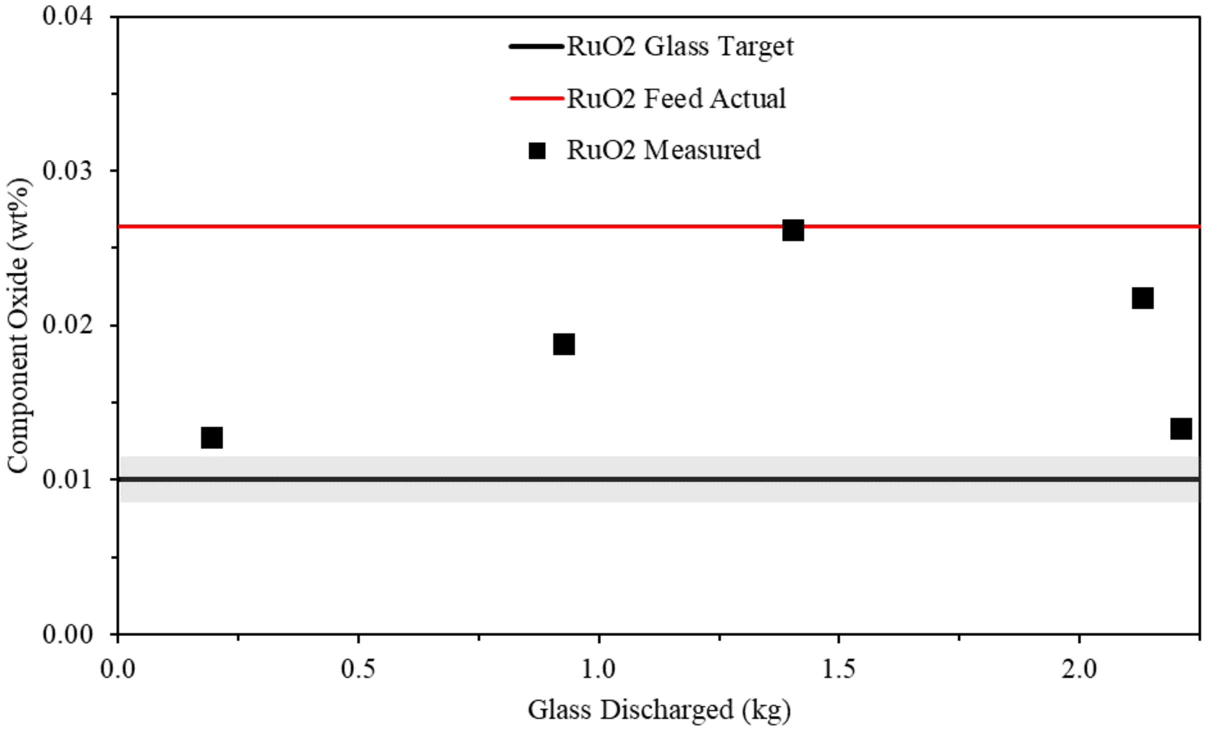

Figure C.33. Measured RuO_2 content in the AlF2-05 run glass product and AlF2-05 melter feed along with the RuO_2 content target from the AlF2-05 glass composition.

Appendix D – Component Mass Flow and Offgas Calculations

The tables in this section display the component mass flow rates for each continuous laboratory-scale melter (CLSM) run calculated over the entire runtimes of LAW Run 1, LAW Run 2, LAW Run 3, and the AlF2-05 run, denoted in the “Sample Duration” row as “Run”. In addition, the tables contain the components mass flow rates calculated exclusively during each offgas sample time period, denoted in the “Sample Duration” row as 1, 2, or 3 as related to the sample number, while the summation of each components mass flow rates listed as the “Total”.

This section also displays the amount of each volatile component (Re, S, K, Cl, and F) recovered in the glass versus the offgas system along with the location of those components in the offgas system units.

Table D.1. Component Mass Flow Rates During LAW Run 1

Component	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$
Sample Duration:	Run	1	2	Run	1	2	Run	1	2
Units	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}
Re	0.10	0.09	0.09	0.03	0.03	0.03	0.03	0.04	0.04
Al	419	395	393	395	389	379	0.4	0.1	0.1
B	380	359	356	362	341	333	1.6	0.3	1.7
Ca	214	202	200	206	200	195	0.1	0.0	0.0
Cr	8.5	8.1	8.0	11	12	11	0.0	0.1	0.0
Fe	528	499	495	506	477	477	0.2	0.1	0.1
K	51	48	48	48	45	45	0.3	0.2	0.2
Mg	101	95	94	96	93	90	0.0	0.0	0.0
Na	2030	1915	1901	1914	1784	1784	5.9	5.6	4.5
Ni	2.1	2.0	2.0	2.9	4.7	3.4	0.0	0.0	0.0
P	7.8	7.4	7.3	8.2	8.5	8.2	0.0	0.0	0.0
Pb	1.0	0.9	0.9	0.9	0.8	0.8	0.0	0.0	0.0
S	24	23	23	22	20	20	0.5	0.3	0.5
Si	2842	2682	2663	2755	2587	2556	3.4	6.4	0.7
Ti	110	104	103	104	99	98	0.0	0.0	0.0
Zn	380	359	356	364	335	332	0.2	0.0	0.0
Zr	271	256	254	258	240	241	0.0	0.0	0.0
Total	7371	6955	6905	7053	6635	6573	13	13	8

Table D.2. Component Mass Flow Rates During LAW Run 2

Component	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$
Sample Duration:	Run	1	2	Run	1	2	Run	1	2
Units	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}
Re	0.09	0.09	0.08	0.04	0.03	0.03	0.04	0.03	0.03
Al	383	356	341	358	340	316	1.8	0.8	1.6
B	386	351	349	342	322	300	4.8	6.4	2.8
Ca	190	180	166	185	177	166	0.5	0.3	0.6
Cr	7.5	6.8	6.8	10	10	10	0.2	0.1	0.2
Fe	447	425	390	439	421	394	1.2	2.7	1.2
K	46	43	40	44	41	38	0.7	0.5	1.0
Mg	72	70	62	81	78	74	0.0	0.0	0.0
Na	1818	1721	1592	1753	1636	1547	16.9	23.2	11.2
Ni	1.3	1.2	1.1	3.8	3.5	6.1	0.0	0.0	0.0
P	7.7	7.4	6.6	7.0	6.6	6.1	0.0	0.1	0.0
Pb	0.8	0.8	0.7	0.8	0.7	0.7	0.0	0.0	0.0
S	23	22	20	21	19	18	0.8	0.9	0.3
Si	2525	2307	2280	2484	2311	2199	1.2	1.4	0.8
Ti	93	87	82	95	89	83	0.0	0.1	0.0
Zn	338	317	298	321	300	283	1.8	1.7	1.4
Zr	228	212	203	231	215	204	0.7	0.1	0.1
Total	6567	6108	5839	6375	5969	5645	31	38	21

Table D.3. Component Mass Flow Rates During LAW Run 3

Component	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$
Sample Duration:	Run	1	2	3	Run	1	2	3	Run	1	2	3
Units	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}
Re	0.11	0.11	0.11	0.11	0.04	0.03	0.04	0.04	0.05	0.05	0.05	0.05
Al	439	440	444	446	431	436	438	436	1.0	0.1	0.1	0.1
B	436	437	441	444	427	422	428	426	1.9	0.7	0.5	1.1
Ca	237	237	239	241	224	198	233	235	0.5	0.3	0.0	0.3
Cr	8.9	8.9	9.0	9.1	11	13	12	12	0.1	0.0	0.0	0.1
Fe	518	519	524	527	517	528	524	524	1.0	0.1	0.1	0.2
K	55	55	55	56	53	51	54	54	0.6	0.7	0.5	0.7
Mg	107	108	109	109	103	88	105	108	0.0	0.0	0.0	0.0
Na	2126	2132	2149	2162	2075	1966	2126	2152	7.8	5.5	5.0	6.5
Ni	1.9	1.9	1.9	1.9	2.8	4.8	3.9	4.0	0.0	0.0	0.0	0.0
P	3.4	3.4	3.4	3.4	2.3	1.9	1.7	1.8	0.0	0.0	0.0	0.0
Pb	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	0.0	0.0	0.0	0.0
S	28	28	28	28	23	22	21	21	0.6	0.3	0.3	0.3
Si	3010	3017	3042	3059	2931	2920	2987	2961	0.7	0.0	0.0	0.0
Ti	117	118	118	119	115	115	116	116	0.0	0.0	0.0	0.0
Zn	417	418	422	424	404	396	406	410	0.7	0.6	0.5	0.8
Zr	284	285	287	289	277	266	284	285	0.0	0.0	0.0	0.0
Total	7790	7809	7874	7919	7596	7429	7741	7749	15	8	7	10

Table D.4. Component Mass Flow Rates During the AlF2-05 Run

Component	$\dot{m}_{i,feed}$	$\dot{m}_{i,feed}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,glass}$	$\dot{m}_{i,offgas}$	$\dot{m}_{i,offgas}$
Sample Duration:	Run	1	Run	1	Run	1
Units	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}	mg min^{-1}
Al	1340	1619	1223	1463	0.4	0.1
B	514	620	474	580	3.9	2.4
Bi	23	28	21	26	0.0	0.0
Ca	11	13	9.0	14	0.1	0.0
Cr	8.5	10	7.0	10	0.1	0.1
Fe	65	79	55	73	0.4	0.0
K	4.0	4.8	3.7	5.0	0.0	0.0
Li	197	238	193	229	0.2	0.1
Mn	77	93	69	83	0.0	0.0
Na	433	523	399	497	1.5	0.3
Ni	5.2	6.2	4.4	5.7	0.0	0.0
Ru	1.50	1.81	1.14	1.64	0.07	0.13
Si	921	1112	800	984	1.2	8.9
Sr	4.7	5.7	3.9	4.7	0.0	0.0
Zr	12	15	12	18	0.0	0.0
Total	3619	4370	3274	3994	8	12

Table D.5. Offgas Recovery for all CLSM Runs

	Re							
	Run 1		Run 2		Run 3		HLW	
	mg	%	mg	%	mg	%	mg	%
Glass	11.8	42.5	16.4	43.6	16.2	42.3	--	--
Offgas System	16.0	57.5	21.3	56.4	22.1	57.7	--	--
	Offgas Units							
Piping and Sampling	3.24	20.2	3.90	18.3	5.63	25.4	--	--
SBS Sump	2.10	13.1	1.80	8.5	2.78	12.6	--	--
Condensate	7.58(a)	47.4	10.9	51.2	10.8	48.7	--	--
Primary HEPA(b)	3.09	19.3	4.68	22.0	2.93	13.2	--	--
	S							
	Run 1		Run 2		Run 3		HLW	
	mg	%	mg	%	mg	%	mg	%
Glass	8046	97.3	9510	95.2	10389	97.5	62	41.5
Offgas System	220	2.7	479	4.8	263	2.5	87	58.5
	Offgas Units							
Piping and Sampling	26	11.6	83	17.3	59	22.5	15	17.6
SBS Sump	46	21.0	56	11.6	50	18.9	8	9.3
Condensate	146(a)	66.3	218	45.4	138	52.4	29	33.6
Primary HEPA(b)	2	1.1	123	25.7	16	6.2	34	39.5
	K							
	Run 1		Run 2		Run 3		HLW	
	mg	%	mg	%	mg	%	mg	%
Glass	18015	99.1	19963	98.1	24039	98.9	--	--
Offgas System	168	0.9	395	1.9	278	1.1	--	--
	Offgas Units							
Piping and Sampling	27	16.2	73	18.5	67	23.9	--	--
SBS Sump	32	18.9	45	11.4	41	14.9	--	--
Condensate	98(a)	58.5	173	43.7	128	45.8	--	--
Primary HEPA(b)	11	6.4	104	26.4	43	15.4	--	--
	Cl							
	Run 1		Run 2		Run 3		HLW	
	mg	%	mg	%	mg	%	mg	%
Glass (Estimate)	7048	75.1	8045	73.8	9495	73.6	--	--
Offgas System	2339	24.9	2855	26.2	3411	26.4	261	--
	Offgas Units							
Piping and Sampling	532	22.8	636	22.3	829	24.3	53	20.3
SBS Sump	407	17.4	286	10.0	587	17.2	22	8.5
Condensate	1331(a)	56.9	1747	61.2	1992	58.4	118	45.3
Primary HEPA(b)	69	2.9	186	6.5	3	0.1	68	25.9
	F							
	Run 1		Run 2		Run 3		HLW	
	mg	%	mg	%	mg	%	mg	%
Glass (Estimate)	2128	90.5	1377	66.4	3205	88.4	--	--
Offgas System	225	9.5	696	33.6	423	11.6	58	--
	Offgas Units							
Piping and Sampling	43	18.9	191	27.4	113	26.7	6	10.7
SBS Sump	37	16.6	128	18.4	122	28.9	6	11.2
Condensate	138(a)	61.3	367	52.7	186	44.0	39	67.4
Primary HEPA(b)	7	3.2	10	1.5	1	0.3	6	10.7

(a) Values were increased due to an un-measured mass of condensate during LAW Run 1.

(b) Values were increased due to a portion of the used filters being un-analyzed.

Values marked with ‘--’ denote that the component was not detected in the source.

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