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Crystallization in High Level Waste (HLW) Glass Melters: Operational Experience from the Savannah River Site

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February 2014

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EXECUTIVE SUMMARY

A road map was recently developed to guide research and development efforts for a crystal tolerant glass processing strategy for the Hanford Tank Waste Treatment and Immobilization Plant (WTP). The basis of this alternative approach is an empirical model predicting the crystal accumulation in the WTP glass discharge riser and melter bottom as a function of glass composition, time, and temperature. When coupled with an associated operating limit (e.g., the maximum tolerable thickness of an accumulated layer of crystals), this model could then be integrated into the process control algorithms to formulate crystal tolerant high level waste (HLW) glasses targeting higher waste loadings while still meeting process related limits and melter lifetime expectancies.

This report provides a review of the scaled melter testing that was completed in support of the Defense Waste Processing Facility (DWPF) melter. Testing with scaled melters provided the data to define the DWPF operating limits to avoid bulk (volume) crystallization in the un-agitated DWPF melter and provided the data to distinguish between spinels generated by K-3 refractory corrosion versus spinels that precipitated from the HLW glass melt pool. This report includes a review of the crystallization observed with the scaled melters and the full scale DWPF melters (DWPF Melter 1 and DWPF Melter 2). Examples of actual DWPF melter attainment with Melter 2 are given. The intent is to provide an overview of lessons learned, including some example data, that can be used to advance the development and implementation of an empirical model and operating limit for crystal accumulation for WTP.

Operation of the first and second (current) DWPF melters has demonstrated that the strategy of using a liquidus temperature predictive model combined with a 100 °C offset from the normal melter operating temperature of 1150 °C (i.e., the predicted liquidus temperature (T_L) of the glass must be 1050 °C or less) has been successful in preventing any detrimental accumulation of spinel in the DWPF melt pool, and spinel has not been observed in any of the pour stream glass samples. Spinel was observed at the bottom of DWPF Melter 1 as a result of K-3 refractory corrosion. Issues have occurred with accumulation of spinel in the pour spout during periods of operation at higher waste loadings. Given that both DWPF melters were or have been in operation for greater than 8 years, the service life of the melters has far exceeded design expectations. It is possible that the DWPF liquidus temperature approach is conservative, in that it may be possible to successfully operate the melter with a small degree of allowable crystallization in the glass. This could be a viable approach to increasing waste loading in the glass assuming that the crystals are suspended in the melt and swept out through the riser and pour spout. Additional study is needed, and development work for WTP might be leveraged to support a different operating limit for the DWPF.

Several recommendations are made regarding considerations that need to be included as part of the WTP crystal tolerant strategy based on the DWPF development work and operational data reviewed here. These include:

- Identify and consider the impacts of potential heat sinks in the WTP melter and glass pouring system
- Consider the contributions of refractory corrosion products, which may serve to nucleate additional crystals leading to further accumulation
- Consider volatilization of components from the melt (e.g., boron, alkali, halides, etc.) and determine their impacts on glass crystallization behavior
- Evaluate the impacts of glass REDuction/OXidation (REDOX) conditions and the distribution of temperature within the WTP melt pool and melter pour chamber on crystal accumulation rate
- Consider the impact of precipitated crystals on glass viscosity
- Consider the impact of an accumulated crystalline layer on thermal convection currents and bubbler effectiveness within the melt pool

- Evaluate the impact of spinel accumulation on Joule heating of the WTP melt pool
- Include noble metals in glass melt experiments because of their potential to act as nucleation sites for spinel crystallization

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LIST OF ABBREVIATIONS

CPC	Chemical Processing Cell
CSEM	Contained Scanning Electron Microscopy
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EDS	Energy Dispersive Spectroscopy
HLW	High Level Waste
IDMS	Integrated DWPF Melter System
LAW	Low Activity Waste
LSFM	Large Slurry Fed Melter
MFT	Melter Feed Tank
ORP	Office of River Protection
PNL	Pacific Northwest Laboratory
POG	Primary Off-Gas
REDOX	REDuction/OXidation
SCM	Small Cylindrical Melter
SGM	Scale Glass Melter
SME	Slurry Mix Evaporator
SRAT	Sludge Receipt and Adjustment Tank
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
$T_{1\%}$	Temperature at which glass contains 1 vol % crystallization
TDS	Technical Data Summary
$\mathrm{T_L}$	Liquidus Temperature
TTT	Time-Temperature-Transformation
WTP	Tank Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project
XRD	X-ray Diffraction

1.0 Introduction

The U.S. Department of Energy (DOE) is building a Tank Waste Treatment and Immobilization Plant (WTP) at the Hanford Site in Washington to remediate 55 million gallons of radioactive waste that is being temporarily stored in 177 underground tanks. The plan is to separate the radioactive waste into high-level waste (HLW) and low-activity waste (LAW) fractions that will then be vitrified in stable borosilicate glass with Joule-heated ceramic melters. Efforts are being made to increase the loading of Hanford tank wastes in glass while maintaining an adequate ability to meet process, regulatory, and product quality requirements.

Recent glass formulation and melter testing data have suggested that significant increases in waste loading in HLW and LAW glasses are possible over current system planning estimates.[1] The existing WTP data (although limited in some cases) were evaluated to determine a set of constraints and models that could be used to estimate the maximum loading of specific waste compositions in glass. It was recognized that some of the models are preliminary in nature and some do not currently address prediction uncertainties that would be needed before they could be used in plant operations. However, the assessments based on these enhanced models or advanced glass formulations show significant improvement in waste loading, and thus, continuing to assess their potential applicability is of utmost importance.

Belsher and Meinert identified five constraints that were most influential on the estimated Hanford HLW glass volumes.[2] One of those constraints was the limit of no more than one volume percent spinel crystals in the melt ($T_{1\%}$) at a temperature of 950 °C. That is, the glass must contain 1 vol% spinel crystals or less at 950 °C when subjected to ASTM C1720, *Standard Test Method for Determining Liquidus Temperature of Immobilized Waste Glasses and Simulated Waste Glasses,* in order to be considered acceptable.

Historically, crystallization constraints are placed in process control systems to prevent premature or catastrophic failure of the melter through bulk devitrification (also known as volume crystallization) or crystal accumulation and, thus, to mitigate negative impacts of crystals as glass is produced.[a] Joule-heated melter technology was successfully used from 1996 to 2002 at the West Valley Demonstration Project (WVDP) in New York, and has been in continuous use at the Defense Waste Processing Facility (DWPF) at the Savannah River Site (SRS) since radioactive operations began there in April 1996.

The baseline method of controlling crystallization in the WTP HLW melter uses a model that predicts the temperature, $T_{1\%}$, at which the equilibrium fraction of spinel crystals in the melt is 1 vol% (nominally at 950 °C).[4] In contrast, the DWPF melter is operated with a model that predicts the liquidus temperature (T_L) of the glass as a function of its composition.[3,5,6] The predicted T_L value for DWPF must be at least 100 °C below the nominal melter operating temperature (1150 °C) in order for the feed to be acceptable for transfer to the melter.[7] This approach sets the liquidus temperature at the point where no spinel crystals are detected. The T_L operating limit is used in DWPF to minimize the risk of bulk devitrification in the melt pool. This approach has been used at DWPF since non-radioactive start-up in April 1994 and has been successful at eliminating bulk devitrification within the melt pool leading to catastrophic melter failure or significant processing issues associated with crystallization in or from the melt pool. In fact, the first DWPF melter operated for 8 years, far exceeding the two-year life expectancy that is based on refractory corrosion.[8] The second melter has continually supported facility operations since March 2003, thus further exceeding the design life.

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[a] Jantzen and Brown provide a brief review of the potential, negative effects of crystallization within a melter.[3]

It is possible that the DWPF liquidus temperature approach is conservative, in that it may be possible to successfully operate the melter with a small degree of allowable crystallization in the glass. An alternative crystal-tolerant glass approach[9] may allow higher waste loading for WTP processing while maintaining a chemically durable glass product. Some crystalline phases, such as spinel, do not impact the durability of the waste form[10] but may accumulate in the melter or riser and restrict or prevent its operation. However, prediction of spinel precipitation and accumulation could potentially allow for formulating higher waste loading, durable glasses if an alternative strategy for operating and idling a melter with some amount of tolerable crystals can be developed and implemented.

Given the identification of the $T_{1\%}$ constraint as one of the most influential constraints for estimated Hanford HLW glass volumes, the DOE-Office of River Protection (ORP) has initiated a program to evaluate whether this constraint can be relaxed or whether new constraints could be developed to replace the current $T_{1\%}$ approach.[11,12] A study of the design and operation of the WTP HLW melter suggests that spinel accumulation in the 76 mm diameter glass discharge riser is the most limiting design aspect of the melter, and can most likely prevent discharge of the molten glass into canisters, especially when considering frequent and periodic idling.[a]

A road map[b] was recently developed to guide research and development efforts for a crystal tolerant glass processing strategy for WTP. The basis of this potential, alternative approach will be an empirical model predicting the crystal accumulation in the WTP glass discharge riser and melter bottom as a function of glass composition, time, and temperature.[9] When coupled with an associated operating limit, this model could then be integrated into the process control algorithms to formulate crystal tolerant HLW glasses targeting higher waste loadings while still meeting other process related limits and melter lifetime expectancies.

This report provides a review of the scaled melter testing that was completed in support of DWPF development, a review of crystallization observed with the full scale DWPF melters, and examples of actual DWPF melter attainment with Melter 2. The intent is to provide an overview of lessons learned, including some example data, that can be used to advance the development and implementation of an empirical model[13] and operating limit for crystal accumulation for WTP.

1.1 Quality Assurance

This review is performed as part of a Task Technical and Quality Assurance Plan.[14] Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. The Savannah River National Laboratory (SRNL) documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.

2.0 Literature Review

2.1 Scale Melter Testing in Support of DWPF Design

Jantzen, et al. provide a description of scale melter testing in support of the design of the DWPF, with a focus on the buildup of crystals in various areas of the melters.[15] This information will be summarized here in the context of crystal accumulation data to support the development of the crystal-tolerant glass approach for the WTP melter. An extensive review of scale melter testing is

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[a] Vienna, J. D., personal communication, February 21, 2014.

[b] Matyáš, J., J. D. Vienna, D. K. Peeler, K. M. Fox, and C. C. Herman, “Road Map for Development of Crystal-Tolerant High Level Waste Glasses,” SRNL-STI-2013-00734, in draft.

included as part of the *DWPF Glass Melter Technology Manual*,[16] portions of which will also be summarized here.

2.1.1 Project S-1941 Melter

The Project S-1941 scale melter was the first prototype designed for DWPF development work.[16] It was a cylindrical melter with electrodes for Joule heating of the melt pool entering from the top of the melter. The melter was originally operated with a calcined feed, and was later slurry fed. The riser was heated with an Inconel® 690 resistance heater. Glass in the riser contacted the heater directly. The riser was refractory lined and 6 inches in diameter. The riser heater, which was centered along the long axis of the riser, was 3 inches in diameter. This created an annular flow channel for the glass in the riser. The pour spout was approximately 1.875 inches in diameter. The pour spout was heated by an element surrounding the pour stream disengagement point. A total of 74 tons of glass were produced with the 1941 melter, including 20 tons produced via slurry feeding.[16]

The 1941 melter was dismantled to evaluate the effects of glass production on the melter materials and deposition of residual products.[17] A slag layer approximately 7 inches deep had accumulated at the bottom of the melter. Material up to 1 inch thick had accumulated on the melter walls, and the riser and pour spout were nearly plugged with glass containing a high concentration of spinel particles. The slag at the bottom of the melter was shown to consist of three layers, consisting mainly of Fe-Ni-Mn and Fe-Ni-Mn-Cr spinel phases in a glass matrix. A sodium calcium iron silicate phase was present in the upper two layers. The material adhered to the melter walls consisted of a reaction zone between the Monofrax K-3 refractory and the glass, and a glass layer containing more than 30 vol % FeNiMn spinel particles. The lack of Cr in the spinel phase that was found in the glass adhered to the walls indicated that the crystallization in this glass layer was not a result of refractory corrosion. The higher viscosity of the glass due to the presence of the spinel crystals was concluded to be the cause of the glass remaining on the walls of the melter.[17]

The accumulation of crystals in the 1941 melter was correlated to the thermal history over the period of operation.[17] The melter was operated above 1200 °C for the first three months, including seven days at about 1300 °C. This resulted in accelerated refractory corrosion, and likely led to the accumulation of Cr-containing spinels and higher concentrations of Al in the glass at the bottom of the melter. This accumulation generated the first of the three layers identified in the later inspection. The upper two layers were determined to have formed due to low temperature operation. The liquidus temperature of the Frit 131 and Technical Data Summary (TDS) waste melter feed was 1081 °C.[a] The 1941 melter experienced two periods of low temperature idling, one for 58 days at 1050 °C, and another for about one month where the melter was shut down (thermally cycled) one to three times per day. The slag layer was probed and found to be 7 inches thick after the 58 day idling period. Additional slag accumulation was not observed after the one month period of thermal cycling. It was hypothesized that the conditions during cycling did not favor the kinetics of spinel crystallization.[17]

The accumulation of spinel in the bottom of the 1941 melter eventually led to spinel coming out of the melter with the glass to the point where the glass quality (qualitative) was considered to be affected.[17] Increased riser temperature and rocking of the melter were needed in order to continue pouring near the end of the melter campaign. Heat loss through the melter bottom refractory contributed in part to the issues with spinel formation. The DWPF melter bottom refractory was

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[a] Jantzen, et al. provide a thorough compilation of available glass composition data for the various SRS pilot scale melter campaigns, along with predicted liquidus temperatures and viscosity values.[15]

later designed to ensure that the glass would freeze in the refractory while maintaining a hot face temperature of 1050 °C.[16] The vertical electrode configuration of the 1941 melter (and the Small Cylindrical Melter, described in Section 2.1.2) likely also contributed to the accumulation of spinels at the bottom of the melter.[18] Spinel (and potentially, reduced metals) accumulation at the bottom of the melter may have reduced the resistance of the glass at the bottom of the melter, leading to power skewing to the bottom and cooling of the upper melt pool to below the liquidus temperature, causing additional spinel formation. The higher viscosity of glass with spinel crystals reduces the ability to transfer its heat to the rest of the melt pool via convective transport. The vertical electrode configuration does not allow for the power profile to be intentionally skewed to the top of the melt pool to prevent this situation.[18] The DWPF melter uses upper and lower pairs of diametrically opposed electrodes to provide better melt pool temperature control.[16]

2.1.2 Small Cylindrical Melter (SCM)

The SCM was used for performance testing of DWPF melter materials of construction with a variety of glass compositions.[19] It was a roughly octagonal melter with electrodes for Joule heating of the melt pool entering from the top of the melter. The riser was not heated, and was constructed with Monofrax K-3 refractory. An Inconel® 690 sleeve was inserted into the riser for the last of the three melter campaigns because of refractory corrosion. Supplementary heat was provided in the pour chamber by silicon carbide elements.[20] The melter ran for 786 days, including idle periods. It produced 51,521 pounds of glass via powder feeding and 11,359 pounds of glass via slurry feeding.[19]

The SCM melter accumulated approximately 0.5 inches of a crystalline slag layer at the bottom after approximately 4.5 months (the first campaign) of processing Frit 211 and simulated TDS waste with a liquidus temperature of approximately 1050 °C.[20] The melter was operated (feeding, pouring, and idling) at temperatures of 1050-1185 °C. At one point, a loss of power incident allowed the melter to cool to approximately 300 °C. The total duration of this incident was about two days.[20] Analysis of samples taken from the slag layer identified the major crystalline phase as $NiFe_2O_4$. It was concluded that circulation in the melt pool must have been sufficient to sweep spinel from the melter since the bottom temperature was generally near the liquidus.[20] An additional 0.5 inches of slag accumulated during the second melter campaign.[21] The last phase of the second campaign involved feeding a mixture of Pacific Northwest Laboratory (PNL) calcine with Frit 211 at a deliberately low[19] melt pool temperature of 1040-1070 °C for about five days. This resulted in the accumulation of another 0.5 inches of slag on the bottom of the melter when the T_L of the glass was approximately 1050 °C.[21]

During the third and final campaign with the SCM melter, Frit 131 and simulated waste slurry at a waste loading of approximately 50 wt % was inadvertently fed to the melter. This resulted in an area of high temperature forming at the bottom of the melter.[19] Several steps were taken to try to alleviate the development of high temperatures at the bottom of the melter, including multiple attempts at feeding frit only to flush the melter, stirring the melt pool with a metal rod, air sparging, and tilting the melter to its maximum angle for draining. In all cases, these measures provided only temporary improvements in the melt pool temperature profile. That is, the melt pool bottom temperature would approach the maximum allowable (1170 °C), where power would then have to be reduced, resulting in the upper melt pool cooling to below the liquidus temperature and the formation of spinel.[19]

Samples taken from the bottom of the SCM after the third campaign consisted mainly of spinels, including trevorite, magnetite, hercynite, and a small amount of acmite. It was concluded that the high temperatures at the bottom of the melter were the result of increased viscosity of the spinel laden glass at the bottom of the melt pool rather than differences in conductivity, since reduced metals were not found in the slag. The higher viscosity of the material at the bottom of the melter hindered heat transfer via convection.[19] Also note that the Project S-1941 Melter and the SCM were fed with calcine material, which was shown to contribute to slag accumulation on the bottom of the melters.[22] Slurry feeding was therefore used with the other scale melters and the DWPF melter.

2.1.3 Large Slurry Fed Melter (LSFM)

The LSFM was designed and operated to evaluate slurry feeding with various glass compositions and off-gas system configurations.[16] The melter was octagonal with a flat bottom. The walls and floor of the LSFM were more heavily insulated as compared to the 1941 melter since the LSFM vessel was not water cooled. There were two pairs of diametrically opposed electrodes with independent power supplies for Joule heating of the melt pool, similar to the final design of the DWPF melter. Supplementary heat was provided in the pour chamber by silicon carbide elements.[23] A riser heater is depicted in engineering drawings of the LSFM.[16,23] The melter produced 234 tons of glass over a period of 749 days. Of this time period, 556 days were spent idling at 1100-1150 °C.[16] The riser temperatures were reported to be in the range of 1125 °C ± 10 °C and the pour spout temperatures were reported to be 1075 °C ± 10 °C during the fifth campaign.[24]

The LSFM was disassembled for inspection after being drained to determine the performance of the materials of construction. A thin layer of crystalline material was found at the bottom of the melter, ranging from 0.0625 to 0.5 inches thick and consisting of chromium-nickel-iron spinel. The accumulation of spinels was determined to be a result of corrosion of the Monofrax K-3 refractory.[23]

2.1.4 Scale Glass Melter (SGM)

The Project S-1941 melter was later converted to the DWPF design under Project S-4234 in order to verify operation of several DWPF equipment designs.[16] The SGM melt pool was scaled to 2/3 of the full scale DWPF melter and used prototypic refractories, including an insulating bottom layer designed to maintain a hot face temperature on the melter floor. There were two pairs of diametrically opposed electrodes with independent power supplies, scaled to 2/3 the size of those in the DWPF melter. The riser and pour spout were heated with Inconel® 690 electrical resistance heaters. The riser heater was designed to maintain the glass temperature at 1050-1170 °C.[25] Changes to the thermocouple positioning in the riser were needed to correct a riser heater failure at startup due to overheating.[16]

Glass samples taken close to the bottom of the SGM after the fifth campaign contained no crystalline phases, although the actual depth from which the sample was retrieved was questioned.[22] The lack of crystallization was attributed to better melter design, slurry feeding rather than feeding calcined material, control of rheology and REDuction/OXidation (REDOX) by formic acid addition, and more soluble frit compositions.[22] The SGM was completely drained after the ninth campaign[15] and the bottom of the melter was inspected with a remote video camera.[26] Material that appeared to be crystalline was noted along the ledge where the melter side walls met the floor. No significant accumulation of crystalline material is noted in the report.[26]

Although no significant accumulation was reported on the melter floor, the SGM riser was plugged multiple times during the first campaign.[27] Samples of the material that plugged the riser were characterized and found to consist largely of acmite. A comparison with time-temperature-transformation (TTT) curves developed for a similar glass chemistry indicated that times of more than 24 hours at temperatures of 600-800 °C would have been necessary for the almost complete devitrification of the glass to acmite and, therefore, the riser was not being kept hot enough. The lack of spinel in the crystalline material from the riser, coupled with the TTT data, further demonstrated that the riser temperature had been below 750 °C.[15,27] Devitrification in the SGM riser and pour spout was remediated via improvements to the insulation design.[28]

2.1.5 Integrated DWPF Melter System (IDMS)

The IDMS was a 1/9 scale demonstration of the DWPF feed preparation, melter (1/9 scale), and off-gas systems.[29] The melter shell was basically the same design as the SCM, with an additional 12 inches of Monofrax K-3 refractory used to reduce the melt pool diameter to 24 inches. There were two pairs of diametrically opposed electrodes with independent power supplies. The riser and pour spout were heated with serpentine Inconel® 690 heaters. The riser was heated to 1100 °C and the pour spout was heated to 1050 °C to maintain the flow of glass.[29]

Issues with pluggage of the pour spout were noted during the early, sludge-only runs (i.e., feed consisting of simulated sludge and glass frit without simulated streams from salt processing) of the IDMS.[29] The pour spout became plugged with glass[a] at least seven times during the second sludge-only runs. The pluggages were attributed to a low rate of glass pouring. This was alleviated by modifying the vacuum pouring system to better control the glass flow rate. Additional pluggages were due to a wavering pour stream causing the glass to contact colder regions of the pour spout below the normal disengagement point. Wavering of the pour stream was attributed to the temperatures in the pour spout being too low. Similar behavior was later observed in the DWPF melter, resulting in the addition of a pour spout insert and a heated bellows liner.[8] Pouring was improved by increasing the set point of the pour spout control thermocouple from 1020 °C to 1100 °C and by increasing the set point of the primary channel exit point thermocouple from 932 °C to 974 °C. [29]

Glass samples were taken from close to the floor of the IDMS (3-5 cm above the refractory) once noble metals were included in the feed.[30] The samples were taken through the melter feed port. The intent was to identify any accumulation of noble metals that could lead to problems with Joule heating. No noble metals deposits were found after two months of operation with noble metals in the feed. RuO_2 deposits with a needle-like morphology were found in a floor sample collected after seven months of operation with noble metals in the feed. After approximately 13 months, a melter floor sample was collected and found to consist of a denser layer of RuO_2 and (Ni,Mn)(Fe,Cr) spinels. Samples collected over the next two months continued to exhibit RuO_2, Rh, and spinel accumulation. A sample collected after the completion of processing of Hanford Waste Vitrification Plant feed, HWVP2, had decreased concentrations of Ru, Rh, and spinel components. These data correlated with analyses of the glass produced during HWVP1 and HWVP2 production, where Cr concentrations were 60-230% higher in the glass product than in the melter feed. These results were attributed to flushing of spinels and noble metals from the melter during this period. A mechanism for this flushing was not identified, although convective currents in the melt pool were suggested as a potential cause.[30]

Additional melter floor samples were taken over time from both the feed port and the borescope port to determine whether the accumulated layer was uniform across the melter.[30] The analysis of multiple samples suggested that the noble metal and spinel layer was not uniform, and that the material accumulated at the outside edges of the melter bottom. This was attributed to the action of convective currents in the melt pool.[30]

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[a] Smith et al.[29] refer to the pluggages as glass and do not mention any crystallization.

Further review of the noble metals data collected during the IDMS campaigns demonstrated the propensity for settling of noble metals and spinels during idle periods.[31] Continuous melter feeding and pouring appears to generate sufficient convective currents to prevent the settling of melt insolubles, while idle periods allow settling to occur. It was recommended that DWPF avoid periods of idling when noble metals are present in the feed. A small number of extended idle periods were recommended as being preferable to multiple short idle periods to minimize the accumulation of noble metals and spinels.[31]

Following seven years of operation, the IDMS was shut down for examination to gather inspection data and minimize the need for future inspections of the DWPF melter and off-gas system.[32] Samples were collected from the floor and drain of the IDMS in order to characterize any crystalline material. A vacuum pour was used to empty the melter since the bottom drain did not function, which left approximately 12 inches of glass remaining on the melter floor. Multiple samples were retrieved from across the melter floor, and their compositions were very consistent.[32] The material was slightly enriched in Cr_2O_3 and contained noble metal oxides on the order of 0.04 wt % (equivalent to the concentration targeted in the glass). Spinels were present in concentrations of 3.2-8.5 wt %, as well as some amount of krinovite, which was attributed to decomposition of the K-3 refractory.[33-35] Higher concentrations of spinels were found in samples that had been embedded in the K-3 refractory floor.[32]

2.2 DWPF Melter 1 Inspection after 1.75 Years of Non-Radioactive Startup Campaigns

The full scale DWPF melter is cylindrical, with a melt pool diameter of about 1.83 m and Monofrax K-3 as the glass contact refractory.[36] All metallic components within the melter are Inconel® 690. The first DWPF melter operated for more than eight years, producing approximately 2.4 x10^6 kg of glass. The melter was operated at a glass temperature of 1050 °C to 1200 °C. Early operations were with an oxidizing melt pool ($Fe^{2+}/\Sigma Fe=0.09$ for Sludge Batch 1A and part of Sludge Batch 1B), and later operations (Sludge Batch 1B to shutdown) targeted a reduced melt pool ($Fe^{2+}/\Sigma Fe=0.2$). A cross section of the DWPF melter is depicted in Figure 2-1.

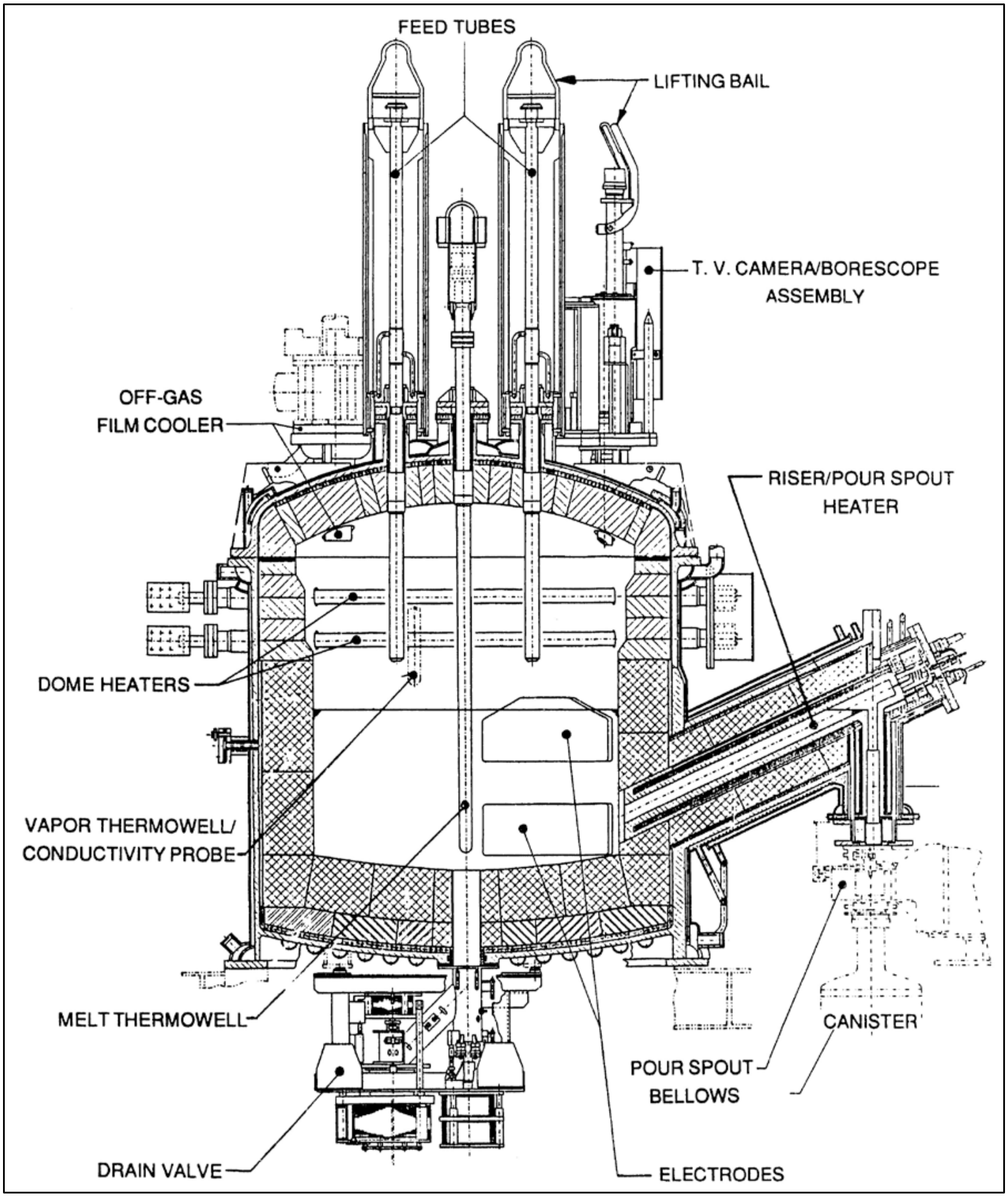

Figure 2-1. Cross-sectional Overview of the DWPF Melter.[36] Note that this diagram shows the melter configuration prior to the installation of bubblers.

In March and April 1996 (prior to radioactive operations), deposits formed in the DWPF melter pour spout on several occasions.[34,35] There was concern that accumulated crystalline material on the floor of the DWPF melter could be a source of the pour spout deposits. Rodding of the melter showed two distinct layers of material on the melter floor. The bottom-most layer, which was about 1.5 inches in depth, was of high density, while the upper, "mushy" layer was less dense and was about 1 inch in depth.[37] The total depth of the deposits accumulated over approximately 1.75

years of non-radioactive startup campaigns was about 2.5 inches. Glass samples and melter bottom deposit samples were obtained by inserting rods with sample cups welded to their bottoms through a nozzle in the melter top head until the bottom of the cups impacted the semi-solid "mushy" layer of deposits on the melter floor near the riser.[37]

The glass collected inside the two cups and the partially crystallized melter bottom deposits adhering to the bottom surfaces of the cups were characterized.[34,35] Visually, a layer of crystalline deposits adhered to the bottom of the cups and partially up the outside of the sample cups. The cups were approximately 4 inches high and impacted the bottom deposits vertically such that no crystalline deposits were found inside the cups or further up the rods above the cups. The crystallized material adhering to the bottom of the sample cups was broken off and analyzed. The glass inside the cup, the glass on the upper surfaces of the cup, and the glass on the rod contained no visible crystalline material. The glass from inside the cup and glass adhering to the side of the rod were also analyzed. The results, provided in detail by Jantzen, et. al, indicated that the crystallized material adhering to the bottom of the sample cups was enriched in NiO, Fe_2O_3, and Cr_2O_3 as compared to the glass within the sample cups.[34,35]

X-ray diffraction analysis confirmed that the crystallized melter bottom deposits adhering to the bottom of the sampler cups were Ni-Fe-Cr spinels.[34,35] The melter bottom deposits contained between 25-34 wt% spinel and some RuO_2 as compared to the glass adhering to the side of the rod that contained only 0.7-5.2 wt % spinel. These DWPF melter bottom deposits were similar in composition to the melter bottom deposits analyzed from the IDMS in that they were enriched in NiO, Fe_2O_3, and Cr_2O_3.[32]

The accumulation of spinels in the DWPF melter has been attributed to refractory corrosion with an oxidizing melter feed, rather than crystallization within the melt, since the DWPF melter feed composition was controlled such that the predicted liquidus temperature was at least 100 °C below the melter temperature. Jantzen, et al. provide a method for, and examples of, calculating the accumulated depth of melter bottom deposits from refractory corrosion data.[34,35] For example, DWPF Melter 1 had processed about 2.8 x 10^5 pounds of glass after about 1.75 years of non-radioactive commissioning. The linear K-3 refractory corrosion equation given by Jantzen, et al. gives a loss of about 860 mils in 1.75 years. Assuming that the melter bottom deposits consist of an average of 35 wt % spinel and 65 wt % glass (from quantitative X-ray diffraction (XRD) analyses of the glass adhering to the cups), Jantzen, et al. calculate the approximate depth of the DWPF Melter 1 slag deposits to be about 2.3 inches after 1.75 years of operation with oxidizing feeds. The result from performing similar calculations for the IDMS near draining (after about 7 years of operation) is approximately 6 inches of slag deposits at time of inspection.[34,35] This depth calculated for the IDMS compares favorably with what was observed during inspection, although the exact deposit depth was indeterminate for the IDMS (due to the use of vacuum pouring to empty the melter as described earlier).

2.3 DWPF Melter 1 Inspection after Radioactive Operation

DWPF Melter 1 was shut down and replaced in November 2002 due to the failure of one set of vapor space heaters, ongoing glass pour stream instabilities, and the opportunity afforded by an extended facility outage.[8] Prior to draining, three glass samples were collected from DWPF Melter 1: one from the melt pool top surface (air interface) that was collected while the melter was still hot and after the cold cap had been consumed, and two retrieved from two depths within the remaining glass after the melter cooled using a specially designed core sampler. The samples were analyzed for chemical composition and the presence of any crystalline phases.[38] The compositions of the three samples were found to be reasonably consistent, although the coring method contributed contamination to those samples. The sample from the top of the melt pool did not contain any crystalline phases that were detectable via XRD. The samples retrieved with the core sampler contained trevorite and acmite, consistent with slow cooling (1-2 days) of the glass. Since the samples cooled slowly within the melter, further conclusions could not be drawn regarding the presence of crystals within the melter during normal operations.[38] To reiterate, the DWPF processing strategy is to operate with glass compositions that have a predicted spinel T_L of at least 100 °C less than the nominal melt pool temperature of 1150 °C; therefore, it is expected that the sample from the top of the melt pool would not contain crystals.

The interior of the DWPF Melter 1 was inspected using a remotely operated camera after it was shut down and cooled. Glass was observed near the bottom of the melter (which remained approximately 1/3 full) but was not characterized to determine whether it contained crystalline phases. Refractory corrosion was observed to be considerably less than expected.[36]

2.4 DWPF Melter 2 Crystallization Issues and Analyses

DWPF Melter 2 began operation in March 2003. About 5 months later (August 28, 2003), glass was sampled from DWPF Melter 2 at three locations: a pour stream sample during processing of Sludge Batch 2 (collected at approximately 7:50 PM on August 28, 2003), a sample scraped from the 2 inch upper pour spout bore while hot, and a sample that had spalled off of a pour spout insert after the insert had cooled. A detailed analysis of these samples is provided by Jantzen, et al.[15] Select DWPF melter pool and riser temperature data for a time period of about one week prior to collection of the pour stream sample are included for reference as Appendix A. The sampling date corresponded to approximately five months of operation of DWPF Melter 2, at a time when the targeted waste loading had been increased to 38 wt % and the new quasi-crystalline liquidus model had been implemented.[3,6] An unusual amount of crystallization in the pour spout was hindering processing.

The upper pour spout bore sample was determined to be about 62% glass, with the remaining fraction consisting of trevorite, $NiCr_2O_4$, and noble metal oxides. The pour spout insert sample contained less spinel, but more Cr_2O_3, which was posited to be due to oxidation of the Inconel® 690 and reaction with the glass.[15] The pour stream sample was shown to be amorphous via XRD. The predicted liquidus temperature of the pour stream sample, based on its measured composition, was 997 °C. Jantzen, et al. describe several potential mechanisms for the accumulation of crystals (including noble metal oxides) in the DWPF melter pour spout, including temperature and oxygen fugacity gradients, heat sink induced crystallization, Inconel® 690 oxidation, and elevated concentrations of Cr_2O_3 in the pour stream glass due to Monofrax K-3 corrosion. Heat sink induced crystallization was shown to be the most likely mechanism.[15]

2.5 DWPF Melter Pour Stream Sample Analyses

Several glass pour stream samples have been collected and analyzed at SRNL during the operation of the DWPF melter. While these analyses have focused on determining the glass composition, radionuclide inventory, and chemical durability in order to meet regulatory requirements, some basic characterization related to crystallization was also completed. In general, contained scanning electron microscopy with energy dispersive spectroscopy (CSEM/EDS) was used to observe small samples of the pour stream glasses and identify any crystalline phases. No spinels were observed in any of the pour stream glasses. Small crystals consisting of the noble metals ruthenium, rhodium, and palladium were identified in several of the pour stream glasses. It is important to note that the volume fraction of crystals observed in these glasses was exceedingly small in all cases and was not determined quantitatively. Also, both the waste loading and noble metals concentration in the melter feed were higher in those batches where noble metals were observed in the pour stream samples. A summary of the observed crystallization in the pour stream glasses is given in Table 2-1.

Table 2-1. Summary of Crystallization Data from DWPF Pour Stream Sample Analyses.

DWPF Melter	DWPF Sludge Batch	Crystallization Detected in Pour Stream Glass	Detection Method	Reference
Melter 1	Sludge Batch 1a (Canister 50)	None	CSEM/EDS	39
	Sludge Batch 1a (Canister 61)	None	CSEM/EDS	40
	Sludge Batch 1a (Canister 409)	None	CSEM/EDS	41
	Sludge Batch 1b	None	CSEM/EDS	42
Melter 2	Sludge Batch 2	None	Visual observation	43
	Sludge Batch 3	Ruthenium, rhodium, and palladium crystals	CSEM/EDS	44
	Sludge Batch 4	Ruthenium crystals	CSEM/EDS	45
	Sludge Batch 5	Ruthenium crystals	CSEM/EDS	45
	Sludge Batch 6	Ruthenium crystals	XRD	46
		Ruthenium and palladium crystals	CSEM/EDS	
	Sludge Batch 7a	Ruthenium and rhodium crystals	CSEM/EDS	47
	Sludge Batch 7b	Ruthenium and rhodium crystals	CSEM/EDS	48

2.6 Suspension of Spinels in the DWPF Melter

A simple computational study was performed to determine whether settled spinels in the DWPF melter could be expected to become re-suspended as a result of convection currents in the melt pool and flow through the riser.[49] The study used a fluid mechanics model to evaluate the propensity for suspending spinel crystals in the melt pool and sweeping them out through the riser. While admittedly simple in nature, the calculations suggested that spinels (assumed to be spherical particles 20 μm in diameter) may be suspended in the melt pool and carried through the riser during pouring.[49]

3.0 DWPF Melter 2 Operating Data

Melter idle time is a critical factor in developing and implementing a crystal tolerant approach to melter operation. Idle periods, assuming that agitation of the melt pool is minimal during these times and that the melter has been operated at or below the T_L of the glass, provide the most opportune time for crystal growth and settling. Example data on actual attainment of the DWPF melter for fiscal years 2011 and 2012 were provided by DWPF engineering.[a] These data are presented here as an example of what might be expected in terms of the actual attainment of the WTP HLW melter (i.e., under prototypical conditions), and in turn, the melt pool idling time that might be expected in a year. Note that bubblers were operational in the DWPF melter during these operating periods (see Table 2-1), although the bubbling rate is reduced to a minimum during idle periods as idle periods are associated with increased vaporization of alkali borates from the melt pool.[50]

DWPF melter attainment (i.e., the amount of time during which feed was supplied to the melter) for FY2011 was approximately 67%. Feeding was stopped for approximately 2,870 hours at various intervals over the course of FY2011. A summary of the FY2011 melter downtime events is provided in Table 3-1. DWPF melter attainment for FY2012 was approximately 66%. Feeding was stopped for approximately 3,030 hours. A summary of the FY2012 melter downtime events is provided in Table 3-2.

A review of these tables shows that planned and unplanned outages occur for durations of days up to several weeks. Time periods on this scale must be considered as part of the development of the crystal tolerant strategy.

DWPF was in an extended outage from early October to late December 2013. This was a unique situation for sampling the melter after an extended idling period.[51] Samples were successfully collected from the melter pour stream when processing resumed. Characterization will be performed to determine the type and extent of crystallization, if any. These results will be coupled with composition data to provide an additional input to development of the crystal-tolerant glass strategy.

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[a] Email communication from Brandon Hodges, Savannah River Remediation, June 5, 2013.

Table 3-1. Fiscal Year 2011 DWPF Melter Downtime Key Event Timeline.

Dates	Type of Outage	Description
11/06/10 – 11/10/10	Unscheduled Maintenance	Shutdown due to lack of space to store filled canisters. Repairs made to Canister Decontamination Chamber #2 in order to blast canisters and generate space for filled canisters.
11/14/10 – 11/19/10	Unscheduled Maintenance	Shutdown due to lack of space to store filled canisters. Replaced the wire rope on the in-cell crane for the Canister Decontamination Cell, existing wire rope had a kink that would not pass through the load block.
12/03/10 – 12/07/10	Unscheduled Maintenance	Trouble restarting the Melter feed loop after a scheduled heated bellows liner replacement. Troubleshooting and repair were performed to put feed loop back in service. Issue resolved by replacing the section of the feed loop jumper between the flow meter and the Hanford wall nozzle.
01/04/11 – 01/07/11	Planned Outage	Visual inspection of the Melter bubblers.
01/26/11 – 01/30/11	Scheduled Maintenance	Replacement of the Melter Primary Off-Gas (POG) quencher and film cooler.
02/28/11 – 03/05/11	Slurry Mix Evaporator (SME) Transfer Delay	Delay in SME batch transfer to Melter Feed Tank (MFT). Clogged sample line caused issues getting the SME product sample to the lab for analysis.
03/20/11 – 03/26/11	SME Transfer Delay	Delay in SME batch transfer to MFT. Replacement of Sludge Receipt and Adjustment Tank (SRAT) transfer pump delayed SME processing. In addition, SME processing delayed due to SME GC #2 column replacement.
03/27/11 – 03/31/11	Shutdown	Delay in Chemical Processing Cell (CPC).

Table 3-1. Fiscal Year 2011 DWPF Melter Downtime Key Event Timeline. (continued)

Dates	Type of Outage	Description
04/01/11 – 04/29/11	Planned Outage	Site steam outage, Load Center B7 work, replaced Melter POG quencher and high efficiency mist eliminator filters, replaced Melter bubblers.
05/24/11 – 05/31/11	SME Transfer Delay	Delay in SME batch transfer to MFT. SME vessel would not steam properly. Replaced steam traps and re-gasketed various SME steam supply jumpers along with other troubleshooting activities.
06/07/11 – 06/14/11	Unscheduled Maintenance	SME coil replacement.

Table 3-2. Fiscal Year 2012 DWPF Melter Downtime Key Event Timeline.

Dates	Type of Outage	Description
10/16/11 – 11/03/11	Planned Outage	Cleaned Melter off-gas condensate tank, installed new heated bellows liner and pour spout insert, cleaned Melter Off-gas Quencher.
11/07/12 – 11/18/11	SME Transfer Delay	Complete outage activities in the CPC.
02/06/12 – 02/09/12	Unscheduled Maintenance	Replace SME coil, repair SME agitator electrical jumper.
06/26/12 – 07/02/12	SME Transfer Delay	Waiting on SME Batch 639 to transfer; process frit line plugged (cleared line and replaced components), replaced SME Hydraguard sampler, remediated batch due to failed flammability constraint.
07/28/12 – 08/24/12	SME Transfer Delay	Processing in CPC on hold.
09/03/12 – 09/20/12	SME Transfer Delay	Waiting on SME Batch 645 to transfer; cleared SME sample line trickle flow piping, replaced flow element in trickle flow piping, replaced SME Hydraguard sample pump.

4.0 Summary

A road map[a] was recently developed to guide research and development efforts for a crystal tolerant glass processing strategy for WTP. The basis of this alternative approach is an empirical model predicting the crystal accumulation in the WTP glass discharge riser and melter bottom as a function of glass composition, time, and temperature. When coupled with an associated operating limit, this model could then be integrated into the process control algorithms to formulate crystal tolerant HLW glasses targeting higher waste loadings while still meeting process related limits and melter lifetime expectancies.

This report provides a review of the scaled melter testing that was completed in support of DWPF development, a review of the crystallization observed with the full scale DWPF melters, and examples of actual DWPF melter attainment in recent years. The intent is to provide an overview of lessons learned, including some example data, that can be used to advance the development and implementation of an empirical model and operating limit for crystal accumulation for WTP.

Operation of the first and second (current) DWPF melters has demonstrated that the strategy of using a liquidus temperature predictive model combined with a 100 °C offset from the normal melter temperature of 1150 °C (i.e., the predicted T_L of the glass must be 1050 °C or less) has been successful in preventing any detrimental accumulation of spinel in the melt pool, and spinel has not been observed in any of the DWPF pour stream glass samples. Spinel was observed at the bottom of DWPF Melter 1 as a result of K-3 refractory corrosion. Issues have occurred with accumulation of spinel in the pour spout during periods of operation at higher waste loadings. Given that both DWPF melters were or have been in operation for greater than 8 years, the service life of the melters has far exceeded design expectations. It is possible that the DWPF liquidus temperature approach is conservative, in that it may be possible to successfully operate the melter with a small degree of allowable crystallization in the glass. This could be a viable approach to increasing waste loading in the glass assuming that the crystals are suspended in the melt and swept out through the riser and pour spout. Additional study is needed, and development work for WTP might be leveraged to support a different operating limit for the DWPF. The DWPF liquidus temperature strategy is geared specifically toward bulk crystallization within the melt pool. Crystallization issues in the pour spout have occurred in the past as a result of temperature gradients or heat sinks in the pour spout. As recommended below, these conditions should be considered in developing the crystal tolerant strategy for WTP.

Several recommendations are made regarding considerations that need to be included as part of the WTP crystal tolerant strategy based on the DWPF development work and operational data reviewed here. These include:

- Identify and consider the impacts of potential heat sinks in the WTP melter and glass pouring system
- Consider the contributions of refractory corrosion products, which may serve to nucleate additional crystals leading to further accumulation
- Consider volatilization of components from the melt (e.g., boron, alkali, halides, etc.) and determine their impacts on glass crystallization behavior
- Evaluate the impacts of glass REDOX conditions and the distribution of temperature within the WTP melt pool and melter pour chamber on crystal accumulation rate
- Consider the impact of precipitated crystals on glass viscosity

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[a] Matyáš, J., J. D. Vienna, D. K. Peeler, K. M. Fox, and C. C. Herman, "Road Map for Development of Crystal-Tolerant High Level Waste Glasses," SRNL-STI-2013-00734, in draft.

- Consider the impact of an accumulated crystalline layer on thermal convection currents and bubbler effectiveness within the melt pool
- Evaluate the impact of spinel accumulation on Joule heating of the WTP melt pool
- Include noble metals in glass melt experiments because of their potential to act as nucleation sites for spinel crystallization

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Appendix A. DWPF Melter Temperature Data for Selected Times during August 2003

Table A-1. Select DWPF Melter Temperature Data

Time Stamp	**Upper Melt Pool Avg Temp (°C)**	**Lower Melt Pool Avg Temp (°C)**	**Riser Temp 1 (°C)**	**Riser Temp 2 (°C)**	**Riser Temp 3 (°C)**	**Riser Temp 4 (°C)**
8/21/2003 8:00	1182	1103	1071	1071	1119	1071
8/21/2003 9:00	1179	1101	1071	1071	1119	1071
8/21/2003 10:00	1172	1099	1072	1071	1120	1070
8/21/2003 11:00	1166	1096	1073	1072	1122	1069
8/21/2003 12:00	1167	1098	1077	1076	1121	1069
8/21/2003 13:00	1167	1101	1075	1074	1119	1069
8/21/2003 14:00	1165	1104	1069	1068	1118	1069
8/21/2003 15:00	1168	1107	1073	1072	1122	1071
8/21/2003 16:00	1174	1110	1069	1068	1122	1073
8/21/2003 17:00	1175	1113	1057	1055	1115	1074
8/21/2003 18:00	1182	1113	1041	1039	1118	1075
8/21/2003 19:00	1187	1111	1042	1040	1121	1076
8/21/2003 20:00	1181	1108	1051	1050	1121	1076
8/21/2003 21:00	1175	1106	1064	1063	1121	1074
8/21/2003 22:00	1170	1104	1069	1069	1120	1072
8/21/2003 23:00	1166	1101	1072	1071	1119	1070
8/22/2003 0:00	1166	1104	1070	1069	1120	1071
8/22/2003 1:00	1154	1107	1067	1067	1120	1073
8/22/2003 2:00	1168	1110	1069	1067	1125	1075
8/22/2003 3:00	1174	1114	1066	1064	1118	1076
8/22/2003 4:00	1178	1116	1065	1065	1122	1076
8/22/2003 5:00	1179	1116	1065	1064	1119	1076
8/22/2003 6:00	1179	1115	1059	1058	1116	1076
8/22/2003 7:00	1171	1115	1061	1060	1120	1076
8/22/2003 8:00	1168	1115	1069	1068	1124	1076
8/22/2003 9:00	1163	1115	1056	1055	1116	1077
8/22/2003 10:00	1178	1115	1044	1042	1118	1078
8/22/2003 11:00	1190	1114	1032	1030	1120	1079
8/22/2003 12:00	1192	1109	1020	1017	1121	1080
8/22/2003 13:00	1188	1102	1016	1013	1120	1078
8/22/2003 14:00	1186	1096	1015	1013	1120	1076
8/22/2003 15:00	1186	1090	1019	1018	1119	1073
8/22/2003 16:00	1185	1084	1024	1022	1119	1071
8/22/2003 17:00	1181	1077	1028	1027	1119	1069
8/22/2003 18:00	1175	1071	1032	1031	1119	1066
8/22/2003 19:00	1168	1065	1037	1035	1119	1064
8/22/2003 20:00	1162	1063	1041	1039	1120	1062
8/22/2003 21:00	1160	1062	1041	1039	1120	1061
8/22/2003 22:00	1160	1063	1041	1039	1120	1061
8/22/2003 23:00	1162	1065	1041	1039	1120	1061
8/23/2003 0:00	1165	1068	1041	1040	1120	1062
8/23/2003 1:00	1169	1071	1041	1040	1120	1063
8/23/2003 2:00	1172	1074	1041	1039	1120	1064
8/23/2003 3:00	1172	1077	1040	1038	1120	1066
8/23/2003 4:00	1171	1079	1039	1037	1120	1067
8/23/2003 5:00	1171	1080	1038	1037	1120	1068

Table A-1. Select DWPF Melter Temperature Data (continued)

Time Stamp	Upper Melt Pool Avg Temp (°C)	Lower Melt Pool Avg Temp (°C)	Riser Temp 1 (°C)	Riser Temp 2 (°C)	Riser Temp 3 (°C)	Riser Temp 4 (°C)
8/23/2003 6:00	1171	1081	1038	1036	1120	1070
8/23/2003 7:00	1170	1081	1037	1035	1120	1070
8/23/2003 8:00	1170	1082	1036	1034	1120	1070
8/23/2003 9:00	1169	1083	1035	1033	1120	1070
8/23/2003 10:00	1169	1084	1035	1033	1120	1070
8/23/2003 11:00	1170	1086	1035	1033	1120	1070
8/23/2003 12:00	1170	1087	1034	1032	1121	1070
8/23/2003 13:00	1170	1088	1034	1032	1121	1071
8/23/2003 14:00	1155	1090	1036	1034	1121	1071
8/23/2003 15:00	1162	1092	1055	1053	1125	1071
8/23/2003 16:00	1170	1096	1064	1063	1124	1072
8/23/2003 17:00	1170	1100	1067	1066	1120	1073
8/23/2003 18:00	1184	1105	1056	1055	1116	1074
8/23/2003 19:00	1191	1101	1042	1040	1117	1075
8/23/2003 20:00	1198	1096	1036	1034	1119	1076
8/23/2003 21:00	1195	1092	1031	1029	1120	1077
8/23/2003 22:00	1187	1086	1028	1025	1120	1075
8/23/2003 23:00	1177	1081	1030	1028	1120	1073
8/24/2003 0:00	1167	1075	1033	1032	1120	1071
8/24/2003 1:00	1165	1074	1036	1035	1120	1069
8/24/2003 2:00	1163	1075	1039	1038	1120	1067
8/24/2003 3:00	1164	1075	1040	1038	1120	1066
8/24/2003 4:00	1165	1076	1040	1038	1120	1067
8/24/2003 5:00	1167	1077	1039	1037	1120	1067
8/24/2003 6:00	1169	1078	1038	1036	1120	1068
8/24/2003 7:00	1170	1079	1037	1036	1120	1069
8/24/2003 8:00	1172	1080	1037	1035	1120	1070
8/24/2003 9:00	1172	1081	1036	1034	1120	1071
8/24/2003 10:00	1172	1082	1035	1033	1120	1071
8/24/2003 11:00	1172	1083	1035	1033	1120	1072
8/24/2003 12:00	1172	1084	1034	1032	1120	1072
8/24/2003 13:00	1172	1085	1034	1032	1120	1072
8/24/2003 14:00	1172	1086	1033	1032	1120	1073
8/24/2003 15:00	1172	1087	1033	1031	1120	1073
8/24/2003 16:00	1172	1087	1033	1031	1120	1073
8/24/2003 17:00	1172	1088	1032	1030	1120	1073
8/24/2003 18:00	1171	1089	1032	1030	1120	1074
8/24/2003 19:00	1172	1090	1032	1030	1120	1074
8/24/2003 20:00	1172	1091	1033	1031	1120	1073
8/24/2003 21:00	1172	1091	1034	1032	1121	1073
8/24/2003 22:00	1163	1092	1044	1043	1122	1073
8/24/2003 23:00	1167	1093	1063	1062	1123	1072
8/25/2003 0:00	1173	1095	1072	1071	1123	1072
8/25/2003 1:00	1177	1098	1075	1073	1122	1072
8/25/2003 2:00	1176	1100	1075	1074	1121	1072
8/25/2003 3:00	1165	1103	1073	1073	1120	1071
8/25/2003 4:00	1175	1105	1072	1071	1119	1071

Table A-1. Select DWPF Melter Temperature Data (continued)

Time Stamp	Upper Melt Pool Avg Temp (°C)	Lower Melt Pool Avg Temp (°C)	Riser Temp 1 (°C)	Riser Temp 2 (°C)	Riser Temp 3 (°C)	Riser Temp 4 (°C)
8/25/2003 5:00	1180	1108	1070	1069	1119	1071
8/25/2003 6:00	1178	1108	1068	1067	1119	1071
8/25/2003 7:00	1177	1106	1068	1067	1118	1071
8/25/2003 8:00	1179	1103	1068	1068	1118	1071
8/25/2003 9:00	1183	1101	1063	1062	1115	1071
8/25/2003 10:00	1184	1097	1050	1049	1116	1071
8/25/2003 11:00	1186	1092	1046	1045	1121	1073
8/25/2003 12:00	1182	1087	1042	1040	1120	1073
8/25/2003 13:00	1162	1084	1040	1039	1119	1071
8/25/2003 14:00	1157	1083	1054	1053	1121	1070
8/25/2003 15:00	1162	1084	1071	1070	1123	1068
8/25/2003 16:00	1173	1086	1072	1072	1120	1066
8/25/2003 17:00	1179	1088	1062	1060	1117	1067
8/25/2003 18:00	1180	1086	1054	1052	1117	1068
8/25/2003 19:00	1180	1083	1049	1047	1119	1070
8/25/2003 20:00	1188	1080	1044	1042	1120	1071
8/25/2003 21:00	1185	1076	1040	1038	1120	1071
8/25/2003 22:00	1179	1073	1040	1038	1120	1069
8/25/2003 23:00	1174	1070	1040	1039	1120	1068
8/26/2003 0:00	1168	1066	1041	1039	1120	1067
8/26/2003 1:00	1166	1065	1041	1040	1120	1066
8/26/2003 2:00	1167	1067	1042	1040	1120	1065
8/26/2003 3:00	1167	1068	1042	1041	1120	1063
8/26/2003 4:00	1168	1069	1043	1041	1120	1064
8/26/2003 5:00	1168	1071	1043	1041	1120	1064
8/26/2003 6:00	1169	1072	1042	1041	1120	1065
8/26/2003 7:00	1170	1073	1042	1040	1120	1066
8/26/2003 8:00	1170	1074	1041	1039	1120	1067
8/26/2003 9:00	1171	1075	1040	1038	1120	1067
8/26/2003 10:00	1171	1076	1040	1038	1120	1068
8/26/2003 11:00	1172	1077	1039	1037	1120	1069
8/26/2003 12:00	1171	1077	1038	1036	1120	1069
8/26/2003 13:00	1171	1078	1037	1036	1120	1069
8/26/2003 14:00	1171	1079	1037	1035	1120	1069
8/26/2003 15:00	1171	1080	1037	1035	1120	1069
8/26/2003 16:00	1171	1080	1037	1035	1120	1069
8/26/2003 17:00	1171	1080	1036	1035	1120	1069
8/26/2003 18:00	1170	1080	1036	1034	1120	1069
8/26/2003 19:00	1170	1081	1036	1034	1120	1069
8/26/2003 20:00	1171	1083	1035	1034	1120	1069
8/26/2003 21:00	1171	1084	1035	1034	1121	1070
8/26/2003 22:00	1172	1085	1037	1034	1121	1070
8/26/2003 23:00	1170	1086	1043	1040	1122	1070
8/27/2003 0:00	1161	1087	1064	1064	1125	1070
8/27/2003 1:00	1171	1090	1073	1073	1122	1068
8/27/2003 2:00	1176	1094	1077	1074	1121	1068
8/27/2003 3:00	1179	1098	1075	1073	1121	1069

Table A-1. Select DWPF Melter Temperature Data (continued)

Time Stamp	Upper Melt Pool Avg Temp (°C)	Lower Melt Pool Avg Temp (°C)	Riser Temp 1 (°C)	Riser Temp 2 (°C)	Riser Temp 3 (°C)	Riser Temp 4 (°C)
8/27/2003 4:00	1171	1100	1073	1071	1120	1069
8/27/2003 5:00	1181	1100	1072	1071	1120	1070
8/27/2003 6:00	1180	1101	1070	1070	1119	1070
8/27/2003 7:00	1165	1102	1070	1069	1119	1070
8/27/2003 8:00	1163	1103	1070	1069	1120	1070
8/27/2003 9:00	1171	1104	1072	1071	1122	1070
8/27/2003 10:00	1177	1105	1072	1072	1120	1070
8/27/2003 11:00	1186	1106	1072	1072	1119	1069
8/27/2003 12:00	1176	1105	1072	1071	1120	1070
8/27/2003 13:00	1167	1103	1072	1071	1121	1070
8/27/2003 14:00	1156	1103	1072	1071	1120	1070
8/27/2003 15:00	1172	1107	1072	1071	1120	1071
8/27/2003 16:00	1186	1110	1067	1066	1120	1071
8/27/2003 17:00	1188	1108	1066	1065	1120	1071
8/27/2003 18:00	1180	1105	1068	1067	1120	1071
8/27/2003 19:00	1163	1103	1070	1069	1119	1070
8/27/2003 20:00	1159	1102	1072	1071	1120	1069
8/27/2003 21:00	1165	1106	1073	1072	1121	1070
8/27/2003 22:00	1171	1111	1071	1070	1122	1071
8/27/2003 23:00	1183	1115	1069	1068	1119	1072
8/28/2003 0:00	1181	1113	1059	1057	1116	1072
8/28/2003 1:00	1173	1111	1045	1044	1116	1072
8/28/2003 2:00	1180	1109	1042	1040	1120	1072
8/28/2003 3:00	1169	1107	1050	1048	1123	1073
8/28/2003 4:00	1171	1105	1063	1062	1122	1072
8/28/2003 5:00	1179	1105	1067	1066	1118	1070
8/28/2003 6:00	1179	1104	1070	1069	1119	1070
8/28/2003 7:00	1166	1104	1072	1072	1120	1071
8/28/2003 8:00	1165	1103	1070	1069	1120	1071
8/28/2003 9:00	1170	1103	1064	1062	1118	1072
8/28/2003 10:00	1177	1102	1048	1047	1118	1073
8/28/2003 11:00	1181	1101	1050	1048	1120	1072
8/28/2003 12:00	1183	1099	1060	1059	1123	1071
8/28/2003 13:00	1171	1096	1067	1066	1121	1069
8/28/2003 14:00	1156	1094	1071	1071	1119	1066
8/28/2003 15:00	1168	1094	1075	1075	1120	1066
8/28/2003 16:00	1176	1094	1077	1077	1121	1067
8/28/2003 17:00	1177	1095	1075	1074	1120	1067
8/28/2003 18:00	1171	1095	1072	1071	1118	1067
8/28/2003 19:00	1173	1096	1070	1070	1119	1067
8/28/2003 20:00	1176	1096	1071	1070	1120	1067

Distribution:

J. W. Amoroso, 999-W
J. M. Bricker, 704-27S
T. B. Brown, 773-A
A. S. Choi, 999-W
S. D. Fink, 773-A
C. C. Herman, 773-A
E. N. Hoffman, 999-W
D. C. Iverson, 704-30S
C. M. Jantzen, 773-A
F. C. Johnson, 999-W
S. L. Marra, 773-A
D.H. McGuire, 999-W
D. H. Miller, 999-W
D. K. Peeler, 999-W
F. M. Pennebaker, 773-42A
M. E. Smith, 704-30S
M. E. Stone, 999-W
W. R. Wilmarth, 773-A
Records Administration (EDWS)

DOE-ORP
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J. V. Crum
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