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Evaluation of the Impact of Additional Manganese from the Recycle Collection Tank (RCT) Glycolate Destruction Process on Glass Properties

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EXECUTIVE SUMMARY

The Defense Waste Processing Facility (DWPF) is planning to implement glycolic acid as a reductant within the waste processing flowsheet. An assessment of the glycolic acid flowsheet has revealed the potential for thermolytic production of hydrogen in the Concentration, Storage and Transfer Facilities (CSTF) from glycolate entrained in the DWPF recycle stream. To mitigate this potential scenario, a glycolate destruction process utilizing sodium permanganate ($NaMnO_4$) is being developed for use in the DWPF Recycle Collection Tank (RCT). The RCT is fed by the Slurry Mix Evaporator Condensate Tank (SMECT) and the Off-Gas Condensate Tank (OGCT). The SMECT could receive glycolate via a foamover from the Sludge Receipt and Adjustment Tank (SRAT) or the Slurry Mix Evaporator (SME), and the OGCT could receive glycolate via carryover of sludge particles in the purge from the melter during surge conditions. The use of $NaMnO_4$ additions in the RCT will result in additional manganese (Mn) in the waste stream and needs to be evaluated.

Model evaluations were performed to examine the impact of additional Mn on the reduction/oxidation (REDOX) and glass properties (durability, viscosity and liquidus temperature) of future sludge batches (SB) projected to be processed at DWPF. A preliminary scoping projection was received from Savannah River Remediation (SRR) System Planning that represented approximately ten years of accumulation of DWPF recycle solids in Tank 22 prior to transfer to a sludge batch. This projection produced calculated melter feed compositions with significantly high concentrations of Mn/MnO that are outside the validated ranges of both the glass property and REDOX models. A revised projection, consisting of 60-gallon $NaMnO_4$ processing additions in the RCT and transfers every two years from Tank 22, predominantly produces melter feed compositions that fall within the validated ranges of the REDOX and glass property models.

Due to the compositional uncertainties associated with the sludge batch projections, it is recommended that these Mn/MnO glass property and REDOX model assessments continue to be performed for each sludge batch as planning evolves over time. Experimental studies to generate supplementary data will be necessary if the Mn/MnO concentrations are projected to exceed those validated by the current glass property and REDOX models.

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LIST OF ABBREVIATIONS

CPC	Chemical Process Cell
CS	calcined solids
CSTF	Concentration, Storage and Transfer Facilities
DWPF	Defense Waste Processing Facility
EE	electron equivalent
HLW	high-level waste
MST	monosodium titanate
OGCT	Off Gas Condensate Tank
PCCS	Product Composition Control System
RCT	Recycle Collection Tank
REDOX	Reduction/Oxidation
SB	Sludge Batch
SME	Slurry Mix Evaporator
SMECT	Slurry Mix Evaporator Condensate Tank
SRAT	Sludge Receipt and Adjustment Tank
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation (Liquid Waste contractor as of 11/2021)
SS	sludge solids
SWPF	Salt Waste Processing Facility
T	total solids
TTQAP	Task Technical Quality Assurance Plan
TTR	Technical Task Request
WL	waste loading
wt.%	weight percent

1.0 Introduction

The Defense Waste Processing Facility (DWPF) is planning to implement glycolic acid as a reductant within the waste processing flowsheet. An assessment of the glycolic acid flowsheet has revealed the potential for thermolytic production of hydrogen in the Concentration, Storage and Transfer Facilities (CSTF) from glycolate entrained in the DWPF recycle stream.[1] To mitigate this potential scenario, a glycolate destruction process utilizing sodium permanganate ($NaMnO_4$) is being developed for use in the DWPF Recycle Collection Tank (RCT). The RCT is fed by the Slurry Mix Evaporator Condensate Tank (SMECT) and the Off-Gas Condensate Tank (OGCT). The SMECT could receive glycolate via a foamover from the Sludge Receipt and Adjustment Tank (SRAT) or the Slurry Mix Evaporator (SME), and potentially during surge conditions in the melter, the OGCT could receive glycolate via carryover of sludge particles in the purge from the melter. The use of $NaMnO_4$ additions in the RCT will result in additional manganese (Mn) in the waste stream that needs to be evaluated. The Savannah River National Laboratory (SRNL) was requested to complete the following tasks as specified by the Technical Task Request (TTR):[2]

- TTR Task 1: Review the glycolate-$NaMnO_4$ kinetic oxidation reaction model and associated data.
- TTR Task 2: Complete chemical reaction modeling scenarios for various initial glycolate concentrations and RCT $NaMnO_4$ additions scenarios that may be encountered during processing in the DWPF.
- TTR Task 3: Evaluate the impact of the additional Mn from the RCT on reduction/oxidation (REDOX) and glass properties.

This report documents the results of the REDOX and glass evaluations in Task 3 only. Tasks 1 and 2 were completed under a separate Task Technical and Quality Assurance Plan (TTQAP) and are documented separately.[3]

2.0 Quality Assurance

This work was requested via a TTR and is directed by a TTQAP.[2, 4] The functional classification of TTR Task 3 is Production Support. Microsoft Excel was used to support this work. Requirements for performing reviews of technical reports and the extent of review are established in Manual E7, Procedure 2.60.[5] This document, including calculations, was reviewed by a Design Check. SRNL documents the Design Check using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.[6] The Design Checklists for this report and data used for this evaluation are stored in laboratory notebook experiment I7770-00338-13.

3.0 Background

3.1 Mn and the REDOX Model

The REDOX state of the sludge batch (SB) plays an important role in the SB processing due to the effects observed in the melter.[7] If the REDOX state of the SB material is too oxidizing (low), higher than nominal volumes of oxygen may be released during the decomposition of the material resulting in foaming in the melter cold cap or within the molten glass itself. Consequently, total system processing efficiency may be impacted, and solid material may also be carried out of the melter and into the offgas system. If the REDOX state of the material is too reducing (high), then metallic species can potentially precipitate out as deposits and build up on the bottom of the melter, eventually shorting out the melter electrodes. Therefore, it is necessary to operate within a specified REDOX range in order to minimize entrainment and reduce deleterious effects.

REDOX is predicted in the DWPF melter by an equation that computes the ratio of reduced iron (Fe^{2+}) to total iron (ΣFe) in the glass based on the oxidants and reductants measured in the SME product slurry. The REDOX model equation is based on multiplying concentrations of oxidizing and reducing species present in the melter feed by electron equivalents (EE) associated with either their respective reduction (gain of electrons) or oxidation (loss of electrons). The current REDOX model equation developed for the glycolate flowsheet is shown below:[8]

$$\frac{Fe^{2+}}{\sum Fe} = 0.2358 + 0.1999\left[\left(2[F] + 4[C] + 4[O_T] + 3.39 * eff\,[C_A] + 6[Gly] - 5[N] - 0[Mn]\right)\frac{45}{T}\right]$$

where F is formate, C is carbon, O_T is total oxalate, C_A is carbon from antifoam, Gly is glycolate, N is nitrate and nitrite, and Mn is manganese in moles per kg of slurry, *eff* is the effective antifoam impact, and T is weight percent (wt.%) total solids.

Mn concentration is one of the factors used to estimate the REDOX potential of each SB due to its oxidizing potential. The oxidizing potential of Mn is variable and will depend on which of the several oxidation states it exists in (e. g. from Mn^{+7} to Mn^{+2}) when it enters the melter. However, due to the chemical environment and processing knowledge, Mn most commonly persists from Mn^{+4} to Mn^{+2} in the melter.[9] The Mn coefficient (EE) term has been adjusted periodically since the inception of the REDOX model. Recently, the Mn EE term was set to zero, which would reflect the successful reduction of Mn in the Chemical Process Cell (CPC) to greater than or equal to the target proportion of Mn^{2+}, thus resulting in no net electron exchange occurring while the Mn species were being vitrified with the glass.[8-10]

The current REDOX model specifically evaluates the impact of Mn as a function of moles of Mn per kilogram of SME slurry, normalized to 45 wt.% total solids (Mn mol/kg*(45/T)). Previous modeling utilizing data from early SBs (pre-SB8) established an operating range from 0 to 0.15 Mn mol/kg*(45/T) based on the assumption that ≥66% of the Mn that enters the melter is in the Mn^{2+} oxidation state. Figure 3-1 shows the calculated Mn concentration factors for SB3 through SB9.[9,a] As shown in Figure 3-1, the Mn concentration factors for SB8 and SB9 are above the validated range (red line) for the REDOX model; however, these sludge batches were successfully processed and resulted in an acceptable overall target REDOX of the glass.[8-10] These data show that although the Mn concentration factor was outside of the REDOX model verified range for SB8 and SB9, the SBs were successfully processed in relation to the targeted overall REDOX of the glass.

[a] As indicated in Figure 3-1, SB8 REDOX testing was performed using SME samples with and without oxalate.

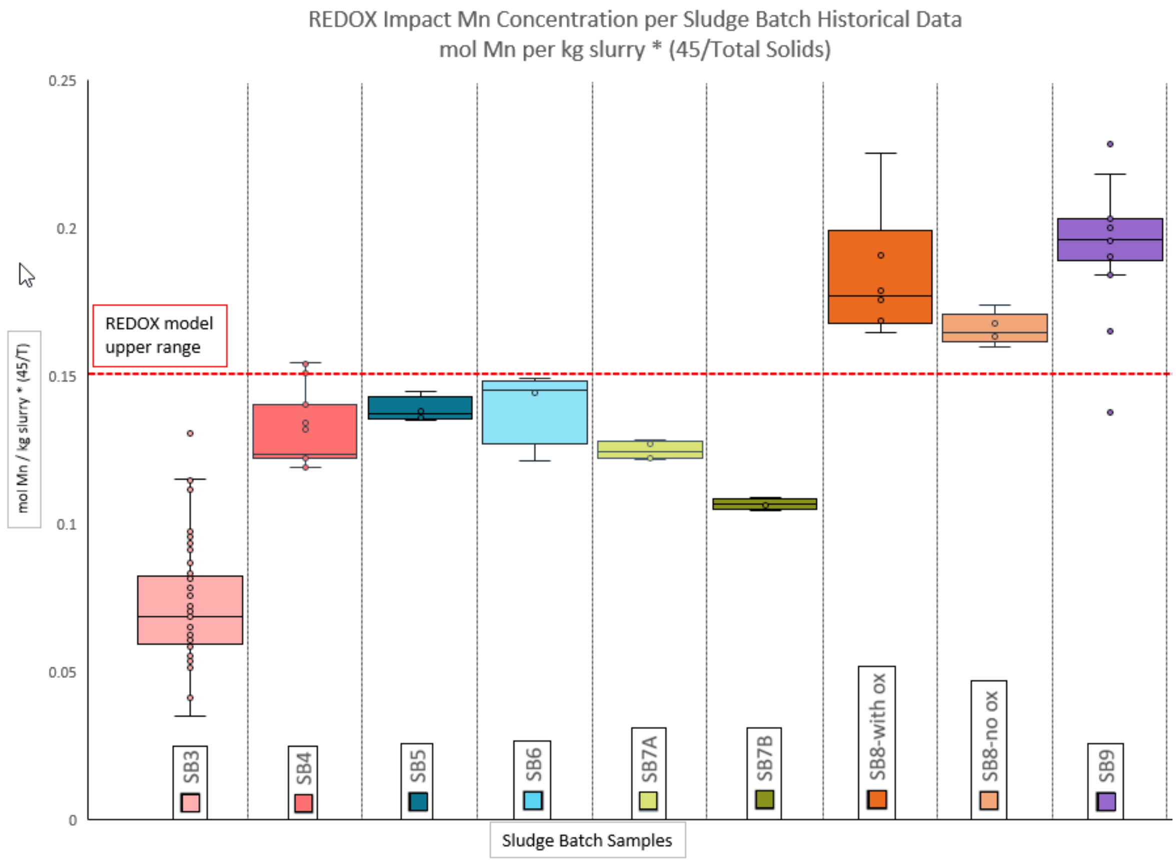

Figure 3-1. Mn concentration factors in previous sludge batches.

3.2 Mn and the Glass Property Models

The primary glass properties of interest (viscosity, liquidus temperature and durability) cannot be measured in-situ during DWPF processing and must be predicted using models that relate these properties to the glass composition. Chemical composition of the glass in the DWPF melter is controlled by ensuring that each batch of melter feed in the SME produces glass that will satisfy the Waste Acceptance Production Specification for product consistency.[11, 12] The Product Composition Control System (PCCS) is a statistical process control system used in DWPF to assess the acceptability of the melter feed composition against various processing, product quality and solubility constraints.[13] The batch of melter feed is only transferred to the melter for vitrification after acceptability of the composition has been demonstrated with PCCS.

Each of the DWPF PCCS glass property models have been developed and validated over specific oxide ranges.[14-16] Table 3-1 shows the overall combined MnO model development and validation ranges for the durability, viscosity and liquidus temperature models. Due to the $NaMnO_4$ additions in the RCT, the subsequent MnO concentration in the glass will also increase. Thus, the projected MnO concentrations in glass need to be evaluated to determine whether the increased MnO concentrations stay within or fall outside of the model ranges.

Table 3-1. Overall MnO Model Development and Validation Ranges for the DWPF PCCS Durability, Viscosity and Liquidus Temperature Models

	Durability Model	Viscosity Model	Liquidus Temperature Model
MnO (wt.%)	0 – 4.61	0 – 4.61	0.3 – 5.50

4.0 Inputs and Assumptions

To support these evaluations, the Savannah River Remediation (SRR) System Planning group provided several iterations of Tank 40 blend projections for future sludge batches that included additions of product from the glycolate destruction process using $NaMnO_4$ as it will be performed in the RCT.[17, 18]

- In May 2021, SB19 projections were received that represent almost ten years of receipt and accumulation of $NaMnO_4$ processing in Tank 22 until the material is transferred to SB19. These projections evaluated 60-gallon and 135-gallon $NaMnO_4$ additions to the RCT for each glycolate destruction process performed.

- In July 2021, SB12 projections were received that represent two years of receipt and accumulation of $NaMnO_4$ processing in Tank 22 until the material is transferred to SB12. These projections evaluated 60-gallon and 135-gallon $NaMnO_4$ additions to the RCT for each glycolate destruction process performed.

- In October 2021, SB11-SB21 projections were received that represent approximately two years of receipt and accumulation of $NaMnO_4$ processing in Tank 22 until the material is transferred to each SB.[19] These projections only evaluated a 60-gallon $NaMnO_4$ addition to the RCT for each glycolate destruction process performed.

The SB19 Tank 40 blend projections are shown in Appendix A Table A-1 and the SB12 projections are shown in Table A-2. The SB11-SB21 Tank 40 blend projections are replicated from Ref. 19 and are shown in Appendix B.

5.0 Results and Discussion

5.1 Tank 22 Transfers to SB19 and SB12

This section evaluates Mn impacts on glass properties based on the preliminary SB19 and SB12 Tank 40 blend projections, which represent approximately ten years and two years of accumulation of $NaMnO_4$ processing in Tank 22, respectively. The SB19 and SB12 elemental Mn concentrations shown in Appendix A Table A-1 and Table A-2 were first converted to an oxide basis (MnO). Projected sludge-only MnO concentrations in glass were then calculated at 36% waste loading (WL) for each of the projections as shown in Table 5-1. Sludge-only projections were evaluated rather than coupled operation projections since the MnO concentration would be diluted by the addition of the monosodium titanate and sludge solids (MST/SS) stream from the Salt Waste Processing Facility (SWPF). Thus, the values in Table 5-1 provide a conservative estimate of the expected MnO concentrations. Mn REDOX concentration factors for the SB19 and SB12 projections were calculated based on the elemental Mn concentrations and the projected calcined solids (CS) masses provided in Appendix A, and an assumed target CS wt.% in the SB slurry of 38 wt.%. The resulting Mn concentration factors for the preliminary REDOX evaluation were normalized to 45 wt.% total solids (T) and are listed in Table 5-2.

Table 5-1. Projected Sludge-only MnO Concentrations in Glass at 36% WL for Preliminary SB19 and SB12 Projections

Projection	$NaMnO_4$ RCT Addition Volume (gallons)	Calculated MnO (wt.%)
SB19	60	10.59
	135	17.09
SB12	60	3.36
	135	5.55

Table 5-2. Projected Mn REDOX Concentration Factors for Preliminary SB19 and SB12 Projections

Sludge Batch (60 gal $NaMnO_4$ RCT Addition)	Mn Concentration Factor (mol Mn / kg slurry * 45/T)
SB19	0.60
SB12	0.18

As shown in Table 5-1, regardless of the $NaMnO_4$ addition volume to the RCT during processing for the SB19 single Tank 22 transfer scenario, the resulting MnO concentrations in glass are above the maximum values of the model ranges (Table 3-1). At the projected concentrations of MnO, the formation of Mn-spinel crystalline phases may be more likely to precipitate from the high-level waste (HLW) glasses depending on the composition and temperature.[15] DWPF glasses are required to be homogeneous (i.e. no secondary phase precipitation/segregation) and the maximum MnO concentration that can be accommodated is uncertain; experimental study would be required to assess the limits and impact from MnO concentrations exceeding the model ranges.

Some work has been done to increase the MnO concentration in HLW glass, such as the proposed 2016 Hanford HLW glass models that incorporate an MnO constraint of 8 wt.%. However, this strategy is based on a spinel concentration limit of 2 volume percent at 950°C,[20] which does not result in a homogeneous glass, and the 8 wt.% MnO constraint is still below the SB19 concentrations projections shown in Table 5-1

As shown in Table 5-1, the 60-gallon $NaMnO_4$ RCT addition during the processing SB12 scenario results in a 3.36 wt.% MnO concentration, which is well within the model ranges provided in Table 3-1. This result confirms that a transfer frequency of two years with the 60-gallon $NaMnO_4$ addition is necessary to maintain the MnO concentration at nominal values. However, the 135-gallon $NaMnO_4$ RCT addition during processing SB12 scenario results in a 5.55 wt.% MnO concentration, which is outside all of the model ranges provided in Table 3-1. In this scenario, given the absolute difference between the predicted MnO concentration and the model ranges, the following may be concluded concerning this addition strategy and glass acceptability:

- Durability: Per the DWPF Glass Product Control Program,[12, 21] a variability study is performed for each sludge batch. The validity of the durability model would be demonstrated at the higher MnO concentration. This testing would also verify homogeneity of the glasses since the durability model is only valid for homogeneous glass (not phase separated nor crystallized).[14]

- Viscosity: Assuming that the variability study demonstrated that the glasses were homogeneous, the viscosities of glasses with higher MnO concentrations would be measured to demonstrate the validity of the viscosity model. The sum of the divalent cations will also be calculated to verify that the sum is not too high to result in a poorly predicted viscosity as demonstrated by the FY09EM21-15 validation glass.[16]

- Liquidus temperature: Assuming that the variability study demonstrated that the glasses were homogeneous, it is unlikely that an additional ~0.05 wt.% MnO would result in a poorly predicted liquidus temperature due to the composition and model uncertainties accounted for in the liquidus temperature model.

For the REDOX evaluation (Table 5-2), only the 60-gallon $NaMnO_4$ addition scenarios are presented. The Mn concentration factor for the 60-gallon SB19 projection scenario was well outside the validated range for REDOX including the region from previous successful sludge batch compositions (i.e. SB8 and SB9); however, the 60-gallon SB12 projection scenario fell within the extended range of REDOX concentration factors for previous successful sludge batches SB8 and SB9 (though outside the validated REDOX concentration factors region). The 135-gallon $NaMnO_4$ addition scenarios were outside the validated range for REDOX, regardless of the SB projection.

5.2 Tank 22 Transfers to Each SB

Based on good agreement between the glass property model and REDOX evaluations for the SB12 60-gallon addition scenario (two years of accumulation in Tank 22), SRR provided projections for SB11 through SB21 where DWPF recycle solids from Tank 22 would be transferred to each SB approximately every two years.[19] Most of the assumptions from the preliminary evaluations were applied to these data with the exception of CS wt.% values, which were directly calculated from the calcine factors provided in Appendix B. The resulting MnO concentrations in glass and REDOX Mn concentration factors are shown in Table 5-3 and Table 5-4, respectively.

Table 5-3. Projected Sludge-only MnO Concentrations in Glass at 36% WL for SB11-SB21.

Projected Sludge Batch	Projected MnO (wt.%)
SB11	1.60
SB12	2.58
SB13	2.98
SB14	3.36
SB15	3.62
SB16	3.22
SB17	3.18
SB18	4.92
SB19	6.84
SB20 (heel)	14.22
SB21 (heel)	15.29

Table 5-4. Projected Mn REDOX Concentration Factors for Future Sludge Batch Projections SB11-SB21.

Projected Sludge Batch	Projected Mn Concentration Factor (mol Mn / kg slurry * 45/T)
SB11	0.08
SB12	0.13
SB13	0.14
SB14	0.16
SB15	0.18
SB16	0.16
SB17	0.15
SB18	0.24
SB19	0.33
SB20 (heel)	0.56
SB21 (heel)	0.71

Note that the average SB9 value was ~0.2 mol Mn/kg slurry*45/T with a maximum of 0.23 as shown in Figure 3-1.

The MnO concentrations of SB11 through SB17 are within the glass property models ranges provided in Table 3-1. For SB18, the upper MnO concentration of the durability and viscosity models are exceeded by ~0.3 wt.%, a difference that has no practical impact on the predictability of either model. For the REDOX model, SB11 through SB17 fall within the model validation range with SB18 only 20% higher than the average region where successful SB8 and SB9 were previously operated outside of the validation range. For SB19, experimental study is recommended (at that time) at higher Mn/MnO concentrations to evaluate glass homogeneity and properties, and REDOX response. SB20 and SB21 consist of heel removal from Tank 40 and Tank 51 and contain a higher percentage of transferred Tank 22 solids than the previous sludge batches. As discussed in Section 5.1, the high MnO concentrations of SB20 and SB21 would likely form Mn-rich phases that could result in non-homogeneous DWPF glass; however, more uncertainty exists with these later SB projections due to the extended time scale for their projected compositions. Per Ref. 19, recycle diversion is possible in the future, which would significantly change the compositions of these heel batches. Also, at this point in time, the 2H and 3H evaporators will likely be shut down and it is possible that $NaMnO_4$ additions would no longer be required.[19]

6.0 Conclusions

The SB19 Tank 40 blend projection representing a single Tank 22 transfer scenario consisting of ten years of accumulated $NaMnO_4$ processing material results in a significantly high concentration of Mn that is considerably outside the validated ranges for both the glass property and REDOX models. The revised strategy consisting of 60-gallon $NaMnO_4$ processing additions in the RCT and transfers every two years from Tank 22 to each sludge batch predominantly produces projections that fall within the validated ranges of the REDOX and glass property models.

7.0 Recommendations

Due to the compositional uncertainties associated with the sludge batch projections, it is recommended that these Mn/MnO glass property and REDOX model assessments continue to be performed for each sludge batch as planning evolves over time. Experimental studies to generate supplementary data will be necessary if the Mn/MnO concentrations are projected to exceed those validated by the current glass property and REDOX models.

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Appendix A. Preliminary Sludge Batch Projections for SB19 and SB12

Table A-1. SB19 Tank 40 Blend Projections

$NaMnO_4$ RCT Addition Volume	60 gallons	135 gallons
Calcine Solids Mass, kg	330,249	443,736
Al, wt.%	10.95	8.15
B, wt.%	0.00	0.00
Ba, wt.%	0.15	0.11
Ca, wt.%	1.14	0.85
Ce, wt.%	0.17	0.13
Cr, wt.%	0.13	0.10
Cu, wt.%	0.05	0.04
Fe, wt.%	13.88	10.33
Gd, wt.%	0.21	0.16
K, wt.%	0.14	0.10
La, wt.%	0.07	0.05
Li, wt.%	0.00	0.00
Mg, wt.%	0.13	0.10
Mn, wt.%	22.79	36.77
Na, wt.%	11.29	8.40
Ni, wt.%	1.08	0.80
Pb, wt.%	0.17	0.13
S, wt.%	0.27	0.20
Si, wt.%	1.60	1.19
Th, wt.%	0.04	0.03
Ti, wt.%	0.02	0.02
U, wt.%	4.86	3.62
Zn, wt.%	0.12	0.09
Zr, wt.%	0.22	0.16
Hg (total solids basis), wt.%	1.32	1.01

Table A-2. SB12 Tank 40 Blend Projection

$NaMnO_4$ RCT Addition Volume	60 gallons	135 gallons
Calcine Solids Mass, kg	283,055	299,233
Al, wt.%	12.57	11.96
B, wt.%	0.00	0.00
Ba, wt.%	0.19	0.18
Ca, wt.%	1.74	1.65
Ce, wt.%	0.15	0.14
Cr, wt.%	0.15	0.14
Cu, wt.%	0.05	0.05
Fe, wt.%	14.68	13.95
Gd, wt.%	0.16	0.17
K, wt.%	0.13	0.13
La, wt.%	0.07	0.07
Li, wt.%	0.00	0.00
Mg, wt.%	0.26	0.24
Mn, wt.%	7.23	11.95
Na, wt.%	17.83	15.72
Ni, wt.%	1.09	1.03
Pb, wt.%	0.35	0.33
S, wt.%	0.23	0.22
Si, wt.%	3.88	3.69
Th, wt.%	0.92	0.88
Ti, wt.%	0.01	0.01
U, wt.%	4.95	4.70
Zn, wt.%	0.05	0.05
Zr, wt.%	0.26	0.25
Hg (total solids basis), wt.%	2.34	2.17

Appendix B. SB11-SB21 Projections with DWPF Recycle Solids with $NaMnO_4$ Addition in DWPF from SRR-LWP-2021-00037

Table B-1. SB11-SB21 Projections on a Calcined Solids Basis

	SB11	SB12	SB13	SB14	SB15	SB16	SB17	SB18	SB19	SB20	SB21
Calculated Calcine Factor	0.64	0.65	0.66	0.66	0.65	0.64	0.67	0.66	0.66	0.72	0.67
Calcine Solids Mass, kg	288,777	306,554	301,917	304,901	292,427	287,890	292,137	240,331	94,292	55,510	27,734
Al, wt.%	11.54	9.33	8.88	7.82	9.19	10.72	8.62	9.60	8.45	4.74	4.22
B, wt.%	0.04	0.05	0.04	0.03	0.03	0.03	0.03	0.05	0.07	0.16	0.17
Ba, wt.%	0.17	0.17	0.17	0.20	0.20	0.20	0.22	0.14	0.12	0.06	0.06
Ca, wt.%	1.97	1.81	1.66	1.53	1.70	1.84	1.74	1.31	1.13	0.60	0.53
Ce, wt.%	0.25	0.25	0.22	0.26	0.24	0.28	0.25	0.26	0.23	0.12	0.11
Cr, wt.%	0.22	0.21	0.20	0.21	0.23	0.24	0.22	0.19	0.16	0.09	0.08
Cu, wt.%	0.09	0.08	0.08	0.07	0.08	0.08	0.09	0.06	0.05	0.03	0.02
Fe, wt.%	18.52	17.70	16.83	17.27	17.38	18.21	19.65	19.83	17.26	9.34	8.25
K, wt.%	0.35	0.32	0.31	0.29	0.31	0.32	0.31	0.25	0.25	0.21	0.20
La, wt.%	0.12	0.12	0.11	0.11	0.11	0.13	0.12	0.10	0.09	0.05	0.04
Li, wt.%	0.14	0.14	0.10	0.06	0.05	0.04	0.03	0.06	0.08	0.18	0.19
Mg, wt.%	0.31	0.29	0.23	0.23	0.23	0.26	0.18	0.18	0.16	0.09	0.08
Mn, wt.%	3.45	5.56	6.41	7.23	7.79	6.92	6.85	10.58	14.72	30.59	32.89
Na, wt.%	18.81	18.53	18.05	17.88	18.29	18.04	16.60	16.51	17.89	17.93	17.81
Ni, wt.%	0.48	0.57	0.67	1.28	0.98	0.72	1.44	0.64	0.53	0.26	0.23
Pb, wt.%	0.42	0.40	0.31	0.28	0.22	0.18	0.24	0.18	0.16	0.08	0.07
S, wt.%	0.22	0.22	0.20	0.19	0.20	0.20	0.18	0.20	0.20	0.18	0.18
Si, wt.%	4.36	4.09	3.18	2.73	3.30	3.90	2.00	2.86	2.93	3.72	3.80
Th, wt.%	1.76	0.74	0.49	0.14	0.05	0.02	0.04	0.17	0.15	0.09	0.08
Ti, wt.%	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.06	0.05	0.03	0.02
U, wt.%	2.57	6.81	10.56	11.78	7.52	4.28	10.51	4.54	3.74	1.84	1.63
Zn, wt.%	0.13	0.12	0.12	0.10	0.11	0.10	0.15	0.25	0.22	0.12	0.10
Zr, wt.%	0.42	0.39	0.36	0.35	0.38	0.41	0.38	0.28	0.24	0.13	0.11
Hg (TS basis), wt.%	2.57	2.54	2.16	2.24	2.76	3.38	1.71	2.36	2.48	3.77	3.75

Table B-2. SB11-SB21 Projections on a Total Solids Basis

	SB11	SB12	SB13	SB14	SB15	SB16	SB17	SB18	SB19	SB20	SB21
Total Solids Mass, kg	449,705	470,100	457,649	460,430	450,915	451,237	438,710	364,983	143,754	76,719	41,238
Ag, wt.%	0.06	0.05	0.06	0.04	0.04	0.03	0.08	0.04	0.03	0.02	0.01
Al, wt.%	7.41	6.08	5.86	5.18	5.96	6.84	5.74	6.32	5.54	3.43	2.84
B, wt.%	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.05	0.12	0.12
Ba, wt.%	0.11	0.11	0.11	0.14	0.13	0.13	0.14	0.09	0.08	0.05	0.04
Ca, wt.%	1.27	1.18	1.09	1.02	1.10	1.18	1.16	0.86	0.74	0.43	0.36
Ce, wt.%	0.16	0.16	0.15	0.17	0.16	0.18	0.17	0.17	0.15	0.09	0.07
Cr, wt.%	0.14	0.14	0.13	0.14	0.15	0.15	0.14	0.13	0.11	0.06	0.05
Cu, wt.%	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.04	0.03	0.02	0.02
Fe, wt.%	11.89	11.54	11.10	11.44	11.27	11.62	13.08	13.06	11.32	6.76	5.55
Hg, wt.%	2.57	2.54	2.16	2.24	2.76	3.38	1.71	2.36	2.48	3.77	3.75
K, wt.%	0.22	0.21	0.21	0.19	0.20	0.21	0.21	0.17	0.16	0.15	0.14
La, wt.%	0.08	0.08	0.07	0.07	0.07	0.08	0.08	0.07	0.06	0.04	0.03
Li, wt.%	0.09	0.09	0.06	0.04	0.03	0.02	0.02	0.04	0.05	0.13	0.13
Mg, wt.%	0.20	0.19	0.15	0.15	0.15	0.16	0.12	0.12	0.10	0.06	0.05
Mn, wt.%	2.22	3.63	4.23	4.78	5.05	4.42	4.56	6.97	9.66	22.13	22.12
Na, wt.%	12.08	12.08	11.91	11.84	11.86	11.51	11.05	10.87	11.74	12.97	11.98
Ni, wt.%	0.31	0.37	0.44	0.85	0.64	0.46	0.96	0.42	0.35	0.19	0.16
Pb, wt.%	0.27	0.26	0.21	0.18	0.14	0.12	0.16	0.12	0.10	0.06	0.05
Pr, wt.%	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.05	0.03	0.02
Pu, wt.%	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ru, wt.%	0.12	0.11	0.12	0.10	0.10	0.08	0.16	0.08	0.07	0.04	0.03
S, wt.%	0.14	0.14	0.13	0.13	0.13	0.13	0.12	0.13	0.13	0.13	0.12
Si, wt.%	2.80	2.67	2.10	1.81	2.14	2.49	1.33	1.88	1.92	2.69	2.55
Sr, wt.%	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.03	0.03	0.02	0.01
Th, wt.%	1.13	0.48	0.33	0.09	0.04	0.01	0.03	0.11	0.10	0.06	0.05
Ti, wt.%	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.04	0.03	0.02	0.02
U, wt.%	1.65	4.44	6.97	7.80	4.88	2.73	7.00	2.99	2.45	1.33	1.10
Zn, wt.%	0.08	0.08	0.08	0.07	0.07	0.06	0.10	0.16	0.14	0.09	0.07
Zr, wt.%	0.27	0.25	0.24	0.23	0.25	0.26	0.26	0.18	0.16	0.09	0.08