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SB5 with the Estimated Impact of Low-Temperature Aluminum Dissolution: Preliminary Frits for Melt Rate Testing

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March 2008

Process Science and Engineering
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Prepared for the U.S. Department of Energy Under
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EXECUTIVE SUMMARY

Composition projections for Sludge Batch 5 (SB5) were developed to evaluate possible impacts of the Al-dissolution process on the availability of viable frit compositions for vitrification at the DWPF. The study included two projected SB5 compositions that bound potential outcomes (or degrees of effectiveness) of the Al-dissolution process, as well as a nominal SB5 composition projection based on the results of the recent Al-dissolution demonstration at SRNL. A Nominal Stage assessment was used to evaluate the two SB5 projections combined with an array of 19,305 frit compositions over a range of waste loading (WL) values against the DWPF process control models. The Nominal Stage results allowed for the down-selection of a small number of frits that provided reasonable projected operating windows (typically 25 to 40 wt %) and permitted some compositional flexibility (i.e., the ability to further tailor the frit to improve melt rate).

Variation Stage assessments were then performed using the down-selected frits and the two SB5 composition projections with variation applied to each sludge component. The Variation Stage results showed that the operating windows were somewhat reduced in width, as expected when sludge variation is applied. Three of the down-selected frits continued to perform well for both SB5 projections through the Variation Stage, providing WL windows of approximately 26 to 35 wt %. The maximum WLs were limited by a processing constraint, T_L, rather than a waste form affecting constraint (e.g., nepheline crystallization) in the Variation Stage assessments.

Subsequent Nominal Stage assessments were performed with an updated SB5 projection based on the results of the Al-dissolution demonstration performed in the SRNL Shielded Cells facility (representing 40% removal of Al). The three frits identified in the earlier paper studies continued to perform well with this updated projection. The available operating windows were slightly wider, although maximum WL was limited by both the T_L and nepheline constraints for all three frits.

Changes in the projected SB5 composition are anticipated before processing begins at the DWPF, which will likely require additional paper study assessments as well as experimental frit development studies. This study identifies several frits which provide insight into potential operating windows for SB5 vitrification in DWPF. However, until experimental studies can be performed to gain information on melt rate and other parameters needed to optimize frit selection, no final frit recommendation can be made.

Information regarding melt rate cannot be inferred from the paper study results. Experimental studies to evaluate this critical factor in DWPF processing must be performed to support frit optimization for any projected sludge composition. Five frit compositions were identified for melt rate testing at SRNL with simulated SB5 Case F SRAT product. The results of these tests will be used to evaluate the impact of the frit components – particularly B_2O_3 and Na_2O – that are expected to influence melt rate for SB5-like sludges. The results of the melt rate testing will be documented in a separate report and will be used to help guide the frit recommendation process as the final SB5 composition becomes clearer.

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LIST OF ABBREVIATIONS

ARP	Actinide Removal Process
CPC	Chemical Process Cell
DOE	Department Of Energy
DWPF	Defense Waste Processing Facility
EVs	Extreme Vertices
highv	high viscosity
homg	homogeneity
lowv	low viscosity
LWO	Liquid Waste Organization
MAR	Measurement Acceptability Region
MRF	Melt Rate Furnace
Neph	Nepheline crystallization
NL	Normalized Leachate
PCCS	Product Composition Control System
SB4	Sludge Batch 4
SB5	Sludge Batch 5
SRAT	Sludge Receipt and Adjustment Tank
SRS	Savannah River Site
T_L	liquidus temperature
WL	Waste Loading

1.0 Introduction

The current contents of Tank 51 will be blended with Purex sludge from Tank 7 to constitute Sludge Batch 5 (SB5). The Savannah River Site (SRS) Liquid Waste Organization (LWO) is performing low-temperature Al-dissolution in Tank 51 to reduce the total mass of sludge solids and Al being fed to the Defense Waste Processing Facility (DWPF). A radioactive demonstration using a 3 L Tank 51 sludge slurry sample was performed to verify the Tank Farm processing parameters.[1] The aluminum dissolved sludge was used to determine potential downstream impacts so that technical issues could be identified before the start of SB5 processing. The potential downstream impacts assessed included the Tank Farm washing and concentration process and the DWPF Chemical Process Cell (CPC) and melter processing envelopes.

This report focuses on the impacts to the development of a glass frit to be combined with the reduced Al concentration sludge for vitrification in the DWPF melter. An assessment is made of the impact of Al-dissolution on the DWPF projected operating windows as defined by the current process control models. The evaluation includes two projected SB5 compositions that bound potential outcomes (or degrees of effectiveness) of the Al-dissolution process, as well as a nominal SB5 composition projection based on the outcome of the recent Al-dissolution demonstration at SRNL.[a] Paper study assessments of the compositional projections are used to assess various frit/sludge options of interest with respect to the projected operating windows (as defined by a waste loading interval) for DWPF. More specifically, for each sludge option, the current Product Composition Control System (PCCS) models were used to assess the waste loading interval over which glasses would concurrently meet all process and acceptability constraints. Candidate frits are identified that provide a reasonable projected operational window over the anticipated composition region of interest and are robust to anticipated sludge composition variations.

The two stages – Nominal Stage and Variation Stage – traditionally performed by Peeler and Edwards[2] were employed to assess the various frit/sludge combinations with respect to these key criteria. The Nominal Stage utilizes nominal compositions representing the potential scenarios outlined above (i.e., various amounts of alumina removed from the sludge). This stage identified candidate frit compositions with respect to their ability to provide a reasonable operating window based solely on a specific nominal composition – no sludge composition variation was considered in this phase.

The Variation Stage assessment was performed to gain insight into the robustness of the candidate frits with respect to potential composition variation resulting from uncertainties in Tank Farm blending strategies or volumes. A down-select process was used to identify primary frit candidates from the Nominal Stage results prior to performing the Variation Stage assessment.

The paper study assessments do not provide specific guidance regarding melt rate differences among the various SB5 flowsheets or frit compositions. The assessments are based strictly on model predictions and the projected operating windows over which all glass properties are deemed acceptable based on current DWPF acceptance criteria. Experimental studies will be necessary to provide melt rate information and guide further decisions on frit compositions for processing SB5 at the DWPF. A select set of frit compositions is identified in this report for this purpose. These frits will be used to determine how general trends in frit composition, such as the concentrations of B_2O_3 and Na_2O, impact melt rate for SB5-like systems.

[a] Note that these projections do not include the addition of waste streams from the Actinide Removal Process (ARP).

This work was performed in response to Technical Task Request HLW-DWPF-TTR-2007-0007 and was carried out following Task Technical and Quality Assurance Plan WSRC-STI-2006-00321.[3, 4]

2.0 Objectives

The intent of this study is to ensure that candidate frits can be identified for use with SB5 that:

- provide reasonable operating windows in terms of percent waste loading (WL), and
- provide sufficient opportunity to vary the concentration of frit components, particularly B_2O_3 and Na_2O, and to assess their impact on melt rate.

This preliminary selection of candidate frits and the subsequent melt rate testing results will allow for the identification of frit compositional trends in melt rate for SB5-like systems. These trends will be used to support the frit recommendation process given that current schedules will provide little time for additional melt rate testing after receipt of the final SB5 composition and prior to the need for a frit recommendation.[a]

3.0 Sludge Batch 5 Composition Projections

SRNL used a modeling approach to project the anticipated composition of SB5 in support of this study. A detailed description of the modeling methodology is provided in WSRC-STI-2008-00001.[5] The model required the following input vectors, which were constructed from available analytical data:

- Tank 51 slurry prior to dilution with Tank 40 supernate[6]
- Tank 40 supernate[b]
- Tank 7 slurry[7]
- Information on various water leaks, miscellaneous additions, missing ion chromatography data, etc.[c]

Five composition projection cases were developed for SB5 at the initiation of this study. The five cases project the potential outcomes of the low-temperature Al-dissolution process based on the partitioning of Al between Gibbsite and Boehmite in Tank 51. The amount of Al partitioning to Gibbsite was varied between 0% and 100% in increments of 25%. The projections are based on the assumption that a blend of approximately 80% material from Tank 51 and 20% material from Tank 40 constitute the SB5 feed to DWPF (i.e., a 40 inch heel remaining in Tank 40 when the blend occurs).[d] These composition projections for SB5 – the output of the SRNL model as elemental values – are given in Table 3-1. The projections are listed as a function of Gibbsite/Boehmite partitioning.

[a] Recognizing that the frits selected in this report are for sludge-only systems (i.e., without the addition of ARP), it is assumed that the trends ascertained from the melt rate studies can be used to support frit selection for coupled and/or sludge-only flowsheets as warranted.
[b] Analytical Laboratories report 23Apr07 09:31 Hr
[c] Tank Farm Spreadsheet 19Jun07
[d] This assumption has a significant impact on the projected compositions. The final blend composition will ultimately be determined by the amount of aluminum removed from Tank 51, the amount of SB4 remaining in Tank 40, any decants that are made from Tank 40 prior to the blend, and any other changes in the LWO washing and/or blending strategy.

Table 3-1. SB5 composition projections as a function of Gibbsite/Boehmite partitioning.

SB5 Case	A	B	C	D	E
Gibbsite (%)	0	25	50	75	100
Boehmite (%)	100	75	50	25	0
Ag	0.008	0.009	0.010	0.011	0.011
Al	17.063	15.326	13.167	11.062	10.140
Ba	0.083	0.091	0.101	0.108	0.110
Ca	1.163	1.273	1.404	1.505	1.539
Cd	0.049	0.053	0.058	0.063	0.065
Ce	0.289	0.316	0.349	0.374	0.383
Co	0.017	0.019	0.020	0.022	0.022
Cr	0.233	0.255	0.281	0.301	0.307
Cu	0.010	0.010	0.010	0.010	0.011
Fe	14.855	16.251	17.926	19.216	19.646
K	0.052	0.055	0.059	0.066	0.069
La	0.127	0.139	0.153	0.164	0.168
Mg	0.649	0.710	0.783	0.839	0.858
Mn	3.439	3.763	4.150	4.449	4.549
Na	18.877	18.413	17.938	18.164	18.545
Ni	1.960	2.144	2.365	2.535	2.592
P	0.211	0.230	0.253	0.271	0.277
Pb	0.019	0.020	0.022	0.024	0.025
Pd	0.001	0.001	0.001	0.001	0.001
Rh	0.024	0.026	0.029	0.031	0.032
Ru	0.091	0.099	0.109	0.117	0.120
S	0.235	0.243	0.254	0.272	0.281
Si	0.818	0.881	0.972	1.044	1.067
Sr	0.246	0.269	0.297	0.318	0.325
Ti	0.014	0.015	0.017	0.018	0.019
U	5.761	6.303	6.952	7.453	7.619
Zn	0.012	0.013	0.013	0.015	0.015
Zr	0.175	0.191	0.211	0.226	0.231
Total (wt %)	66.483	67.120	67.906	68.681	69.026
Tk51 Transfer (kg)	238,491	200,032	173,315	161,004	160,709
Tk40 Heel (kg)	37,733	37,733	37,733	37,733	37,733
Tk51 Solids (%)	86	84	82	81	81
Tk40 Solids (%)	14	16	18	19	19

During the course of this study, the results of the 3L demonstration in the SRNL Shielded Cells facility showed that approximately 35% of the Al was removed after dissolution and washing.[1] This suggested that the SB5 composition would fall between Case B (25% Gibbsite) and Case C (50% Gibbsite). The data from the Shielded Cells demonstration were used to develop a revised projection, labeled Case F, which is given in Table 3-2. The concentration of each component in Case F falls between its corresponding concentration in Cases B and C.

Table 3-2. Updated SB5 composition projection (SB5 Case F) based on 40% dissolution of aluminum. Cases B and C are included for comparison.

SB5 Case	B	C	F
Gibbsite (%)	25	50	40
Boehmite (%)	75	50	60
Ag	0.009	0.010	0.009
Al	15.326	13.167	14.38
Ba	0.091	0.101	0.096
Ca	1.273	1.404	1.345
Cd	0.053	0.058	0.056
Ce	0.316	0.349	0.331
Co	0.019	0.020	0.019
Cr	0.255	0.281	0.266
Cu	0.010	0.010	0.010
Fe	16.251	17.926	17.120
K	0.055	0.059	0.057
La	0.139	0.153	0.145
Mg	0.710	0.783	0.747
Mn	3.763	4.150	3.967
Na	18.413	17.938	17.967
Ni	2.144	2.365	2.249
P	0.230	0.253	0.242
Pb	0.020	0.022	0.021
Pd	0.001	0.001	0.001
Rh	0.026	0.029	0.028
Ru	0.099	0.109	0.104
S	0.243	0.254	0.249
Si	0.881	0.972	0.921
Sr	0.269	0.297	0.286
Ti	0.015	0.017	0.016
U	6.303	6.952	6.612
Zn	0.013	0.013	0.013
Zr	0.191	0.211	0.202
Total (wt %)	67.120	67.906	67.459
Tk51 Transfer (kg)	200,032	173,315	268,317
TK40 Heel (kg)	37,733	37,733	54,322
Tk51 Solids (%)	84	82	83
Tk40 Solids (%)	16	18	17

4.0 Candidate Frit Compositions

An array of frit compositions was developed to be combined with the SB5 composition projections (Cases B, C and F) in the Nominal Stage assessment. The frit components and their concentration ranges were selected based on SRNL experience in previous frit development efforts,[8-15] DWPF operational constraints, and practicality issues related to frit production. The frit components and their concentrations that define the frit array used are shown in Table 4-1. A total of 19,305 frits were defined using this array.

Table 4-1. Frit components and concentration ranges used to define the frit composition array for MAR assessments.

Component	Min. Concentration (wt %)	Max. Concentration (wt %)	Increment (wt %)
B_2O_3	8.0	20.0	1.0
CaO	0.0	8.0	2.0
Li_2O	4.0	12.0	1.0
MgO	0.0	4.0	2.0
Na_2O	2.0	12.0	1.0
SiO_2	44.0	86.0	1.0

5.0 Nominal Stage Assessments

Sludge Cases B and C were each combined with the array of frits (19,305 total frit compositions) over a WL interval of 25 to 60 wt % and evaluated against the models currently implemented in the DWPF to constitute the Nominal Stage assessment. The property predictions assessed included those for liquidus temperature (T_L), viscosity (η), durability (normalized leachate for boron, NL[B]), homogeneity (homg), high viscosity (highv), low viscosity (lowv), high chromia concentration (Cr_2O_3), high sulfate concentration (SO_4^{2-}) and nepheline formation (Neph).[a]

The Nominal Stage results were evaluated in order to down-select a small number of frits for the Variation Stage and for melt rate testing. Four frit compositions were chosen based on their ability to provide a relatively wide operating window for both SB5 Case B and Case C. These frits will be referred to as Frit 530, Frit 531, Frit 532 and Frit 533. Two additional frits were selected based on the operating windows available individually for Case B (Frit 534) and Case C (Frit 535). An additional factor in the choice of these frits was the range of B_2O_3 concentrations (10-16 wt %) and Na_2O (4-8 wt %) concentrations that they represent. These components are known to have a significant impact on melt rate and will be used to identify general trends in melt rate for SB5. The compositions of the down-selected frits are given in Table 5-1.

Table 5-1. Candidate frits for SB5 down-selected from the Nominal Stage results.

Frit ID	B_2O_3 (wt %)	CaO (wt %)	Li_2O (wt %)	MgO (wt %)	Na_2O (wt %)	SiO_2 (wt %)
530	10.0	4.0	7.0	0.0	7.0	72.0
531	11.0	2.0	7.0	0.0	7.0	73.0
532	14.0	2.0	6.0	0.0	7.0	71.0
533	16.0	0.0	5.0	0.0	8.0	71.0
534	15.0	0.0	9.0	0.0	4.0	72.0
535	14.0	0.0	7.0	0.0	8.0	71.0

[a] It should also be noted that a SO_4^{2-} solubility limit of 0.4 wt % was used in these assessments. It is anticipated that the sulfate limit for the SB5 system will be the same as that for the Sludge Batch 4 (SB4) system: 0.60 wt % SO_4^{2-} or 0.88 wt % Na_2SO_4 in glass. This should be considered for any frit/sludge systems that may be limited by the 0.4 wt % SO_4^{2-} constraint. The SO_4^{2-} constraint is not encountered in the discussion of the paper study assessments provided in the main text of this report. However, the data in the appendices show cases where the frit/sludge systems studied were limited by several constraints, including the SO_4^{2-} limit.

A summary of the Nominal Stage assessment for the five candidate frits identified for SB5 Case B is given in Table 5-2. The widths of the available operating windows range from 13 to 16 percentage points in WL. The minimum WL was limited only for Frits 533 and 534 by the homogeneity constraint (at the Property Acceptability Region).[a] The maximum WL was limited by predictions of nepheline crystallization for all frits, as well as T_L for Frit 534. The T_L constraint relates to the DWPF process and does not necessarily affect waste form performance. Nepheline formation can reduce the durability of the glass product and is of greater concern. However, for the purpose of preliminary melt rate testing, it was considered more important to identify frits that covered a wide compositional range while allowing for wide operating windows, rather than focusing on the limiting constraints.

Table 5-2. Summary of Nominal Stage results for SB5 Case B with the candidate frits.

	Frit 530	Frit 531	Frit 532	Frit 533	Frit 534
Operating Window (% WL)	25-40	25-40	25-39	27-39	27-42
Lower Limiting Constraint(s)	-	-	-	Homg	Homg
Upper Limiting Constraint(s)	Nepheline	Nepheline	Nepheline	Nepheline	T_L, Nepheline

A summary of the Nominal Stage assessment for the five candidate frits identified for SB5 Case C is given in Table 5-3. The widths of the operating windows range from 12 to 16 percentage points in terms of available WLs. The minimum WL was limited by the homogeneity constraint for Frits 533 and 535. The maximum WL was limited by T_L predictions for all frits, as well as the nepheline constraint for Frit 535. The shift away from nepheline as a limiting constraint for Case C is due to the reduced concentrations of Al_2O_3 and Na_2O in this composition projection, as well as the increased SiO_2 concentration. This may be beneficial for DWPF processing, because the limiting constraints for Case C are generally process related, rather than waste form affecting.

Table 5-3. Summary of Nominal Stage results for SB5 Case C with the candidate frits.

	Frit 530	Frit 531	Frit 532	Frit 533	Frit 535
Operating Window (% WL)	25-40	25-40	25-39	28-39	28-41
Lower Limiting Constraint(s)	-	-	-	Homg	Homg
Upper Limiting Constraint(s)	T_L	T_L	T_L	T_L	T_L, Nepheline

The complete results of the Nominal Stage assessment for the six candidate frits combined with SB5 Cases B and C are given in Tables A1 and A2, respectively, in Appendix A. The six candidate frits were next carried into the Variation Stage assessments.

[a] Note that SRNL has previously recommended that the homogeneity and high frit constraints be replaced by alumina concentration and alkali concentration constraints for sludge only processing in the DWPF.[16] However, these changes have not yet been implemented in PCCS.

6.0 Variation Stage Assessments

The focus of the Variation Stage assessments is to evaluate the performance of candidate frits when the anticipated compositional variation is applied to the sludge systems of interest. Variation was applied individually to several of the sludge components. For the major components – Al_2O_3, Fe_2O_3, Na_2O and U_3O_8 – a variation of 7.5 % of each component's concentration was applied. A variation of 0.25 wt % was applied to CaO, MgO, MnO and NiO. A variation of 0.1 wt % was applied to SO_4^{2-} and a variation of 0.5 wt % was applied to SiO_2. The remaining sludge components were grouped into a category called 'Others'. A variation of 0.25 wt % was applied to the total concentration of the 'Others' components. The compositions of SB5 Cases B and C with the variation applied are given in Table 6-1.

Table 6-1. Compositions of SB5 Cases B and C with variation applied.

Component	Variation	Case B		Case C	
		Min. (wt %)	Max. (wt %)	Min. (wt %)	Max. (wt %)
Al_2O_3	7.5 %	26.787	31.131	23.014	26.746
CaO	0.25 wt %	1.531	2.031	1.714	02.214
Fe_2O_3	7.5 %	21.492	24.977	23.706	27.550
MgO	0.25 wt %	0.927	1.427	1.048	1.548
MnO	0.25 wt %	4.608	5.108	5.109	5.609
Na_2O	7.5 %	22.959	26.682	22.367	25.994
NiO	0.25 wt %	2.479	2.979	2.759	3.259
SO_4^{2-}	0.1 wt %	0.629	0.829	0.661	0.861
SiO_2	0.5 wt %	1.385	2.385	1.580	2.580
U_3O_8	7.5 %	6.875	7.990	7.583	8.813
Others	0.25 wt %	1.159	1.659	1.299	1.799

Statistical mixture experimental design methods were used to obtain an initial set of feasible sludge compositions based on the variation applied to SB5 Cases B and C. These methods included algorithms that were used to determine the extreme vertices (EVs) of the sludge region (the bounding compositions) for each case. After the EVs were determined for each sludge region, the Variation Stage assessments were made over the same waste loading interval (25 to 60% WL) using the DWPF PCCS models. Acceptable predicted properties for this assessment were based on satisfying the Measurement Acceptability Region (MAR) limits of PCCS. All MAR constraints were based on the current PCCS limits.

A summary of the Variation Stage results for SB5 Case B with its five candidate frits is given in Table 6-2. The operating windows shown indicate regions where all of the EVs were satisfied for the given frit/sludge combination. As is typically the case, the projected operating windows are reduced as compared to the Nominal Stage assessment. The widths of the operating windows for SB5 Case B range from 8 to 12 percentage points. The minimum WLs are limited by the high viscosity and homogeneity constraints. The maximum WLs are limited by the T_L constraint.

Table 6-2. Summary of Variation Stage results for SB5 Case B with the candidate frits.

	Frit 530	Frit 531	Frit 532	Frit 533	Frit 534
Operating Window (% WL)	26-37	26-37	26-36	29-36	29-36
Lower Limiting Constraint(s)	highv	highv, homg	homg	homg	homg
Upper Limiting Constraint(s)	T_L	T_L	T_L	T_L	T_L

A summary of the Variation Stage results for SB5 Case C with its five candidate frits is given in Table 6-3. The widths of the operating windows range from 5 to 11 percentage points. The minimum WLs are limited by the homogeneity constraint for Frits 531, 533 and 535. The maximum WLs are limited by the T_L constraint for each frit.

Table 6-3. Summary of Variation Stage results for SB5 Case C with the candidate frits.

	Frit 530	Frit 531	Frit 532	Frit 533	Frit 535
Operating Window (% WL)	25-35	27-35	25-34	30-34	30-36
Lower Limiting Constraint(s)	-	homg	-	homg	homg
Upper Limiting Constraint(s)	T_L	T_L	T_L	T_L	T_L

The Variation Stage results indicate that Frits 530, 531 and 532 are reasonable candidates for both SB5 composition projections. They provide the widest projected operating windows and are limited by process constraints rather than waste form affecting constraints. The complete Variation Stage results for SB5 Case B and Case C are included in Tables A3 and A4, respectively, in Appendix A. It is important to note that these results do not include any predictions of melt rate performance. Experimental studies will be necessary to provide melt rate data to aid in any frit recommendation decisions. These frits should provide sufficient compositional freedom to allow for tailoring toward improved melt rate.

7.0 Additional Nominal Stage Assessments at 40% Aluminum Removal

Additional Nominal Stage assessments were performed for the SB5 Case F projection (based on the results received from the SRNL Shielded Cells demonstration) combined with Frits 530, 531 and 532 (those that provided relatively wide operating windows for Cases B and C in the earlier assessments) over a WL interval of 25 to 60 wt %. The results are summarized in Table 7-1.

Table 7-1. Summary of Nominal Stage results for SB5 Case F with the candidate frits.

	Frit 530	Frit 531	Frit 532
Operating Window (% WL)	25-41	25-41	25-40
Lower Limiting Constraint(s)	-	-	-
Upper Limiting Constraint(s)	T_L, nepheline	T_L, nepheline	T_L, nepheline

The assessment gives projected operating windows with widths of 16 to 17 percentage points for SB5 Case F, which is slightly larger than the operating windows projected for SB5 Cases B and C. The maximum WLs are limited by the T_L and nepheline constraints. It is interesting to note that predictions of nepheline crystallization continue to be limiting for SB5 after Al-dissolution is performed. This may be partially due to high Na_2O concentrations in the sludge, coupled with Na_2O added with the frit. It may be possible to push the nepheline constraint to higher waste loadings by reducing the Na_2O concentration in the frit, although this could negatively impact melt rate.[a] Alternatives for further tailoring the frit composition to avoid predictions of nepheline crystallization are likely to be available, but melt rate data is necessary to aid in evaluating the various options.

8.0 Frit Selection for Experimental Melt Rate Studies

Experimental melt rate studies will be performed using several of the frit compositions described above. Specifically, Frits 530, 531, 532, 533, and 534 will be procured for evaluation. Frit 535 was excluded because it was not a good candidate for SB5 Case B and it was the only frit that had an operating window limited by predictions of nepheline crystallization for SB5 Case C. SRNL will fabricate a simulated SB5 Case F Sludge Receipt and Adjustment Tank (SRAT) product to be combined with the candidate frits for testing in the Melt Rate Furnace (MRF). The MRF is a resistance heated, static melter that is used to provide comparisons of relative melting rate between various frit/sludge combinations. Results of the MRF testing will be used to evaluate the impact of the frit components, particularly B_2O_3 and Na_2O,[b] which are expected to influence melt rate for SB5-like sludges. The results of the melt rate testing will be documented in a separate report, and will be used to help guide the frit recommendation process as the final SB5 composition becomes better known.

[a] High Na_2O concentration frits were previously recommended for improved melt rates in DWPF processing of high Fe_2O_3 / low Al_2O_3 concentration (PUREX-type) sludges.
[b] Selection of these frits for melt rate testing was also due in part to the range of B_2O_3 (10-16 wt %) and Na_2O (4-8 wt %) concentrations that they represent. The relatively wide ranges available for these components are likely to be advantageous for tailoring the frit composition for enhanced melt rate.

9.0 Summary

Composition projections for SB5 were developed to evaluate possible impacts of the Al-dissolution process on the availability of viable frit compositions for vitrification at the DWPF. The study included two projected SB5 compositions that bound potential outcomes (or degrees of effectiveness) of the Al-dissolution process, as well as a nominal SB5 composition projection based on the results of the recent Al-dissolution demonstration at SRNL. The bounding projections, representing 25% and 50% removal of Al, were the focus of a paper study to assess the availability of candidate frits and their ability to tolerate the anticipated variation in sludge composition. A Nominal Stage assessment was used to evaluate the two SB5 projections combined with an array of 19,305 frit compositions over a range of WL values against the DWPF process control models. The Nominal Stage results allowed for the down-selection of a small number of frits that provided reasonable projected operating windows (typically 25 to 40 wt %) and permitted some compositional flexibility (i.e., the ability to further tailor the frit to improve melt rate).

Variation Stage assessments were then performed using the down-selected frits and the two SB5 composition projections with variation applied to each sludge component. The Variation Stage results showed that the operating windows were somewhat reduced in width, as expected when variation is applied. Three of the down-selected frits continued to perform acceptably for this study for both SB5 projections through the Variation Stage, providing WL windows of approximately 26 to 35 wt %. The maximum WLs were limited by a processing constraint, T_L, rather than a waste form affecting constraint (e.g., nepheline crystallization) in the Variation Stage assessments.

While acceptable, the operating windows are relatively small for the variation stage assessments for the selected frits. However, the compositional variation of the frits should provide opportunity to explore important relationships between frit composition and melt rate for SB5-like systems.

Subsequent Nominal Stage assessments were performed with an updated SB5 projection based on the results of the Al-dissolution demonstration performed in the SRNL Shielded Cells facility (representing 40% removal of Al). The three frits identified in the earlier paper studies continued to perform acceptably with this updated projection. The available operating windows were slightly wider, although maximum WL was limited by both the T_L and nepheline constraints for all three frits.

These paper study assessments have identified candidate frits which, when combined with the current, projected SB5 compositions after Al-dissolution, have projected operating windows that should be reasonable for DWPF processing. Changes in the projected SB5 composition are anticipated before processing begins at the DWPF, which will likely require additional paper study assessments as well as experimental frit development studies. This study identifies several frits which provide insight into potential operating windows for SB5 vitrification in DWPF. However, until experimental studies can be performed to gain information on melt rate and other parameters needed to optimize frit selection, no final frit recommendation can be made.

No information regarding melt rate can be inferred from the paper study results. Experimental studies to evaluate this critical factor in DWPF processing must be performed before a frit recommendation could be made for any projected sludge composition. Five frit compositions were identified for melt rate testing at SRNL with the simulated SB5 Case F SRAT product. The results of these tests will be used to evaluate the impact of the frit components – particularly B_2O_3 and Na_2O – that are expected to influence melt rate for SB5-like sludges. The results of the melt rate testing will be documented in a separate report, and will be used to help guide the frit recommendation process when the final SB5 composition becomes clearer.

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Appendix A

Complete Results for the Nominal Stage Assessments

Table A1. Complete Nominal Stage results for Sludge Case B with Frits 530, 531, 532, 533 and 534.

WL	Frit 530	Frit 531	Frit 532	Frit 533	Frit 534
25				Homg hFrit	Homg hFrit
26				Homg	Homg
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
40			Neph	Neph	
41	Neph	Neph	Neph	Neph	
42	Neph	Neph	Neph	Neph	
43	Neph	Neph	T_L Neph	T_L Neph	T_L Neph
44	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L Neph
45	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L Neph
46	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L Neph
47	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L Neph
48	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
49	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
50	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
51	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
52	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
53	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
54	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
55	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
56	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
57	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
58	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
59	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
60	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph

Table A2. Complete Nominal Stage results for Sludge Case C with Frits 530, 531, 532, 533 and 535.

W_L	Frit 530	Frit 531	Frit 532	Frit 533	Frit 535
25				Homg	Homg
26				Homg	Homg
27				Homg	Homg
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
40			T_L	T_L	
41	T_L	T_L	T_L	T_L	
42	T_L	T_L	T_L	T_L Neph	T_L Neph
43	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L Neph
44	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
45	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
46	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
47	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
48	T_L Neph	T_L Neph	T_L Neph	T_L Neph	T_L lowv Neph
49	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
50	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
51	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
52	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
53	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
54	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
55	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
56	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
57	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph
58	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph
59	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph
60	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph

Table A3. Results of the Variation Stage Assessment for sludge Case B with the five candidate frits.

WL	Frit 530		Frit 531		Frit 532		Frit 533		Frit 534	
	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)
25	99.8	highv	99.6	highv Homg	99.8	Homg	22.5	highv Homg hFrit	22.6	Homg hFrit
26	100.0		100.0		100.0		41.6	highv Homg	41.6	Homg
27	100.0		100.0		100.0		89.0	Homg	89.0	Homg
28	100.0		100.0		100.0		98.5	Homg	98.5	Homg
29	100.0		100.0		100.0		100.0		100.0	
30	100.0		100.0		100.0		100.0		100.0	
31	100.0		100.0		100.0		100.0		100.0	
32	100.0		100.0		100.0		100.0		100.0	
33	100.0		100.0		100.0		100.0		100.0	
34	100.0		100.0		100.0		100.0		100.0	
35	100.0		100.0		100.0		100.0		100.0	
36	100.0		100.0		100.0		100.0		100.0	
37	100.0		100.0		99.1	T_L	99.4	T_L	97.9	T_L
38	99.7	T_L	99.8	T_L	86.1	T_L Neph	73.3	T_L Neph	92.8	T_L
39	76.2	T_L Neph	83.2	T_L Neph	58.3	T_L Neph	42.5	T_L Neph	83.0	T_L
40	45.2	T_L Neph	59.3	T_L Neph	17.5	T_L Neph	1.3	T_L Neph	74.0	T_L
41	2.2	T_L Neph	6.2	T_L Neph	0.1	T_L Neph	0.0	T_L Neph	42.9	T_L Neph
42	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	13.6	T_L lowv Neph
43	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.1	T_L lowv Neph
44	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L lowv Neph
45	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L lowv Neph
46	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L lowv Neph
47	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph
48	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph
49	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
50	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
51	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
52	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
53	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
54	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
55	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
56	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
57	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
58	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
59	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
60	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph

Table A4. Results of the Variation Stage assessment for sludge Case C with the five candidate frits.

WL	Frit 530		Frit 531		Frit 532		Frit 533		Frit 535	
	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)	Percent of EVs	Limiting Constraint(s)
25	100.0		90.7	Homg	90.7		0.0	Homg hFrit	0.0	Homg hFrit
26	100.0		99.4	Homg	99.4		21.4	Homg	21.4	Homg
27	100.0		100.0		100.0		34.0	Homg	34.0	Homg
28	100.0		100.0		100.0		85.6	Homg	85.6	Homg
29	100.0		100.0		100.0		97.1	Homg	97.1	Homg
30	100.0		100.0		100.0		100.0		100.0	
31	100.0		100.0		100.0		100.0		100.0	
32	100.0		100.0		100.0		100.0		100.0	
33	100.0		100.0		100.0		100.0		100.0	
34	100.0		100.0		100.0		100.0		100.0	
35	100.0		100.0		98.6	T_L	98.9	T_L	100.0	
36	99.4	T_L	99.6	T_L	91.8	T_L	92.2	T_L	100.0	
37	93.6	T_L	94.0	T_L	79.9	T_L	80.4	T_L	99.4	T_L
38	84.1	T_L	84.8	T_L	71.1	T_L	71.5	T_L	93.6	T_L
39	73.9	T_L	74.4	T_L	59.6	T_L	59.8	T_L	72.0	T_L lowv
40	63.0	T_L	63.8	T_L	49.2	T_L	30.2	T_L Neph	25.7	T_L lowv Neph
41	34.8	T_L Neph	45.1	T_L Neph	16.0	T_L Neph	12.9	T_L Neph	2.5	T_L lowv Neph
42	15.0	T_L Neph	18.5	T_L Neph	4.7	T_L Neph	0.1	T_L Neph	0.0	T_L lowv Neph
43	0.3	T_L Neph	5.2	T_L Neph	0.0	T_L Neph	0.0	T_L Neph	0.0	T_L lowv Neph
44	0.0	T_L lowv Neph	0.0	T_L Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph
45	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph
46	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph	0.0	T_L lowv Neph
47	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
48	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph	0.0	T_L lowv SO_4^{2-} Neph
49	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
50	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
51	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
52	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
53	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
54	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
55	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
56	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
57	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
58	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
59	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph
60	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph	0.0	T_L lowv SO_4^{2-} Cr_2O_3 Neph

Table A5. Complete Nominal Stage results for Sludge Case F with Frits 530, 531, and 532.

W_L	Frit 530	Frit 531	Frit 532
25			
26			
27			
28			
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41			T_L Neph
42	T_L Neph	T_L Neph	T_L Neph
43	T_L Neph	T_L Neph	T_L Neph
44	T_L Neph	T_L Neph	T_L Neph
45	T_L Neph	T_L Neph	T_L Neph
46	T_L Neph	T_L Neph	T_L Neph
47	T_L Neph	T_L Neph	T_L Neph
48	T_L Neph	T_L Neph	T_L Neph
49	T_L Neph	T_L Neph	T_L Neph
50	T_L Neph	T_L Neph	T_L Neph
51	T_L Neph	T_L Neph	T_L lowv Neph
52	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
53	T_L lowv Neph	T_L lowv Neph	T_L lowv Neph
54	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
55	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
56	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
57	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
58	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
59	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph	T_L lowv SO_4^{2-} Neph
60	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph	T_L lowv SO_4^{2-} Cr_2O_3 Neph

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