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FRIT DEVELOPMENT EFFORTS FOR SLUDGE BATCH 4 (SB4): MODEL-BASED ASSESSMENTS

D.K. Peeler
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Immobilization Technology Section
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EXECUTIVE SUMMARY

The model-based assessments of nominal Sludge Batch 4 (SB4) compositions suggest that a viable frit candidate does not appear to be a limiting factor as the Closure Business Unit (CBU) considers various tank blending options and/or washing strategies. This statement is based solely on the projected operating windows derived from model predictions and does not include assessments of SO_4 solubility or melt rate issues. The viable frit candidates covered a range of Na_2O concentrations (from 8% to 13% - including Frit 418 and Frit 320) using a "sliding Na_2O scale" concept (i.e., 1% increase in Na_2O being balanced by a 1% reduction in SiO_2) which effectively balances the alkali content of the incoming sludge with that in the frit to maintain and/or increase the projected operating window size while potentially leading to improved melt rate and/or waste loadings. This strategy or approach allows alternative tank blending strategies and/or different washing scenarios to be considered and accounted for in an effective manner without wholesale changes to the frit composition.

In terms of projected operating windows, in general, the sludge / frit systems evaluated resulted in waste loading intervals from 25 to the mid-40%'s or even the mid-50%'s. The results suggest that a single frit could be selected for use with all 20 options which indicates some degree of frit robustness with respect to sludge compositional variation. In fact, use of Frit 418 or Frit 320 (the "cornerstone" frits given previous processing experience in the Defense Waste Processing Facility (DWPF)) are plausible for most (if not all) options being considered. However, the frit selection process also needs to consider potential processing issues such as melt rate. Based on historical trends between melt rate and total alkali content, one may elect to use the frit with the highest alkali content that still yields an acceptable operating window. However, other constraints may restrict access to higher waste loading or the proposed blending option being considered (e.g., sulfate content of the high-level waste and/or Chemical Processing Cell (CPC) issues may necessitate a more-washed sludge).

TABLE OF CONTENTS

LIST OF ACRONYMS

ASTM	American Society for Testing and Materials
CBU	Closure Business Unit
CPC	Chemical Processing Cell
DWPF	Defense Waste Processing Facility
ΔG_P	preliminary glass dissolution estimator
MAR	Measurement Acceptability Region
NL [B]	normalized boron release (in g/L)
PCCS	Product Composition Control System
PCT	Product Consistency Test
SB	sludge batch
SME	Slurry Mix Evaporator
SRAT	Sludge Receipt and Adjustment Tank
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
T_L	liquidus temperature
η	viscosity
WL	waste loading
WSRC	Westinghouse Savannah River Company

LIST OF TABLES

1.0 INTRODUCTION

The Defense Waste Processing Facility (DWPF) is currently processing Sludge Batch 3 (SB3) as a "sludge-only" composition by combining SB3 with Frit 418, melting the slurry mix of sludge and frit, and pouring the molten glass in stainless steel canisters to create the final waste form for this high-level waste at the Savannah River Site (SRS). In preparation for the qualification and receipt of the next sludge batch, Sludge Batch 4 (SB4), development and definition of the baseline flowsheet have been initiated (Lilliston 2005). Various tank blending strategies are being contemplated for SB4 in an effort to meet critical Closure Business Unit (CBU) objectives including issues associated with the durability of the DWPF glass waste form and the efficiency and effectiveness of the DWPF operation. Critical components of DWPF's operational efficiency and effectiveness include sludge/frit processability, melter attainment (the percentage of time DWPF's melter is pouring), melt rate, waste loading, and canister production rates. An early yet meaningful assessment of the processability of a sludge option and of the durability of the final waste form for candidate frits at various waste loadings is provided by using predictions generated by property/composition models. The models employed are the same as those used by DWPF's Product Composition Control System (PCCS), and this investigation of candidate sludge/frit glass systems may be described as a paper study whose purpose is to identify a viable frit or frits for each sludge option being contemplated. A frit is considered viable if its composition allows for economic fabrication and if, when it is combined with a sludge option under consideration, DWPF's property/composition models indicate that the combination has an operating window (a waste loading interval over which the sludge/frit glass system satisfies processability and durability constraints) that allows DWPF to meet its goals for waste loading and canister production.

The Savannah River National Laboratory (SRNL) has been asked via a technical task request (Washburn 2004) to provide frit development support for SB4. In response, SRNL has issued a task technical and quality assurance plan (Peeler 2004), and it is under the auspices of that plan that this report has been prepared. The purpose of this report is to identify candidate frits and to assess their viability for the 20 options being contemplated for SB4 as provided by Lilliston (2005). The assessments performed are strictly model-based, and no experimental work was conducted to support this task. Specifically, no experiments on melt rate were conducted for the systems explored. Although not included in the scope of this report, such experimental work is planned as part of the support for SB4 (Peeler and Smith 2004) since the results from melt rate studies are a critical input to the final selection of a frit for SB4.

This report summarizes the assessments of 20 SB4 tank blending scenarios that were provided by the CBU. Candidate frits were identified based on a review of each projected sludge composition and assessed using model-based predictions to project operational windows. It should be noted that only the Nominal Stage assessment was performed. That is, given the large number of options, the Variation Stage which introduces variation around the nominal SB4 compositions in an effort to gain insight into the robustness or tolerance of a candidate frit to anticipated compositional variation was not performed.[1] The information resulting from these efforts will provide part of the technical basis for selecting the blending and/or washing strategy for SB4 processing. It should be noted that a parallel activity is being performed to address other operational issues associated with Sludge Receipt and Adjustment Tank (SRAT) / Slurry Mix Evaporator (SME) processing (e.g., H_2 generation issues and acid addition and redox control strategies). Therefore, the results from both

[1] Although the Variation Stage was not performed, the 20 nominal SB4 blending options provided by Lilliston (2005) will provide some insight into the ability of a specific frit composition to tolerate some degree of sludge compositional variation.

tasks, as well as melt rate assessments, should be considered prior to formalizing a decision regarding a baseline flowsheet for SB4.

Objectives for this task are specified in Section 2.0. In Section 3.0, a brief review of the strategy or approach for developing and assessing new or existing frits is provided as well as the criteria used to make acceptability decisions. Projected SB4 nominal compositions are summarized in Section 4.0 from which the assessments will be founded. Section 5.0 summarizes the Nominal Stage, Measurement Acceptability Region (MAR) based assessments for the 20 SB4 blending scenarios. Section 6.0 provides a summary of these assessments.

2.0 OBJECTIVE

The objective of this task is to provide technical information to the DWPF from which a business decision can be made in terms of identifying candidate frit compositions for the SB4 flowsheet. The information provided in this report is solely focused on model-based projections of the PCCS operational windows for various SB4 blending strategies of interest. Experimental assessments of melt rate or SO_4 solubility are not addressed in this report but are being addressed in parallel tasks.

3.0 THE APPROACH AND CRITERIA FOR ACCEPTABILITY

To meet the programmatic objectives, the Nominal Stage assessments as proposed by Peeler and Edwards (2002) were used to assess various frit/sludge combinations. The assessment utilized nominal SB4 compositions representing potential tank blending scenarios as outlined by Lilliston (2005). In general, this stage assessed candidate frit compositions with respect to their ability to provide a relatively large projected operating window based solely on a specific nominal composition – no sludge variation was accounted for in this phase. Assessments were made using predictions from models currently implemented in DWPF's PCCS over the waste loading (WL) interval of interest (25 – 60 wt%). The primary property predictions assessed included those for liquidus temperature (T_L), viscosity (η), and durability (normalized boron release – NL[B]).

It is recognized that the Nominal Stage assessments do not account for anticipated compositional variation. However, the compositional projections provided by Lilliston (2005) were based on various percentages of possible tanks that could represent or be included in SB4, along with different heel volumes for SB3. The selected compositions also specifically targeted upper and lower bounds for DWPF affecting elements. Therefore, the compositions do represent or provide a measure of sludge variation that provides some insight into the robustness of candidate frits with respect to compositional variation. If needed, and as the SB4 flowsheet becomes more mature (primary blending options are defined), a formal Variation Stage assessment could be performed to address this issue.

As previously mentioned, the property predictions assessed in this study included durability (Product Consistency Test [PCT] [ASTM 2002] response in terms of the preliminary glass dissolution estimator (ΔG_P) (Jantzen et al. 1995)), viscosity at 1150°C ($\eta_{1150°C}$), T_L, and Al_2O_3 and alkali concentrations. Jantzen et al. (1995) and Brown et al. (2001) provide a more detailed discussion on the development of these models. To establish or project operational windows for sludge/frit scenarios of interest, the predicted properties must be assessed relative to established acceptance criteria. Acceptable predicted properties for this assessment were based on satisfying their respective

MAR limit values. Brown, Postles, and Edwards (2002) provide a detailed discussion of how the MAR limits are utilized in PCCS.

Although the SO_4 limit for SB4 has not been established, various SO_4 limits can be used (e.g., 0.4, 0.5, and 0.6 wt% in glass) to assess if SO_4 will have a negative impact on the projected operating window. The SO_4 concentrations in glass will be calculated, but an assumed SO_4 limit will not be used to restrict the projected operating windows based on the model predictions. Given there is no MAR uncertainty associated with the SO_4 concentration, the maximum WL for each SB4 option can be determined as a function of an assumed SO_4 solubility limit based strictly on mathematics (i.e., the assumed SO_4 solubility limit divided by the SO_4 concentration in sludge times 100). For example, if the SO_4 concentration in sludge was 1.09 wt% and the assumed SO_4 solubility limit was 0.4 wt% (in glass), then the maximum WL achievable (based strictly on the SO_4 solubility limit) would be ~36.7 wt%. If the SO_4 solubility limit was 0.5 wt%, then the maximum achievable WL ((based strictly on the SO_4 solubility limit) would be 45.9%. Although one can easily calculate the maximum WL for a given SO_4 solubility limit, properties other than SO_4 solubility may restrict access to higher WLs. Therefore, a nominal SO_4 value has been added to each of the 20 options but a SO_4 solubility limit in PCCS was not activated with respect to limiting or imposing restrictions on the MAR based assessments for the initial assessments.

4.0 BASIS FOR SB4 COMPOSITIONAL SCENARIOS

Two primary inputs are required to assess the projected operating windows, the waste loading intervals and the robustness to compositional variation. The primary inputs are: sludge (or waste stream) and frit composition(s). Given the focus of this study is to develop and assess frit compositions for SB4, defining the nominal SB4 waste stream(s) is the only required input. For a given waste stream composition, one can select candidate frit compositions and ultimately assess or define glass compositional regions or operating windows based on established acceptance criteria.

4.1 Projected SB4 Compositions

Table 5-1 provides the elemental compositions (in weight percent, wt%) of the 20 options outlined by Lilliston (2005) for SB4. It should be noted that Lilliston (2005) did not report anion concentrations (in particular SO_4 which is anticipated to be relatively high in SB4). Additional information obtained from the CBU provided a technical basis for a projected SO_4 concentration (~1.09 wt% in calcined sludge solids) in SB4 based on the baseline flowsheet. Although Lilliston (2005) did not incorporate SO_4 into the 20 options, this study will utilize the nominal 1.09 wt% value (pre-normalized) in order to assess the potential impact of SO_4 solubility on the projected operating windows.[2] That is, the elemental compositions provided by Lilliston (2005) were converted to oxides by multiplying the concentrations by the appropriate gravimetric factor. The 1.09 wt% SO_4 was then added to this list of oxides. The oxide compositions were then normalized to sum to 100 wt% for each of the 20 options. The resulting normalized oxide compositions for each of the twenty sludge options are shown in Table 5-2. It should be noted that the SO_4 concentration for each of the 20 options is not "constant" given the sum of oxide differences among the various options prior to normalization.

[2] Shah et.al. (2004) provided the nominal supernate composition for SB4, which included sulfate. For this study, all of the sulfate was assumed to be soluble and the sulfate in the calcined solids was estimated to be 1.09 wt% assuming a calcine factor similar to that seen for SB4 simulant flowsheet testing.

Table 4-1. SB4 Blending Options – as Elemental Concentrations (wt%) (from Lilliston (2005))

	SB4 Only Baseline	SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	1100 Can Baseline	1100 Can 2nd Transfer, Baseline	1100 Can Min Al, Na; Max Ce, Fe, Mn, U	1100 Can Max Al, Na; Min Mn, Ni, U	1100 Can Min Ce, Mg, Ti	1100 Can Min Fe	1100 Can Max Mg	1100 Can Max Ni	1100 Can Max Ti	1200 Can Baseline	1200 Can 2nd Transfer, Baseline	1200 Can Min Al, Na; Max Ce, Fe, Mn, U	1200 Can Max Al, Na; Min Fe, Mn, Ni, U	1200 Can Max Ni	1200 Can Min Ce	1200 Can Min Mg, Ti	1200 Can Max Mg, Ti
Cation	wt%	wt%	wt%	wt%	wt%	wt%	wt%	Wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
Al	16.319	13.486	24.268	11.908	13.209	10.267	16.472	13.947	14.932	11.374	11.807	14.890	12.747	13.433	10.824	17.366	11.824	15.034	13.852	15.801
Ba	0.166	0.202	0.071	0.144	0.150	0.158	0.095	0.165	0.139	0.144	0.178	0.101	0.147	0.150	0.165	0.092	0.178	0.139	0.164	0.097
Ca	1.177	1.134	1.210	1.584	1.442	1.611	1.559	1.271	1.354	1.605	1.343	1.644	1.491	1.417	1.512	1.510	1.339	1.343	1.282	1.593
Ce	0.161	0.159	0.159	0.176	0.170	0.178	0.173	0.162	0.164	0.176	0.166	0.177	0.172	0.169	0.173	0.170	0.165	0.163	0.162	0.174
Cr	0.194	0.206	0.160	0.171	0.177	0.175	0.155	0.186	0.174	0.169	0.189	0.154	0.175	0.178	0.179	0.154	0.189	0.174	0.185	0.154
Cu	0.063	0.067	0.045	0.066	0.065	0.069	0.056	0.063	0.059	0.065	0.067	0.059	0.065	0.064	0.068	0.055	0.067	0.058	0.063	0.057
Fe	14.160	15.310	10.457	18.051	16.678	18.994	15.685	15.420	15.359	18.415	16.842	16.902	17.153	16.432	18.205	14.988	16.813	15.252	15.522	16.188
K	1.574	1.239	2.501	0.844	1.068	0.627	1.397	1.227	1.288	0.747	0.936	1.168	0.987	1.106	0.737	1.525	0.939	1.303	1.209	1.298
La	0.067	0.068	0.057	0.079	0.074	0.081	0.072	0.069	0.069	0.078	0.073	0.076	0.075	0.073	0.078	0.070	0.073	0.068	0.069	0.073
Mg	0.211	0.201	0.243	1.162	0.852	1.258	1.090	0.525	0.748	1.285	0.694	1.278	0.964	0.800	1.056	0.984	0.689	0.729	0.551	1.171
Mn	3.941	4.568	2.490	4.486	4.278	4.826	3.656	4.248	4.125	4.693	4.631	3.928	4.360	4.249	4.765	3.511	4.634	4.117	4.265	3.783
Na	14.720	14.348	15.643	16.214	16.200	16.043	16.749	16.076	16.297	16.170	15.899	16.653	16.205	16.197	15.991	16.797	15.897	16.298	16.078	16.701
Ni	4.574	6.083	0.965	2.896	3.404	3.387	1.130	4.370	3.319	2.951	4.743	1.172	3.223	3.491	3.872	1.107	4.755	3.347	4.321	1.148
Pb	0.184	0.160	0.242	0.153	0.161	0.139	0.185	0.163	0.168	0.145	0.148	0.174	0.158	0.162	0.142	0.191	0.148	0.168	0.163	0.180
Si	1.117	0.951	1.549	1.267	1.210	1.214	1.478	1.108	1.242	1.276	1.063	1.472	1.233	1.202	1.163	1.485	1.063	1.241	1.114	1.479
Th	0.035	0.027	0.057	0.030	0.032	0.027	0.042	0.031	0.036	0.030	0.026	0.040	0.031	0.032	0.026	0.044	0.026	0.035	0.031	0.041
Ti	0.008	0.006	0.013	0.013	0.011	0.012	0.015	0.009	0.011	0.013	0.009	0.015	0.012	0.011	0.011	0.015	0.009	0.011	0.009	0.015
U	7.238	9.447	0.974	7.805	7.564	8.841	4.417	7.793	6.450	7.895	9.044	5.184	7.653	7.526	8.917	3.990	9.047	6.422	7.807	4.750
Zn	0.091	0.101	0.051	0.102	0.098	0.108	0.080	0.094	0.084	0.100	0.103	0.087	0.099	0.096	0.105	0.075	0.102	0.083	0.094	0.082
Zr	0.233	0.250	0.171	0.205	0.212	0.210	0.174	0.221	0.198	0.197	0.228	0.176	0.208	0.212	0.215	0.172	0.227	0.197	0.220	0.173

Table 4-2. SB4 Blending Options –as Normalized Oxide Concentrations (wt%)[3]

	SB4 Only Baseline	SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	1100 Can Baseline	1100 Can 2nd Transfer, Baseline	1100 Can Min Al, Na; Max Ce, Fe, Mn, U	1100 Can Max Al, Na; Min Mn, Ni, U	1100 Can Min Ce, Mg, Ti	1100 Can Min Fe	1100 Can Max Mg	1100 Can Max Ni	1100 Can Max Ti	1200 Can Baseline	1200 Can 2nd Transfer, Baseline	1200 Can Min Al, Na; Max Ce, Fe, Mn, U	1200 Can Max Al, Na; Min Fe, Mn, Ni, U	1200 Can Max Ni	1200 Can Min Ce	1200 Can Min Mg, Ti	1200 Can Max Mg, Ti
Oxide	wt%	wt%	wt%	wt%	wt%	wt%	wt%	Wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
Al_2O_3	31.074	25.590	46.666	22.675	25.149	19.523	31.529	26.528	28.471	21.659	22.422	28.476	24.273	25.576	20.573	33.258	22.454	28.666	26.350	30.234
BaO	0.187	0.226	0.081	0.162	0.168	0.177	0.108	0.185	0.157	0.162	0.200	0.114	0.166	0.169	0.185	0.104	0.200	0.157	0.184	0.110
CaO	1.659	1.594	1.722	2.233	2.034	2.268	2.210	1.791	1.912	2.263	1.889	2.328	2.102	1.997	2.129	2.141	1.883	1.897	1.806	2.257
Ce_2O_3	0.190	0.187	0.189	0.208	0.201	0.209	0.205	0.191	0.194	0.208	0.195	0.210	0.203	0.199	0.203	0.202	0.195	0.193	0.191	0.206
Cr_2O_3	0.286	0.303	0.238	0.252	0.261	0.257	0.229	0.274	0.256	0.249	0.277	0.228	0.257	0.262	0.264	0.229	0.277	0.256	0.273	0.228
CuO	0.079	0.084	0.057	0.084	0.082	0.087	0.072	0.080	0.074	0.082	0.085	0.075	0.082	0.081	0.086	0.069	0.084	0.074	0.080	0.073
Fe_2O_3	20.401	21.980	15.216	26.009	24.026	27.328	22.717	22.192	22.159	26.533	24.200	24.457	24.714	23.673	26.183	21.718	24.158	22.005	22.341	23.439
K_2O	1.912	1.499	3.067	1.025	1.297	0.760	1.706	1.488	1.566	0.908	1.134	1.424	1.199	1.343	0.893	1.863	1.137	1.584	1.467	1.584
La_2O_3	0.079	0.080	0.068	0.093	0.088	0.095	0.086	0.082	0.081	0.093	0.086	0.090	0.089	0.087	0.092	0.083	0.086	0.081	0.082	0.087
MgO	0.353	0.334	0.410	1.942	1.424	2.099	1.830	0.876	1.251	2.147	1.156	2.145	1.610	1.336	1.761	1.654	1.148	1.220	0.919	1.966
MnO	5.127	5.923	3.272	5.838	5.566	6.271	4.782	5.521	5.375	6.106	6.010	5.134	5.674	5.528	6.189	4.595	6.014	5.364	5.545	4.946
Na_2O	19.996	19.422	21.461	22.028	22.005	21.763	22.871	21.814	22.169	21.967	21.539	22.721	22.014	22.001	21.683	22.949	21.538	22.170	21.819	22.799
NiO	5.866	7.773	1.249	3.715	4.365	4.337	1.456	5.598	4.262	3.785	6.065	1.509	4.133	4.476	4.957	1.427	6.081	4.298	5.536	1.480
PbO	0.200	0.173	0.265	0.166	0.175	0.151	0.202	0.177	0.183	0.157	0.160	0.190	0.171	0.176	0.153	0.209	0.160	0.183	0.176	0.196
SO_4	1.098	1.095	1.109	1.099	1.098	1.097	1.104	1.097	1.100	1.099	1.095	1.103	1.098	1.098	1.096	1.105	1.095	1.100	1.097	1.104
SiO_2	2.407	2.044	3.373	2.732	2.607	2.615	3.204	2.385	2.681	2.751	2.285	3.187	2.659	2.591	2.504	3.220	2.286	2.679	2.400	3.205
ThO_2	0.040	0.031	0.066	0.035	0.036	0.030	0.049	0.036	0.041	0.034	0.030	0.046	0.035	0.036	0.030	0.051	0.030	0.041	0.035	0.047
TiO_2	0.013	0.010	0.021	0.021	0.018	0.021	0.025	0.015	0.019	0.022	0.015	0.026	0.020	0.018	0.019	0.025	0.015	0.019	0.015	0.026
U_3O_8	8.601	11.187	1.169	9.276	8.988	10.491	5.276	9.251	7.674	9.382	10.718	6.187	9.095	8.942	10.577	4.769	10.722	7.642	9.267	5.673
ZnO	0.114	0.126	0.065	0.128	0.123	0.135	0.101	0.117	0.106	0.125	0.129	0.109	0.124	0.121	0.132	0.095	0.128	0.105	0.117	0.103
ZrO_2	0.317	0.339	0.235	0.279	0.289	0.285	0.238	0.301	0.270	0.268	0.309	0.240	0.283	0.289	0.291	0.235	0.308	0.268	0.299	0.236
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[3] The SO_4 values shown in Table 4-2 were not reported by Lilliston (2005) but represent normalized values calculated using the 1.09 wt% SO_4 value from Shah et al. (2005).

4.2 Candidate Frit Compositions

Based upon preliminary assessments of the SB4 compositions, six candidate frits were identified (see Table 5-3) for consideration with each of the normalized sludge oxide compositions of Table 5-2. The glass system formed by combining a frit candidate with a sludge option was explored at 36 different WLs, from 25 to 60% in increments of 1. Thus for the 20 SB4 options, six frit candidates, and 36 WLs, there were 4320 glass compositions generated.

A closer review of the frits listed in Table 5-3 indicates fixed concentrations of B_2O_3 and Li_2O at 8 wt% with only the Na_2O and SiO_2 concentrations varying. In general, the frit compositions increase in Na_2O by 1% and decrease respectively in SiO_2 proceeding from Frit 418 (the most refractory frit being considered) to Frit 431. Throughout this report, this system will be referred to as a "sliding Na_2O scale" concept which has been developed to accommodate potential Na_2O concentration differences in the sludge as a result of varying blending and/or washing strategies being considered.[4] More specifically, frit development and selection would like to take advantage of the "cornerstone" DWPF frits (Frit 320 and Frit 418) that were developed to improve WL and/or melt rate for SB2 and SB3, respectively. A primary difference between SB2 and SB3 was the washing endpoint which resulted in a dramatic difference in Na_2O concentrations (i.e., SB2 was considered to be an "overwashed" sludge having a much lower Na_2O content than SB3 which was considered to be "underwashed"). Frit development efforts accommodated this shift in Na_2O content between SB2 and SB3 by a reduction in Na_2O content in the frit – transitioning from Frit 320 (with 12% Na_2O) to Frit 418 (with 8% Na_2O). This shift or "sliding Na_2O scale" concept has proven effective for DWPF as waste throughputs for SB3 with Frit 418 have been at their highest since radioactive operations began. If possible, frit development efforts for SB4 would like to continue the use of this concept given DWPF has process history with the cornerstone frits and their use (or slight modifications to their compositions) would hopefully minimize the risk or "unknowns" of using a frit with drastically different ratios and/or new oxides. If the projected operating windows do not meet expectations (i.e., in terms of upper WL or range of WLs) with the frits listed in Table 5-3, alternative frit compositions will be developed. However, if the "sliding Na_2O scale" approach is successful for SB4,[5] consideration of these frits may have their advantages (if only based on lower perceived risks).

Table 4-3. Identification and Composition of Candidate Frits (wt%)[6]

Frit ID	B_2O_3	Li_2O	Na_2O	SiO_2
418	8	8	8	76
426	8	8	9	75
425	8	8	10	74
417	8	8	11	73
320	8	8	12	72
431	8	8	13	71

[4] The 20 SB4 options outlined by Lilliston (2005) are based on various blending strategies represented by various percentages of the tank volumes/masses. The projected nominal composition do not specifically address the possibly of different washing options that could be performed in the tank farm. In this report, gross assumptions are made regarding the washing impacts and are used to assess this impact on the frit selection process (see Section 5.6).

[5] "Success" being defined based on the ability of this concept to effectively compensate for the various blending and/or washing strategies developed by the CBU to produce operating windows (in terms of model predictions) meeting DWPF expectations.

[6] Frit 441, which contains 15% Na_2O (69% SiO_2), is not shown in Table 4-3 but will be utilized in some of the MAR assessments to demonstrate the continual concept of the "sliding Na_2O scale". The projected operating windows for Frit 441 are not summarized but details can be found in Appendix A which are discussed in the text for some blending options.

5.0 PROJECTED OPERATING WINDOWS FOR THE SB4 BLENDING OPTIONS

Each of the 4320 glass compositions was assessed against the MAR criteria of PCCS. Table A1 in the Appendix provides a summary of the outcomes from this investigation by providing the MAR results for each sludge option/frit candidate combination. For each sludge / frit system, these results are indicated relative to WL. That is, the "Min WL" and "Max WL" columns represent the minimum and maximum WLs, respectively, which met all MAR criteria thus establishing the projected operating window. The "limited below by" and "limited above by" columns indicates the property (or properties) that limit access to lower or higher WLs, respectively. The next six columns represent the predicted durability, viscosity, and T_L at the minimum and maximum WL, respectively. As previously mentioned, although a nominal SO_4 concentration of 1.09 wt% was added to each of the 20 pre-normalized compositions, an assumed SO_4 limit was not activated, therefore, no SO_4 restrictions are imposed on the projected operating windows.

Numerous comparisons can be made among the 20 SB4 blending scenarios. The authors have elected to highlight some of the more interesting comparisons within each primary classification (i.e., SB4-only, 1100 canister, and 1200 canister options).[7] Comparisons among these primary classifications will be made as warranted.

5.1 SB4-Only

Table 5-1 provides a summary of the results for model-based MAR assessments for the SB4 Only options (Baseline, Max Al, and Min Al) with each candidate frit. Also shown in Table 5-1 is the wt% Na_2O for each frit. The projected operating windows in terms of upper and lower WLs that satisfy the MAR constraints for the specific sludge / frit blend as well as the property that limits access to higher WLs are also provided.[8] For example, consider the Frit 418 – SB4 Only Baseline case. The projected operating window is 33 – 36% WL with predictions of high viscosity (η) and liquidus temperature (T_L) limiting access to WLs of < 33% and > 37%, respectively. As the Na_2O concentration in the frit gradually increases (transitioning from Frit 426 to Frit 320), the higher alkali content gradually reduces predictions of viscosity and T_L which have a positive impact on the operating window size. For example, Frit 320 (with 12% Na_2O) results in an operating window from 25 – 40% WL with predictions of T_L limiting access to higher WLs. Transitioning from Frit 320 (with 12% Na_2O) to Frit 431 (with 13% Na_2O) indicates no advantage in terms of the projected operating window – perhaps an advantage in terms of melt rate given the higher alkali content. Given the gradual trend of increasing upper WLs with increasing Na_2O concentrations in the frit, the obvious question to ask is what happens if frit composition with > 13% Na_2O are used – in terms of the projected operating window. Although not shown in Table Table 5-1, Frit 441, with 15% Na_2O, was coupled with the SB4-only Baseline option and the result was an operating window from 30 – 42% WL (see Table A1). Predictions of durability restrict access to WLs < 30% while T_L limits access to WLs > 42%. Although there are potential advantages with Frit 441 (42% upper WL), the disadvantage may be the loss of robustness to compositional variation.

[7] Lilliston (2005) uses the SB4-only, 1100 canister and 1200 canister options to denote the various volumes or mass of the SB3 heel to be blended with SB4. The SB4-only case assumes no SB3 heel is blended. The 1100 and 1200 canister options refer to the volume or mass of SB3 remaining after 1100 and 1200 canisters have been produced.

[8] Liquidus temperature is denoted by T_L and high viscosity by high η. In addition, for two of the Frit 418 – SB4-Only Baseline cases, high η also restricts access to lower WLs.

The last column of Table 5-1 provides the frit and maximum WL as determined by Lilliston (2005) using the limits for durability currently in DWPF's PCCS and a 20°C "offset" for the T_L MAR.[9] For the assessments of this paper study, the new, proposed durability limits (Edwards et al., 2003) and the "true" T_L MAR were used. Use of the new durability limits allows for consideration of frits with higher alkali content for a given sludge composition which provides access to compositional regions which have been shown to improve melt rate and/or waste loading – both critical factors in defining waste throughput for DWPF. More will be said regarding the potential impact on the frit selection process based on the use of the current versus proposed durability limits. For now it suffices to say that Lilliston identified the use of Frit 431 as a leading candidate for all three SB4-only options. The results of the MAR-based assessments agree quite well.

Table 5-1. SB4 Only Options - MAR Results

	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431	Lilliston (2005)
% Na_2O (in frit)	8	9	10	11	12	13	
Baseline	(high η) 33 - 36 (T_L)	25 – 37 (T_L)	25 – 38 (T_L)	25-39 (T_L)	25 – 40 (T_L)	25 – 40 (T_L)	Frit 431, 39.4%
Max Al	-	-	-	-	25 – 60	25 – 60	Frit 431, 61.3%
Min Al	(high η) 27 – 32 (T_L)	25 – 33 (T_L)	25 – 34 (T_L)	25 – 35 (T_L)	25 – 35 (T_L)	25 – 36 (T_L)	Frit 431, 35.5%

The "Max Al" option is extremely interesting. Model based predictions restrict the use of Frits 418, 426, 425, and 417 – predictions of high viscosity result in no operating windows over the entire 25 – 60% WL interval. However, a 1% shift in the Na_2O content of the frit transitions from a system with no operating window (with Frit 417) to one that is not restricted over the entire 25 – 60% WL interval (with Frit 320). This demonstrates the sensitivity of the PCCS model interactions to slight changes in frit composition and the need to consider robustness to compositional variation during the frit selection process.

The "red" shading in Table 5-1 indicates that the SB4-only "Min Al" case is somewhat troubling from the paper study perspective, since it has consistently smaller windows as compared to the other options. Use of the term "troublesome" is subjective but it reflects the inability of the existing frits to obtain upper WLs of at least 40%. For the "Min Al" case, the maximum upper WL obtained is 36% with the use of Frit 431 (the highest Na_2O containing frit at 13%). As with the SB4-Only baseline case, the use of higher alkali containing frits (Frit 441 with 15% Na_2O) may be beneficial in terms of broadening the projected operating window. However, use of Frit 441 with the "Min Al" case results in almost complete elimination of the window as predictions of durability and low viscosity restrict the operating window to 36 – 38% WL (refer to Table A1). It should be noted that the "Min Al" case (as it is being referred to) also has the minimum Na_2O concentration for the three SB4-only options (see Table 5-1). Therefore, the use of higher alkali frits to balance the Na_2O-deficient sludge was expected to be less effective.[10]

[9] Yellow shading is used to highlight the "candidate" frit that was identified by Lilliston (2005) during his assessment of the various SB4 options.

[10] Although not a primary focus of this report, previous assessments of preliminary SB4 compositional projections have provided insight into the impact of the Na_2O concentration in the sludge versus that in the frit on the ability of frit development effort to compensate or retain similar projected operating windows. Preliminary assessments of SB4 compositions (referred to as Set #2 in WSRC-NB-2004-00134 with much lower Na_2O concentrations for all 20 options) indicate that the ability of the "Na_2O sliding scale" concept to account for or balance the alkali content was less effective when the Na_2O concentration in the sludge was less than that in the frit. If Na_2O

5.2 1100 Canister Options

Table 5-2 provides a summary of the MAR results for the 1100 Canister Options.[11] The shading of the table provides some general insight into the frit selection process as well as the impact of the current versus proposed durability limits. Yellow shading is used to highlight the frit that was identified by Lilliston (2005) during his assessment of the various SB4 options. Green is used to highlight the frit that provides the "maximum" upper WL (with a relatively large window). Blue is used to highlight a frit / sludge combination with a relatively large operating window (albeit subjective) and that has a relatively high alkali content, which may help improve melt rate. If there is no "blue" cell in a row, then the "green" cell is considered to meet this criterion.

Table 5-2. 1100 Canister Options - MAR Results

	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431	Lilliston (2005)
% Na_2O (in frit)	8	9	10	11	12	13	
Baseline	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 44 (low η)	(ΔG_P) 27 – 41 (low η)	Frit 418, 40.5%
2nd transfer baseline	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 43 (low η)	Frit 418, 39.3%
Min Al	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 41 (low η)	-	Frit 418, 38.9%
Max Al	(high η) 27 – 51 (T_L)	25 – 52 (T_L)	25 – 53 (T_L)	25 – 54 (T_L)	25 – 53 (low η)	25 – 50 (low η)	Frit 418, 49.4%
Min Ce	25 – 38 (T_L)	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	Frit 418, 36.8%
Min Fe	(high η) 26 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L)	Frit 418, 40.0%
Max Mg	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 43 (low η)	(ΔG_P) 32 – 40 (low η)	Frit 418, 40.2%
Max Ni	25 – 36 (T_L)	25 – 37 (T_L)	25 – 38 (T_L)	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L/low η)	Frit 418, 35.5%
Max Ti	25 – 50 (T_L)	25 – 51 (T_L)	25 – 52 (T_L)	25 – 52 (low η)	25 – 49 (low η)	25 – 46 (low η)	Frit 418, 48.0%

concentration in the sludge is greater than that in the frit, then as WL increases, the Na_2O content in the glass increases which (in general) should reduce T_L and provide access to higher WLs for T_L limited systems. If the Na_2O content in the sludge is less than that in the frit, as WL increases the glass (in general) becomes more refractory, and predictions of T_L and/or high viscosity not only restrict access to higher WLs but begin to collapse the projected operating window altogether.

[11] See Table A1 for more details associated with these systems. In addition, Table A1 includes the use of Frit 441 (15% Na_2O) with all SB4 options which are not summarized in Table 5-2.

The first general observation is the difference between Frit 418, the frit that Lilliston (2005) identified as the primary frit for each of the 1100 canister options (see "yellow" cells and last column), and the "green" or "blue" shaded cells which represent systems based on higher alkali frits which increased the projected operating window size and/or have the potential to improve melt rate. This difference is solely based on the durability limits utilized. Lilliston (2005) used the current (more conservative) limits while this assessment used those limits proposed by Edwards et al. (2003). As previously mentioned, the proposed limits allow the use of higher alkali frits (for a given sludge composition) which have been shown to improve melt rate and/or waste loading. As an example, consider the 1100 Canister Baseline option. Lilliston (2005) suggested the use of Frit 418 while this assessment allows either the use of Frit 417 or Frit 320 (both higher alkali frits) which may improve melt rate and/or waste throughput. Assuming the historical trend between melt rate and total alkali content holds for the SB4 system, selection of a "primary" frit candidate may depend on the sludge option being considered. That is, one may elect to use Frit 320 for the 1100 Canister Baseline option, but Frit 431 for the 1100 Canister, 2nd Transfer Baseline option. The challenge for the frit selection process will be to assess the robustness of a candidate frit to anticipated compositional changes and then use experimental melt rate data to select an optimal frit that is robust and yields high waste throughputs.

In general, the results for the 1100 canister options suggest that typical operating windows cover WLs from 25 to the mid-40%'s or low-50%'s. For most of the sludge options (all but 2 – "Min Ce" and "Min Fe"), as higher alkali frits are used, the resulting glass systems transition from being T_L limited at the maximum WL to being low η limited systems. This trend was expected as higher alkali systems typically result in lower T_L and lower viscosity predictions with the anticipated result being a reduction in T_L which gradually allows higher WLs to be obtained up to the point where predictions of low viscosity become limiting. It is interesting to note that both T_L and low viscosity limit access to higher WLs in the Frit 431 – "Max Ni" option which may be indicative of an "optimized" system for that specific blending option. In general terms, the use of the "sliding Na_2O scale" concept does allow one to compensate or balance the Na_2O through frit selection to maximize the projected operating windows. The desire to push the frit Na_2O concentrations to their highest must be balanced with the Na_2O content in the sludge. This compensation is realized in the fact that some maximum operating windows are obtained with an "intermediate" Na_2O-based frit (e.g., the Frit 417 – 1100 Can Baseline option).

Another general observation is the fact that most of the candidate frits appear to provide some measure of robustness with respect to the various sludge blending options. More specifically, consider the cornerstone frits (Frit 418 and Frit 320). These two frits provide operating windows (perhaps not optimal) for all nine SB4 1100 Canister options being considered based on model predictions. The identification of a primary frit for a specific sludge option will ultimately be based not only on the operating window size but also robustness and melt rate – two inputs not addressed in this study.

In addition to the general comparisons noted above, there are a few specific systems that should be mentioned.

- Based on the model predictions, it appears that a frit change would not be required between the SB4 1100 canister baseline and the 2nd transfer baseline. For example, Frit 320 provides identical projected operating windows for both sludge options.
- The "Min Al" case demonstrates the "collapse" of the "sliding Na_2O scale" concept as one transitions from a 25 – 41% WL interval with Frit 320 to the complete elimination of the operating window with a 1% increase in Na_2O content in the frit. The difference is that Frit 431 has 1 wt% higher Na_2O (and 1 wt% lower SiO_2) than Frit 320, which demonstrates the sensitivity of the PCCS model interactions to slight changes in frit composition and the need to consider robustness to compositional variation during the frit selection process.

- The "Max Al" and "Max Ti" sludge options provide operating windows from 25% WL to the low-to-mid 50%'s. These options may be attractive from a paper study perspective but issues associated with melt rate need to be addressed prior to further exploring these blending options or scenarios. More specifically, the high Al_2O_3 content of the "Max Al" could impede melt rate which may make that blending strategy less attractive.
- In terms of a "troublesome" sludge option, there do not appear to be any 1100 Canister blending options that meet this subjective criterion (i.e., maximum upper WL of ≤ 40% for all frits).

5.3 1200 Canister Options

Table 5-3 provides a summary of the MAR results for the 1200 Canister Options.[12] The shading of the table follows the pattern used in Table 5-2. As with the 1100 canister options, the use of the proposed durability limits allows higher alkali frits to be investigated relative to the use of the current limits. This is demonstrated by Lilliston's (2005) identifying Frit 418 as a "leading" candidate (yellow shaded cells) for all eight 1200 canister options with the current durability limits while this assessment against the proposed limits allows the use higher alkali frits for each sludge option. Based on model predictions, use of the higher alkali frits does allow higher WLs to be obtained for all 1200 canister options. A second potential advantage may be an improved melt rate given historical trends between melt rate and total alkali in the frit.

In general, the results for the 1200 canister options suggest that typical operating windows cover WLs from 25 to the mid-40%'s or low-50%'s. For most of the sludge options (all but 2 – "Min Ce" and "Min Mg"), as higher alkali frits are used, the resulting glass systems transition from being T_L limited at the maximum WL to being low η limited. Again, this trend was anticipated with the use of the "sliding Na_2O scale" concept. As in previous assessments, as one transitions toward the more alkali-rich frits, the gradual reduction in T_L allows higher WLs to be accessed until predictions of low viscosity become the limiting property.

As with the 1100 canister options, the cornerstone frits (Frit 418 and Frit 320) also show robustness as their use does result in projected operating windows (perhaps not optimal) for all eight options being considered. The challenge for the frit selection process will be to assess the robustness of a candidate frit to anticipated compositional changes and then use experimental melt rate data to select an optimal system that is robust and yields high throughputs.

In addition to the general comparisons noted above, there are a few specific systems in the 1200 canister options that should be mentioned or discussed.

- Based on the model predictions, it appears that a frit change would not be required between the SB4 1200 canister baseline and the 2nd transfer baseline.
- The "Min Al" case demonstrates the "collapse" of the "sliding Na_2O scale" concept as one transitions from a 25 – 42% WL interval with Frit 320 to almost complete elimination of the operating window (35 – 39% WL) with a 1% increase in Na_2O content in the frit (Frit 431). Again, this highlights the sensitivity of the PCCS model interactions to slight changes in frit composition and the need to consider robustness to compositional variation during the frit selection process.
- The "Max Al" and "Max Mg" sludge options provide operating windows from 25% WL to the low-to-mid 50%'s. These options may be attractive from a paper study perspective, but

[12] See Table A1 for more details associated with these systems. In addition, Table A1 includes the use of Frit 441 (15% Na_2O) with all SB4 options which are not summarized in Table 5-3.

issues associated with melt rate need to be addressed prior to these blending options or scenarios being explored further. More specifically, the high Al_2O_3 content of the "Max Al" could impede melt rate which may make that blending strategy less attractive.

- In terms of a "troublesome" sludge option, there does not appear to be any 1200 Canister blending option that meets this subjective criterion (i.e., maximum upper WL of ≤ 40% for all frits). That is, a frit can be selected for each option to provide a relatively large operating window that has an upper WLs that exceeds the 40% mark.

Table 5-3. 1200 Canister Options - MAR Results

	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431	Lilliston (2005)
% Na_2O (in frit)	8	9	10	11	12	13	
Baseline	25 -41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L/low η)	25 – 42 (low η)	Frit 418, 39.7%
2nd transfer baseline	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 44 (low η)	Frit 418, 39.1%
Min Al	25 – 39 (T_L)	25 – 40 (T_L)	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L/low η)	(ΔG_P) 35 – 39 (low η)	Frit 418, 37.6%
Max Al	(high η) 29 – 53 (T_L)	25 – 54 (T_L)	25 – 54 (T_L)	25 – 55 (T_L)	25 – 56 (T_L/low η)	25 – 53 (low η)	Frit 418, 50.3%
Max Ni	25 – 36 (T_L)	25 – 37 (T_L)	25 – 38 (T_L)	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L/low η)	Frit 418, 35.4%
Min Ce	(high η) 26 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L)	Frit 418, 40.0%
Min Mg	25 – 38 (T_L)	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 42 (T_L)	Frit 418, 36.9%
Max Mg	(high η) 26 – 51 (T_L)	25 – 52 (T_L)	25 – 53 (T_L)	25 – 54 (T_L/low η)	25 – 51 (low η)	25 – 48 (low η)	Frit 418, 48.8%

5.4 Impact of the SO_4 Solubility Limit

The projected operational windows shown in Table 5-1 through Table 5-3 were based on MAR assessments of the predicted properties. As previously noted, a SO_4 solubility limit was not activated for this assessment and therefore did not or could not restrict or influence the projected operating windows. Previous SO_4 solubility limits (in glass) have been set at 0.4 wt% (for SB1 and SB2) and 0.6 wt% (for SB3). The 0.6 wt% limit was specifically established for the Frit 418 – SB3 system (Peeler et al. (2004)) and may not be applicable for the SB4 system. A program is currently in progress to set the SO_4 solubility limit for SB4, which is highly dependent upon the overall glass composition (sludge composition, frit selection, and WL all play a role). Table 5-4 provides guidance on the impact of the SO_4 solubility limit on projected operating windows for SB4. In this table, the SO_4 limit is varied from 0.4 to 0.6 wt% (in 0.1% increments) and the maximum WL that could be obtained (based solely on the assumed

SO_4 limit) is calculated based on the nominal SO_4 content in sludge. For example, consider the SB4-only Baseline option where the normalized SO_4 concentration in sludge is 1.098 wt% (see Table 4-2). If the SO_4 solubility limit were set at 0.4 wt% (in glass), a maximum WL of 36.4% would be achievable (i.e., 0.4 / 1.098 * 100 = 36.4%) at which higher WLs would exceed the 0.4 wt% limit. Comparing this upper WL to those projected in Table 5-1 through Table 5-3, the 0.4 wt% SO_4 limit would further restrict the projected operating windows for almost all frit/sludge combinations.

Table 5-4. Maximum WLs for Each SB4 Options as a Function of the SO_4 Solubility Limit.

Type	Sludge SO_4 (wt%)	MAX WL 0.4	MAX WL 0.5	MAX WL 0.6
SB4 Only Baseline	1.098	36.4	45.5	54.6
SB4 Only Min Al	1.095	36.5	45.7	54.8
SB4 Only Max Al	1.109	36.1	45.1	54.1
1100 Can Baseline	1.099	36.4	45.5	54.6
1100 Can 2nd Transfer, Baseline	1.098	36.4	45.5	54.6
1100 Can Min	1.097	36.5	45.6	54.7
1100 Can Max Al	1.104	36.2	45.3	54.3
1100 Can Min Ce	1.097	36.5	45.6	54.7
1100 Can Min Fe	1.100	36.4	45.5	54.5
1100 Can Max Mg	1.099	36.4	45.5	54.6
1100 Can Max Ni	1.095	36.5	45.6	54.8
1100 Can Max Ti	1.103	36.3	45.3	54.4
1200 Can Baseline	1.098	36.4	45.5	54.6
1200 Can 2nd Transfer, Baseline	1.098	36.4	45.5	54.6
1200 Can Min Al	1.096	36.5	45.6	54.7
1200 Can Max Al	1.105	36.2	45.3	54.3
1200 Can Max Ni	1.095	36.5	45.6	54.8
1200 Can Min Ce	1.100	36.4	45.5	54.5
1200 Can Min Mg	1.097	36.5	45.6	54.7
1200 Can Max Mg	1.104	36.2	45.3	54.4

Table 5-5 summarizes the impact of the SO_4 solubility limit on the 1100 canister baseline option. The first column (labeled SO_4) indicates the assumed SO_4 limit (either "not activated", 0.4, 0.5, or 0.6). When the SO_4 limit is "not activated", the projected operating windows are identical to those shown in Table 5-2 (typical WL intervals from 25 – mid-40%'s). When a 0.4 wt% SO_4 limit is imposed in PCCS, the impact is significant as SO_4 becomes the upper WL limiting property for this option (i.e., regardless of the frit selection, the maximum WLs would be limited to 36%). Imposing a 0.5 or 0.6 wt% SO_4 limit in PCCS does not limit the projected windows for the 1100 canister baseline option (these systems remain either T_L or low viscosity limited – the one exception is the Frit 417, 1100 Canister Baseline option with a 0.5 wt% SO_4 limit). For this system, the projected operating window remains the same (relative to the "not activated" case) but now both T_L and SO_4 are limiting properties at 46% WL.

Table 5-5. 1100 Canister Baseline Option - MAR Results with SO_4 Activated

SO_4	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431
Not activated	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 44 (low η)	(ΔG_P) 27 – 41 (low η)
0.4	25 – 36 (SO_4)	25 – 36 (SO_4)	25 – 36 (SO_4)	25 – 36 (SO_4)	25 – 36 (SO_4)	(ΔG_P) 27 – 36 (SO_4)
0.5	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L/ SO_4)	25 – 44 (low η)	(ΔG_P) 27 – 41 (low η)
0.6	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 44 (low η)	(ΔG_P) 27 – 41 (low η)

Although the impact of the various SO_4 solubility limits is not summarized in tabular form for all 20 options, the most significant impact would be the imposition of a 0.4 wt% limit. This would have a significant (negative) impact on the projected operating windows for almost all sludge options being considered – limiting upper WLs to 36% or less. The 0.5 wt% limit (coupled with the nominal SO_4 concentrations assumed in the sludge) becomes a limiting factor at ~45% WL. Most of the operating windows would not be impacted with the 0.5 wt% SO_4 limit. The exceptions include the 1100 Canister "Max Al" and "Max Ti" options and the 1200 canister "Max Al" and "Max Mg" options. Upper WLs for these blending options with the SO_4 limit deactivated exceed the 45% WL mark.

Obviously the least imposing SO_4 limit or constraint would be the 0.6 wt% case – which would allow projected operating windows to exceed ~54% WL prior to SO_4 becoming a limiting factor based on the nominal SO_4 values used. With the exception of the "Max Al" cases for all three primary classifications (SB4-only, 1100 canister, and 1200 canister), the 0.6 wt% SO_4 limit would not restrict projected operating windows. For the cases for which a 0.6 wt% limit would restrict the model-based upper WL, it is unlikely that DWPF would process SB4 at WLs this high (> 54%) given the dependence or interaction between melt rate and WL and the impact on waste throughput.

5.5 Frittability of Candidate Frits

One factor to be considered during frit selection is the ability to manufacture or produce the desired frit composition. Based on the six candidate frits being evaluated, there are no primary concerns associated with the fabrication potential. The most refractory frit utilized in this assessment of SB4 options was Frit 418, which has been manufactured by a vendor and used to support the processing of SB3.

5.6 Impact of Washing

Selecting among alternative washing scenarios for the HLW that is to comprise SB4 may be one of the challenging decisions facing the CBU as it develops the integrated flowsheet. Technical issues associated with the consideration of less washing include SO_4 solubility, Chemical Process Cell (CPC) processing (including rheology, acid addition strategies, H_2 generation, and nitrate/nitrite destruction), and the ability to counter the increased Na_2O concentration in sludge versus that in frit. These technical issues must be balanced with the fact that the ability to transfer a less washed sludge also has beneficial impacts to the tank farm system and evaporators (less water being transferred). To provide some feedback to CBU on the impact of going to less-washed scenarios for the 20 cases outlined in this report, additional SB4 options were developed and evaluated as part of this study. Specifically, for each of the 20 cases provided by Lilliston (2005), a "1 less-washed" case was considered using the assumption that if a sludge is washed one less time its elemental Na concentration would increase by 2 wt% - all other components being renormalized.[13] More specifically, the elemental Na concentration was increased by 2%, then the elemental compositions were converted to oxides by multiplying the concentrations by the appropriate gravimetric factor. Since SO_4 is a component that is specifically impacted by washing and has the potential to impact waste loading, an adjusted SO_4 level was used for the one less wash case. A 1.14 wt% SO_4 was added to each sludge option and the compositions were normalized.[14] This led to the 1 less-washed sludge compositions listed in Table 5-6. It is noted that the 20 options provided by Lilliston (2005) were based on different tank blending strategies and did not include various washing scenarios.

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[13] The assumptions used to develop the "1-less" wash cases are known not to fully represent the actual compositional impacts due to washing (i.e., the concentrations of other oxides besides Na_2O will be affected). However, the compositional information supplied by Lilliston (2005) was based on a nominal wash endpoint. Based on the results of the MAR assessments, the use of the "Na_2O sliding scale" concept does provide the opportunity to assess the impact of less washing. That is, as the sludge becomes more Na_2O -rich, one would expect the use of more refractory frits (i.e., those containing less Na_2O).

[14] Based on personnel communication with J.M. Gillam, the SO_4 value for a "1 less washed" scenario was projected to be 1.14 wt% (compared to the "baseline" wash with a 1.09 wt% SO_4 value). Therefore, not only did the Na_2O concentration change for the "1 less washed" sludges but the SO_4 value as well. This number reflects a change in SO_4 supernate from 0.0220 to 0.0235 M, with the respective insoluble solids and supernate density changes.

Table 5-6. SB4 Blending Options – "1 Less Wash" as Normalized Oxide Concentrations (wt%)

	SB4 Only Baseline	SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	1100 Can Baseline	1100 Can 2nd Transfer, Baseline	1100 Can Min Al, Na; Max Ce, Fe, Mn, U	1100 Can Max Al, Na; Min Mn, Ni, U	1100 Can Min Ce, Mg, Ti	1100 Can Min Fe	1100 Can Max Mg	1100 Can Max Ni	1100 Can Max Ti	1200 Can Baseline	1200 Can 2nd Transfer, Baseline	1200 Can Min Al, Na; Max Ce, Fe, Mn, U	1200 Can Max Al, Na; Min Fe, Mn, Ni, U	1200 Can Max Ni	1200 Can Min Ce	1200 Can Min Mg, Ti	1200 Can Max Mg, Ti
Oxide	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	Wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
Al_2O_3	30.237	24.903	45.398	22.065	24.472	18.998	30.676	25.815	27.703	21.076	21.820	27.706	23.619	24.888	20.020	32.357	21.851	27.893	25.641	29.416
BaO	0.182	0.220	0.079	0.157	0.164	0.172	0.105	0.180	0.153	0.158	0.195	0.111	0.161	0.165	0.180	0.101	0.195	0.153	0.179	0.107
CaO	1.615	1.551	1.676	2.173	1.979	2.207	2.150	1.743	1.860	2.202	1.838	2.265	2.045	1.944	2.072	2.083	1.833	1.845	1.758	2.196
Ce_2O_3	0.185	0.182	0.184	0.202	0.195	0.204	0.200	0.186	0.188	0.202	0.190	0.204	0.197	0.194	0.198	0.197	0.189	0.188	0.186	0.201
Cr_2O_3	0.278	0.295	0.231	0.245	0.254	0.250	0.223	0.266	0.249	0.242	0.270	0.222	0.250	0.255	0.257	0.222	0.270	0.249	0.265	0.222
CuO	0.077	0.082	0.056	0.082	0.079	0.085	0.070	0.077	0.072	0.080	0.082	0.073	0.080	0.079	0.083	0.067	0.082	0.072	0.077	0.071
Fe_2O_3	19.852	21.390	14.802	25.309	23.379	26.593	22.102	21.595	21.562	25.819	23.550	23.796	24.049	23.035	25.479	21.130	23.510	21.411	21.740	22.804
K_2O	1.860	1.459	2.983	0.997	1.262	0.740	1.660	1.448	1.523	0.883	1.104	1.386	1.167	1.307	0.869	1.813	1.106	1.542	1.428	1.541
La_2O_3	0.077	0.078	0.066	0.090	0.085	0.093	0.083	0.080	0.079	0.090	0.084	0.088	0.087	0.084	0.089	0.081	0.084	0.078	0.080	0.085
MgO	0.343	0.325	0.399	1.890	1.386	2.042	1.781	0.853	1.218	2.089	1.125	2.087	1.567	1.300	1.714	1.609	1.117	1.187	0.894	1.913
MnO	4.989	5.764	3.183	5.681	5.416	6.102	4.652	5.373	5.230	5.942	5.848	4.995	5.521	5.379	6.022	4.471	5.853	5.219	5.395	4.812
Na_2O	22.101	21.536	23.547	24.079	24.056	23.817	24.909	23.869	24.218	24.019	23.598	24.761	24.065	24.052	23.739	24.986	23.596	24.220	23.873	24.839
NiO	5.708	7.565	1.215	3.615	4.247	4.221	1.417	5.447	4.147	3.683	5.903	1.469	4.021	4.355	4.824	1.389	5.918	4.182	5.387	1.440
PbO	0.195	0.168	0.258	0.161	0.170	0.147	0.197	0.172	0.178	0.153	0.156	0.185	0.166	0.171	0.149	0.203	0.156	0.178	0.172	0.191
SO_4	1.118	1.114	1.129	1.118	1.118	1.116	1.124	1.117	1.119	1.118	1.115	1.123	1.118	1.118	1.116	1.124	1.115	1.119	1.117	1.123
SiO_2	2.343	1.989	3.281	2.659	2.537	2.544	3.117	2.321	2.608	2.677	2.223	3.101	2.587	2.522	2.436	3.133	2.224	2.607	2.335	3.118
ThO_2	0.039	0.030	0.064	0.034	0.035	0.030	0.048	0.035	0.040	0.033	0.029	0.044	0.034	0.035	0.029	0.049	0.029	0.040	0.034	0.046
TiO_2	0.012	0.010	0.021	0.021	0.018	0.020	0.024	0.014	0.018	0.022	0.015	0.025	0.019	0.018	0.018	0.024	0.015	0.018	0.015	0.025
U_3O_8	8.370	10.887	1.137	9.026	8.746	10.209	5.133	9.002	7.467	9.130	10.430	6.020	8.850	8.701	10.293	4.640	10.434	7.436	9.018	5.519
ZnO	0.111	0.123	0.063	0.125	0.119	0.132	0.098	0.114	0.103	0.122	0.125	0.106	0.120	0.118	0.128	0.093	0.125	0.102	0.114	0.100
ZrO_2	0.308	0.330	0.229	0.271	0.281	0.277	0.232	0.293	0.262	0.260	0.301	0.234	0.275	0.281	0.284	0.229	0.300	0.261	0.291	0.230
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.0#3

As an example of the impact of less washing on the composition of a sludge option, consider the SB4 Only Baseline case. Based on the nominal wash endpoint, this case had 19.996 wt% Na_2O on a normalized basis (see Table 5-1). The "1 less-washed" case has 22.101 wt% Na_2O concentration on a normalized basis. Given the higher Na_2O concentrations in these "less washed" cases, the expectation is that frits with less Na_2O must be used to "compensate" for the increased Na_2O concentration in sludge in order to retain projected operating windows. These "less-washed" options for the 20 SB4 cases were combined with the 6 frits listed in Table 4-3 and MAR assessments were performed. It should be noted that the SO_4 concentrations in glass were used in the model-based assessments but a SO_4 solubility limit was not activated in determining the projected operating windows. As previously demonstrated, the impact of the SO_4 solubility limit can be significant.

Table A2 in the Appendix provides a summary of the MAR results for the 1 less-washed case for the 20 SB4 options. Tables 5-7, 5-8, and 5-9 summarize the projected operating windows for the "1 less washed" SB4-only, 1100 canister, and 1200 canister cases, respectively.

Table 5-7. Impact of Washing Strategy on Operating Windows for SB4-Only Options - MAR Results

Case	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431
Baseline	(high η) 28 - 38 (T_L)	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)
Max Al	-	-	(high η) 43 – 60	25 – 60	25 – 60	25 – 60
Min Al	25 – 34 (T_L)	25 – 35 (T_L)	25 – 36 (T_L)	25 – 37 (T_L)	25 – 37 (T_L)	25 – 38 (T_L)

Table 5-8. Impact of Washing Strategy on Operating Windows for 1100 Canister Options - MAR Results

	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431
Baseline	25 – 45 (T_L)	25 – 46 (T_L)	25 – 46 (low η)	25 – 43 (low η)	25 – 41 (low η)	-
2nd transfer baseline	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L/low η)	25 – 43 (low η)	-
Min Al	25 – 43 (T_L)	25 – 44 (T_L)	25 – 44 (low η)	25 – 41 (low η)	-	-
Max Al	25 – 56 (T_L)	25 – 56 (low η)	25 – 54 (low η)	25 – 51 (low η)	25 – 49 (low η)	25 – 46 (low η)
Min Ce	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	(ΔG_P) 41 – 42 (low η)
Min Fe	25 – 44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L)	25 – 47 (T_L)	25 – 47 (low η)	(ΔG_P) 33 – 44 (low η)
Max Mg	25 – 44 (T_L)	25 – 45 (T_L)	25 – 45 (low η)	25 – 43 (low η)	25 – 34 (ΔG_P)	-
Max Ni	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 42 (low η/T_L)	-
Max Ti	25 – 54 (T_L)	25 – 53 (low η)	25 – 50 (low η)	25 – 48 (low η)	25 – 45 (low η)	(ΔG_P) 38 – 42 (low η)

Table 5-9. Impact of Washing Strategy on Operating Windows for 1200 Canister Options - MAR Results

	Frit 418	Frit 426	Frit 425	Frit 417	Frit 320	Frit 431
Baseline	25 -44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L)	25 – 45 (low η)	25 – 42 (low η)	-
2nd transfer baseline	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L/ low η)	25 – 44 (low η)	-
Min Al	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (low η)	25 – 42 (low η)	25 – 30 (ΔG_P)	-
Max Al	(high η) 26 – 52 (T_L)	25 – 58 (T_L/ low η)	25 – 56 (low η)	25 – 54 (low η)	25 – 51 (low η)	25 – 48 (low η)
Max Ni	25 – 39 (T_L)	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 42 (T_L/low η)	-
Min Ce	25 – 44 (T_L)	25 – 45 (T_L)	25 – 46 (T_L)	25 – 47 (T_L)	25 – 47 (low η)	(ΔG_P) 32 – 44 (low η)
Min Mg	25 – 40 (T_L)	25 – 41 (T_L)	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	-
Max Mg	25 – 55 (T_L)	25 – 55 (low η)	25 – 52 (low η)	25 – 50 (low η)	25 – 47 (low η)	(ΔG_P) 29 – 44 (low η)

In general (and compared to the nominal sludge options previously discussed), the results suggest that as sludge becomes "enriched" in Na_2O (i.e., as less-washed versions of these sludge options are considered) there is less dependency on higher alkali frits to yield glass systems with attractive operating windows. More specifically, coupling high alkali frits with the higher alkali sludges typically results in predictions of low viscosity or durability either dramatically reducing the operating window size or completely eliminating the window. Consider the 1100 canister baseline options with Frit 320 and Frit 431. For the nominal wash scenario, both frits yield relatively large operating windows of 25 – 44% and 27 – 41%, respectively (see Table 5-2). When the "1 less washed" 1100 canister baseline option is utilized, the model based predictions restrict the use of Frit 431 (i.e., no operating window due to predictions of low viscosity and/or durability) and show a negative impact when Frit 320 is considered (reduces the upper WL to 41% down from 44%). Again, this needed shift (reduction) in the frit Na_2O content to compensate for the higher Na_2O content in the sludge was expected and conforms to the use of the "sliding Na_2O scale" concept.

Although the use of higher alkali frits is somewhat limited when considering the "less washed" sludge options, the projected operating windows for the more refractory frits appear to be enhanced relative to the nominal wash cases. Again, consider the 1100 canister baseline option coupled with Frit 418, Frit 426, Frit 425, and Frit 417. Table 5-10 summarizes the projected operating windows for the 1100 canister baseline nominal and "1 less washed" cases. The results indicate that the projected operating windows are enhanced with the use of the "less washed" sludge for each frit. This observation is in-line with preliminary assessments which indicated that the ability of the "sliding Na_2O scale" concept to account for or balance the alkali content was less effective for sludges containing less Na_2O. The hypothesis is based on the need to have more Na_2O in the sludge than in the frit. If there is more Na_2O in the sludge than in the frit, then as WL increases, the Na_2O content in the glass increases which (in general) should reduce T_L and provide access to higher WLs for T_L-limited systems. If the Na_2O content in the sludge is less than that in the frit, as WL increases, the glass (in general) becomes more refractory, and predictions of T_L and/or high viscosity not only restrict access to higher WLs but begin to collapse the projected operating window altogether.

Table 5-10. Impact of Washing on the 1100 Canister Baseline Sludge Options.

	Frit 418	**Frit 426**	**Frit 425**	**Frit 417**
Baseline	25 – 42 (T_L)	25 – 43 (T_L)	25 – 44 (T_L)	25 – 45 (T_L)
Baseline “1 less wash”	25 – 45 (T_L)	25 – 46 (T_L)	25 – 46 (T_L/low η)	25 – 43 (low η)

Again, numerous comparisons can be made between the nominal and “less washed” SB4 options. Although the reader is encouraged to draw conclusions between or among various systems, the general results of the “washing” assessment suggest that frits are available that provide relatively large operating windows for the “less washed” cases. In fact, there appears to be some advantage of having more Na_2O in the sludge with respect to the ability of the existing frits to enhance the projected operating windows. These latter two statements are based solely on model-predictions and do not account for the potential impacts of SO_4 solubility issues, melt rate, and/or CPC processing issues that may necessitate a more-washed sludge.

6.0 SUMMARY

The model-based assessments of nominal Sludge Batch 4 (SB4) compositions suggest that a viable frit candidate does not appear to be a limiting factor as the Closure Business Unit (CBU) considers various tank blending options and/or washing strategies. This statement is based solely on the projected operating windows derived from model predictions and does not include assessments of SO_4 solubility or melt rate issues. The viable frit candidates covered a range of Na_2O concentrations (from 8% to 13%) using a "sliding Na_2O scale" concept (i.e., 1% increase in Na_2O being balanced by a 1% reduction in SiO_2), which effectively balanced the alkali content of the incoming sludge with that in the frit to maintain and/or increase the projected operating window size while potentially leading to improved melt rate and/or waste loadings. This strategy or approach allows alternative tank blending strategies and/or different washing scenarios to be considered and accounted for in an effective manner without wholesale changes to the frit composition.

In terms of projected operating windows, in general, the sludge / frit systems evaluated resulted in waste loading intervals from 25 to the mid-40%'s or even the mid-50%'s. The results suggest that a single frit could be selected for use with all 20 options which indicates some degree of frit robustness with respect to sludge compositional variation. In fact, use of Frit 418 or Frit 320 (the "cornerstone" frits given previous processing experience in the Defense Waste Processing Facility (DWPF)) are plausible for most (if not all) options being considered.

However, the frit selection process also needs to consider potential processing issues such as melt rate. Based on historical trends between melt rate and total alkali content, one may elect to use the frit with the highest alkali content that still yields an acceptable operating window. However, other constraints may restrict access to higher waste loading or the proposed blending option being considered (e.g., sulfate content of the high-level waste and/or Chemical Processing Cell (CPC) issues may necessitate a more-washed sludge).

Although various washing scenarios were not provided by Lilliston (2005), projected alternative washing scenarios for the 20 nominal options were developed using very basic or rudimentary assumptions. Specifically, for each of the 20 cases provided, a 1 "less-washed" case was developed using the assumption that if a sludge is washed one less time its elemental Na concentration would increase by 2 wt% - all other components being renormalized. The results of this assessment demonstrated the practicality of imposing or using the "sliding Na_2O scale" concept. As the sludge compositions become more Na_2O-rich, adjustments to Na_2O concentrations in frit can be made to accommodate the impact of "less washing" while retaining relatively large projected operating windows. Although these model-based assessments indicate the ability to accommodate "less washed" sludges, technical issues associated with SO_4 solubility and CPC processing (including rheology, acid addition strategies, H_2 generation, and nitrate/nitrite destruction) must be addressed. If no technical show-stoppers are identified, then a business decision regarding the ability to transfer a less-washed sludge to DWPF must be made in light of the potential beneficial impacts to the tank farm system and evaporators (less water being sent).

Based on the results of this assessment, use of the new durability limits do allow the possible use of higher alkali frits for a given sludge system. This is reflected in the fact the assessments performed by Lilliston and Shah (2004) suggest that more refractory frits (lower Na_2O content) would be the primary candidates for most SB4 options being considered. Their assessments were based on the use of the existing (more conservative) durability limits which restrict assess to higher alkali-based systems. With the use of the proposed durability limits by Edwards et al. (2003), access to higher alkali systems is observed, and assuming the trend between melt rate and total alkali content holds for the SB4 system, this could be extremely beneficial to DWPF in terms of enhanced melt rates and/or waste throughput. Again, the challenge will be to assess the robustness of a candidate frit to anticipated compositional changes and then use historical trends (coupled with experimental confirmation tests) with respect to melt rate to select an optimal system that is robust and yields high throughputs.

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8.0 APPENDIX A

Results of MAR Assessments for SB4 Options

Table A1. MAR Results and Various Predicted Properties for the Nominal SB4 Blending Options.

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
SB4 Only Baseline	320	25	40		TL	-11.6951	50.37	790.7	-10.8755	66.81	1000.1
SB4 Only Baseline	417	25	39		TL	-11.0022	59.3	801.9	-10.3665	76.71	998.2
SB4 Only Baseline	418	33	36	hvisc	TL	-8.7817	94.1	956	-8.7286	99.65	994.1
SB4 Only Baseline	425	25	38		TL	-10.3092	69.48	813.5	-9.839	87.75	996.6
SB4 Only Baseline	426	25	37		TL	-9.6162	81.04	825.5	-9.2931	100.03	995.2
SB4 Only Baseline	431	25	40		TL	-12.3881	43.6	779.8	-11.4299	57.97	990.6
SB4 Only Baseline	441	30	42	Del Gp	TL	-13.3623	30.72	837.9	-12.3739	39.66	995.7
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	320	25	60			-10.7009	90.55	721.4	-7.3962	95.19	971.9
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	417	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	418	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	425	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	426	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	431	25	60			-11.3938	78.95	713.5	-7.7658	83.64	968.9
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U	441	25	60			-12.7798	59.3	698.2	-8.505	63.89	962.8
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	320	25	35		TL	-12.0464	47.53	817.8	-11.6404	60.27	984.8
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	417	25	35		TL	-11.3534	54.8	830.5	-11.0398	69.32	997.1
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	418	27	32	hvisc	TL	-9.2672	88.53	907.4	-9.249	99.03	990.6
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	425	25	34		TL	-10.6604	64.61	843.6	-10.4614	79.42	994.7
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	426	25	33		TL	-9.9674	75.81	857.2	-9.8644	90.67	992.5
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	431	25	36		TL	-12.7394	39.94	805.6	-12.1912	52.21	987.9
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U	441	36	38	Del Gp	TL	-13.3739	27.72	965	-13.2373	29.43	994.7
1100 Can Baseline	320	25	44		lvisc	-12.7645	24.51	741.7	-12.5389	51.08	989.7
1100 Can Baseline	417	25	45		TL	-12.0715	27.03	752.8	-12.0189	58.85	1009.7
1100 Can Baseline	418	25	42		TL	-10.419	47.81	788.4	-9.9925	88.04	1008.2
1100 Can Baseline	425	25	44		TL	-11.5041	32.9	764.2	-11.3785	67.55	1008.9
1100 Can Baseline	426	25	43		TL	-10.9708	39.78	776.1	-10.6855	77.25	1008.4
1100 Can Baseline	431	27	41	Del Gp	lvisc	-13.4153	24.36	762.1	-13.1197	41.56	946.9
1100 Can Baseline	441	.	.			.	.	.	.	.	.

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1100 Can 2nd Transfer, Baseline	320	25	44		TL	-12.5731	28.43	752.7	-12.202	54.48	1000.9
1100 Can 2nd Transfer, Baseline	417	25	43		TL	-11.8801	34.42	763.7	-11.6948	62.71	999.6
1100 Can 2nd Transfer, Baseline	418	25	40		TL	-10.0625	58.93	799.2	-9.8011	93.6	997.4
1100 Can 2nd Transfer, Baseline	425	25	42		TL	-11.1871	41.41	775.1	-11.1692	71.92	998.6
1100 Can 2nd Transfer, Baseline	426	25	41		TL	-10.6251	49.54	786.9	-10.4941	82.19	997.8
1100 Can 2nd Transfer, Baseline	431	25	43		lvisc	-13.266	25.56	742	-12.7482	47.14	980.9
1100 Can 2nd Transfer, Baseline	441	.	.			.	.	.	.	.	.
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	320	25	41		lvisc	-12.9716	24.82	746.8	-12.9142	47.91	971.7
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	417	25	43		TL	-12.3803	25.94	758.4	-12.2786	55.24	1005.9
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	418	25	40		TL	-10.7002	46.32	795.8	-10.1996	82.86	1004.5
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	425	25	42		TL	-11.8388	31.68	770.4	-11.5856	63.47	1005.1
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	426	25	41		TL	-11.2787	38.42	782.9	-10.8926	72.64	1004.6
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	431	.	.			.	.	.	.	.	.
1100 Can Min Al, Na; Max Ce, Fe, Mn, U	441	.	.			.	.	.	.	.	.
1100 Can Max Al, Na; Min Mn, Ni, U	320	25	53		lvisc	-12.2079	25.61	715.3	-11.252	60.89	991.3
1100 Can Max Al, Na; Min Mn, Ni, U	417	25	54		TL	-11.5149	28.23	724.7	-10.7928	69.96	1003.9
1100 Can Max Al, Na; Min Mn, Ni, U	418	27	51	hvisc	TL	-9.5093	49.05	781.3	-9.4415	99.81	1002.5
1100 Can Max Al, Na; Min Mn, Ni, U	425	25	53		TL	-10.8219	34.14	734.4	-10.3834	80.09	1003.2
1100 Can Max Al, Na; Min Mn, Ni, U	426	25	52		TL	-10.1289	41.04	744.4	-9.9556	91.36	1002.7
1100 Can Max Al, Na; Min Mn, Ni, U	431	25	50		lvisc	-12.9008	25.27	706.1	-11.8164	52.79	963.7
1100 Can Max Al, Na; Min Mn, Ni, U	441	40	42	Del Gp	lvisc	-13.359	25.14	864.4	-13.2352	26.81	883.4
1100 Can Min Ce, Mg, Ti	320	25	41		TL	-12.4479	35.59	770.9	-12.0553	57.1	993.3
1100 Can Min Ce, Mg, Ti	417	25	41		TL	-11.7549	41.14	782.2	-11.5101	65.7	1003.3
1100 Can Min Ce, Mg, Ti	418	25	38		TL	-9.8374	68.85	818.6	-9.6759	97.92	1000.3
1100 Can Min Ce, Mg, Ti	425	25	40		TL	-11.0619	49.11	793.9	-10.971	75.31	1002
1100 Can Min Ce, Mg, Ti	426	25	39		TL	-10.4134	58.3	806	-10.3689	86.02	1001
1100 Can Min Ce, Mg, Ti	431	25	42		TL	-13.1409	29.52	760	-12.5666	49.43	995.2
1100 Can Min Ce, Mg, Ti	441	.	.			.	.	.	.	.	.
1100 Can Min Fe	320	25	45		TL	-12.3563	32.67	753.2	-11.7924	58.8	1002.1
1100 Can Min Fe	417	25	44		TL	-11.6634	39.25	763.8	-11.3031	67.62	1000.8

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1100 Can Min Fe	418	26	41	hvisc	TL	-9.7246	65.82	813.2	-9.5931	98.49	998.6
1100 Can Min Fe	425	25	43		TL	-10.9704	46.88	774.8	-10.7954	77.47	999.8
1100 Can Min Fe	426	25	42		TL	-10.2774	55.7	786.1	-10.2692	88.44	999
1100 Can Min Fe	431	25	46		TL	-13.0493	27.03	742.8	-12.2631	50.94	1003.6
1100 Can Min Fe	441	.	.			.	.	.	.	.	.
1100 Can Max Mg	320	25	43		lvisc	-12.8438	24.59	742	-12.6872	50.02	982
1100 Can Max Mg	417	25	44		TL	-12.161	27.12	753.2	-12.1508	57.64	1002.8
1100 Can Max Mg	418	25	41		TL	-10.524	48	789.2	-10.0718	86.29	1001.2
1100 Can Max Mg	425	25	43		TL	-11.6338	33.01	764.8	-11.4578	66.18	1001.9
1100 Can Max Mg	426	25	42		TL	-11.0881	39.93	776.8	-10.7648	75.7	1001.4
1100 Can Max Mg	431	32	40	Del Gp	lvisc	-13.4112	24.45	835.2	-13.2677	34.13	937.7
1100 Can Max Mg	441	.	.			.	.	.	.	.	.
1100 Can Max Ni	320	25	40		TL	-12.7227	30.97	774.9	-12.5195	52.27	997.3
1100 Can Max Ni	417	25	39		TL	-12.0297	37.42	786.9	-11.9694	60.21	995.6
1100 Can Max Ni	418	25	36		TL	-10.2083	63.73	825.4	-9.9507	90.06	992.2
1100 Can Max Ni	425	25	38		TL	-11.4009	44.94	799.3	-11.3367	69.11	994.2
1100 Can Max Ni	426	25	37		TL	-10.8138	53.67	812.1	-10.6437	79.03	993
1100 Can Max Ni	431	25	41		TL lvisc	-13.4157	25.47	763.4	-13.0511	45.19	999.4
1100 Can Max Ni	441	.	.			.	.	.	.	.	.
1100 Can Max Ti	320	25	49		lvisc	-12.4189	25.2	715.4	-11.8022	56.83	973.1
1100 Can Max Ti	417	25	52		lvisc	-11.7259	25.05	725.1	-11.2816	65.36	1003
1100 Can Max Ti	418	25	50		TL	-9.9286	42.27	756.3	-9.647	97.3	1009
1100 Can Max Ti	425	25	52		TL	-11.0329	28.94	735.2	-10.8381	74.9	1009.6
1100 Can Max Ti	426	25	51		TL	-10.3926	35.09	745.6	-10.34	85.51	1009.2
1100 Can Max Ti	431	25	46		lvisc	-13.1119	24.9	705.9	-12.3783	49.22	941
1100 Can Max Ti	441	.	.			.	.	.	.	.	.
1200 Can Baseline	320	25	45		TL lvisc	-12.6418	25.73	748.7	-12.3063	53.27	1007.5
1200 Can Baseline	417	25	44		TL	-11.9489	31.29	759.8	-11.8056	61.34	1006.3
1200 Can Baseline	418	25	41		TL	-10.1928	54.26	795.3	-9.8699	91.61	1004.4
1200 Can Baseline	425	25	43		TL	-11.2865	37.82	771.2	-11.2559	70.36	1005.4

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1200 Can Baseline	426	25	42		TL	-10.7489	45.43	783	-10.5629	80.43	1004.7
1200 Can Baseline	431	25	42		lvisc	-13.3348	25.43	738.1	-12.8925	46.08	965.7
1200 Can Baseline	441	.	.			.	.	.	.	.	.
1200 Can 2nd Transfer, Baseline	320	25	44		TL	-12.5407	29.18	754.4	-12.1451	55.1	1002.5
1200 Can 2nd Transfer, Baseline	417	25	43		TL	-11.8478	35.28	765.4	-11.6393	63.42	1001.2
1200 Can 2nd Transfer, Baseline	418	25	40		TL	-10.0108	60.2	800.8	-9.7688	94.61	998.9
1200 Can 2nd Transfer, Baseline	425	25	42		TL	-11.1548	42.4	776.8	-11.1149	72.72	1000.1
1200 Can 2nd Transfer, Baseline	426	25	41		TL	-10.5721	50.67	788.6	-10.4618	83.09	999.4
1200 Can 2nd Transfer, Baseline	431	25	44		lvisc	-13.2337	25.09	743.7	-12.6625	47.68	993.4
1200 Can 2nd Transfer, Baseline	441	.	.			.	.	.	.	.	.
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	320	25	42		TL lvisc	-12.8827	25.2	756.8	-12.7612	49.45	997.7
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	417	25	41		TL	-12.2232	30.73	768.6	-12.1897	57.01	996.3
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	418	25	39		TL	-10.5281	51.42	806.4	-10.1107	85.42	1006.4
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	425	25	40		TL	-11.6667	37.24	780.7	-11.4967	65.47	995.2
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	426	25	40		TL	-11.1123	42.87	793.3	-10.8037	74.91	1006.7
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	431	35	39	Del Gp	lvisc	-13.4118	25.02	896.7	-13.3463	29.81	949.8
1200 Can Min Al, Na; Max Ce, Fe, Mn, U	441	.	.			.	.	.	.	.	.
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	320	25	56		TL lvisc	-12.0878	25.44	714.8	-10.8808	63.34	1002.8
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	417	25	55		TL	-11.3949	30.82	724	-10.5039	72.74	1001.9
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	418	29	53	hvisc	TL	-9.308	50.72	803.9	-9.2605	100.19	1006.5
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	425	25	54		TL	-10.7019	37.1	733.5	-10.1086	83.23	1001.2
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	426	25	54		TL	-10.0089	42.54	743.3	-9.6835	94.89	1006.8
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	431	25	53		lvisc	-12.7808	25.15	705.8	-11.4318	54.94	978.1
1200 Can Max Al, Na; Min Fe, Mn, Ni, U	441	37	45	Del Gp	lvisc	-13.3669	25.01	831.6	-12.8337	31.5	905.6
1200 Can Max Ni	320	25	40		TL	-12.7206	31.04	775.1	-12.5162	52.32	997.6
1200 Can Max Ni	417	25	39		TL	-12.0276	37.5	787	-11.9662	60.28	995.8
1200 Can Max Ni	418	25	36		TL	-10.2053	63.84	825.6	-9.9487	90.16	992.4
1200 Can Max Ni	425	25	38		TL	-11.3977	45.03	799.4	-11.3346	69.19	994.4
1200 Can Max Ni	426	25	37		TL	-10.8108	53.77	812.3	-10.6417	79.12	993.2
1200 Can Max Ni	431	25	41		TL lvisc	-13.4136	25.53	763.5	-13.0477	45.24	999.6

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1200 Can Max Ni	441	.	.			.	.	.	.	.	.
1200 Can Min Ce	320	25	45		TL	-12.3425	33.08	753.6	-11.7675	59.11	1002.3
1200 Can Min Ce	417	25	44		TL	-11.6495	39.71	764.2	-11.2788	67.97	1001
1200 Can Min Ce	418	26	41	hvisc	TL	-9.7019	66.48	813.6	-9.5788	98.99	998.8
1200 Can Min Ce	425	25	43		TL	-10.9565	47.41	775.2	-10.7717	77.86	1000
1200 Can Min Ce	426	25	42		TL	-10.2636	56.29	786.6	-10.246	88.88	999.2
1200 Can Min Ce	431	25	46		TL	-13.0355	27.38	743.3	-12.2377	51.2	1003.8
1200 Can Min Ce	441	.	.			.	.	.	.	.	.
1200 Can Min Mg, Ti	320	25	42		TL	-12.4624	33.93	769.9	-12.0552	56.83	1003.7
1200 Can Min Mg, Ti	417	25	41		TL	-11.7695	40.75	781.2	-11.534	65.4	1002.2
1200 Can Min Mg, Ti	418	25	38		TL	-9.8596	68.29	817.6	-9.6905	97.48	999.2
1200 Can Min Mg, Ti	425	25	40		TL	-11.0765	48.67	792.9	-10.9944	74.97	1000.9
1200 Can Min Mg, Ti	426	25	39		TL	-10.4362	57.8	805	-10.3835	85.63	999.9
1200 Can Min Mg, Ti	431	25	42		TL	-13.1554	29.22	759	-12.5911	49.2	994.1
1200 Can Min Mg, Ti	441	.	.			.	.	.	.	.	.
1200 Can Max Mg, Ti	320	25	51		lvisc	-12.2967	25.75	715.3	-11.5016	59.17	982.3
1200 Can Max Mg, Ti	417	25	54		TL lvisc	-11.6037	25.65	724.9	-10.9848	68.02	1009.7
1200 Can Max Mg, Ti	418	26	51	hvisc	TL	-9.6905	45.17	769.1	-9.5311	98.98	1008.4
1200 Can Max Mg, Ti	425	25	53		TL	-10.9107	31.17	734.7	-10.5718	77.89	1009
1200 Can Max Mg, Ti	426	25	52		TL	-10.2178	37.64	744.9	-10.1404	88.89	1008.6
1200 Can Max Mg, Ti	431	25	48		lvisc	-12.9897	25.39	706	-12.0738	51.28	952.5
1200 Can Max Mg, Ti	441	.	.			.	.	.	.	.	.

Table A2. MAR Results and Various Predicted Properties for the "1 Less Washed" SB4 Blending Options.

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
SB4 Only Baseline (1 less wash)	320	25	42		TL	-12.2102	40.84	771.7	-11.6314	61.97	995.9
SB4 Only Baseline (1 less wash)	417	25	41		TL	-11.5172	48.59	782.6	-11.1203	71.23	994.3
SB4 Only Baseline (1 less wash)	418	28	38	hvisc	TL	-9.4761	79.31	863.2	-9.4469	99.89	991.1
SB4 Only Baseline (1 less wash)	425	25	40		TL	-10.8242	57.49	793.8	-10.5907	81.56	992.9
SB4 Only Baseline (1 less wash)	426	25	39		TL	-10.1312	67.69	805.4	-10.0426	93.07	991.9
SB4 Only Baseline (1 less wash)	431	25	43		TL	-12.9031	34.14	761.1	-12.124	53.71	997.7
SB4 Only Baseline (1 less wash)	441	40	43	Del Gp	lvisc	-13.3626	25.11	946.7	-13.1773	27.62	980.5
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	320	25	37		TL	-12.5502	39.59	796.8	-12.3049	56.06	985.3
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	417	25	37		TL	-11.8572	45.74	809	-11.7228	64.54	997
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	418	25	34		TL	-9.9269	75.83	848.4	-9.7783	96.32	992.1
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	425	25	36		TL	-11.1642	54.43	821.7	-11.1426	74.02	995
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	426	25	35		TL	-10.544	64.41	834.8	-10.4712	84.59	993.4
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	431	25	38		TL	-13.2432	32.94	785	-12.8573	48.51	987.9
SB4 Only Min Al, Na, Mg, Ti; Max Ce, Fe, Mg, Ni, U (1 less wash)	441	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	320	25	60			-11.2478	66.53	707	-8.709	83.27	954.9
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	417	25	60			-10.5548	75.84	715	-8.3394	95.28	958
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	418	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	425	43	60	hvisc		-8.8888	86.16	879.7	-7.9698	99.64	961
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	426	.	.			.	.	.	.	.	.
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	431	25	60			-11.9408	58.17	699.3	-9.0786	72.51	951.9
SB4 Only Max Al, Na, Mg, Ti; Min Ce, Fe, Mn, Ni, U (1 less wash)	441	25	60			-13.3268	43.98	684.2	-9.8178	54.33	945.8
1100 Can Baseline (1 less wash)	320	25	41		lvisc	-13.372	24.64	723.4	-13.2507	47.73	929.8
1100 Can Baseline (1 less wash)	417	25	43		lvisc	-12.8605	25.74	734.1	-12.5578	55.04	960.4
1100 Can Baseline (1 less wash)	418	25	45		TL	-11.3695	35.41	768.5	-10.4788	82.56	1008.7
1100 Can Baseline (1 less wash)	425	25	46		lvisc	-12.412	25.12	745.2	-11.8648	63.23	999.5
1100 Can Baseline (1 less wash)	426	25	46		TL	-11.913	29.03	756.6	-11.1718	72.38	1008.7
1100 Can Baseline (1 less wash)	431	.	.			.	.	.	.	.	.
1100 Can Baseline (1 less wash)	441	.	.			.	.	.	.	.	.

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1100 Can 2nd Transfer, Baseline (1 less wash)	320	25	43		lvisc	-13.0666	25.42	734.3	-13.0644	50.81	962.7
1100 Can 2nd Transfer, Baseline (1 less wash)	417	25	46		TL lvisc	-12.568	25.25	745	-12.3714	58.55	1001.8
1100 Can 2nd Transfer, Baseline (1 less wash)	418	25	43		TL	-10.9599	45.1	779.3	-10.2924	87.62	1000.3
1100 Can 2nd Transfer, Baseline (1 less wash)	425	25	45		TL	-12.0504	30.84	756	-11.6784	67.21	1001
1100 Can 2nd Transfer, Baseline (1 less wash)	426	25	44		TL	-11.5144	37.41	767.4	-10.9854	76.88	1000.5
1100 Can 2nd Transfer, Baseline (1 less wash)	431	.	.			.	.	.	.	.	.
1100 Can 2nd Transfer, Baseline (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	320	.	.			.	.	.	.	.	.
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	417	25	41		lvisc	-13.1562	25.19	739	-12.7586	51.75	953.4
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	418	25	43		TL	-11.6259	34.62	775.1	-10.6796	77.83	1007.2
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	425	25	44		lvisc	-12.7133	24.48	750.6	-12.0656	59.51	996.8
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	426	25	44		TL	-12.1959	28.31	762.7	-11.3726	68.18	1007.1
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	431	.	.			.	.	.	.	.	.
1100 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	320	25	49		lvisc	-12.7116	24.9	699.2	-12.3759	56.61	939.1
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	417	25	51		lvisc	-12.0186	26.08	708.3	-11.8951	65.11	959.4
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	418	25	56		TL	-10.6517	30	737.6	-9.9396	96.95	1008.1
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	425	25	54		lvisc	-11.4559	25.54	717.8	-11.3256	74.61	984.9
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	426	25	56		lvisc	-11.0583	26.1	727.5	-10.6326	85.2	1002.6
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	431	25	46		lvisc	-13.4046	24.64	690.3	-12.9168	49.02	909.7
1100 Can Max Al, Na; Min Mn, Ni, U (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Min Ce, Mg, Ti (1 less wash)	320	25	44		TL	-12.9421	26.83	752	-12.8515	53.19	998.6
1100 Can Min Ce, Mg, Ti (1 less wash)	417	25	43		TL	-12.3296	32.6	763	-12.2491	61.26	997.3
1100 Can Min Ce, Mg, Ti (1 less wash)	418	25	40		TL	-10.653	56.35	798.1	-10.1701	91.56	995
1100 Can Min Ce, Mg, Ti (1 less wash)	425	25	42		TL	-11.7892	39.36	774.3	-11.5561	70.29	996.2
1100 Can Min Ce, Mg, Ti (1 less wash)	426	25	41		TL	-11.2303	47.23	786	-10.8631	80.36	995.5
1100 Can Min Ce, Mg, Ti (1 less wash)	431	41	42	Del Gp	lvisc	-13.4109	25.28	956.5	-13.3969	26.42	967.7
1100 Can Min Ce, Mg, Ti (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Min Fe (1 less wash)	320	25	47		lvisc	-12.8542	24.95	735.2	-12.6719	54.73	994
1100 Can Min Fe (1 less wash)	417	25	47		TL	-12.1822	28.94	745.5	-12.1612	63	1001.9

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1100 Can Min Fe (1 less wash)	418	25	44		TL	-10.627	50.6	778.6	-10.0822	94.01	1000.3
1100 Can Min Fe (1 less wash)	425	25	46		TL	-11.6823	35.08	756.2	-11.4682	72.25	1001.1
1100 Can Min Fe (1 less wash)	426	25	45		TL	-11.1639	42.26	767.2	-10.7752	82.56	1000.6
1100 Can Min Fe (1 less wash)	431	33	44	Del Gp	lvisc	-13.407	24.7	835.3	-13.2142	37.57	957.4
1100 Can Min Fe (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Max Mg (1 less wash)	320	25	34		Del Gp	-13.4239	33.1	723.5	-13.3279	46.76	849.2
1100 Can Max Mg (1 less wash)	417	25	43		lvisc	-12.9932	24.6	734.4	-12.6349	53.94	963.2
1100 Can Max Mg (1 less wash)	418	25	44		TL	-11.4608	35.79	769.2	-10.5559	80.96	1002.8
1100 Can Max Mg (1 less wash)	425	25	45		lvisc	-12.5248	25.39	745.6	-11.9419	61.98	993.2
1100 Can Max Mg (1 less wash)	426	25	45		TL	-12.0166	29.35	757.1	-11.2489	70.96	1002.8
1100 Can Max Mg (1 less wash)	431	.	.			.	.	.	.	.	.
1100 Can Max Mg (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Max Ni (1 less wash)	320	25	42		TL lvisc	-13.309	24.45	755.2	-13.2087	48.8	992.4
1100 Can Max Ni (1 less wash)	417	25	42		TL	-12.7731	28.41	766.8	-12.5157	56.28	1002.8
1100 Can Max Ni (1 less wash)	418	25	39		TL	-11.0368	50.21	803.9	-10.4368	84.41	1000.7
1100 Can Max Ni (1 less wash)	425	25	41		TL	-12.2128	34.56	778.7	-11.8227	64.65	1001.8
1100 Can Max Ni (1 less wash)	426	25	40		TL	-11.634	41.79	791.1	-11.1298	74	1001
1100 Can Max Ni (1 less wash)	431	.	.			.	.	.	.	.	.
1100 Can Max Ni (1 less wash)	441	.	.			.	.	.	.	.	.
1100 Can Max Ti (1 less wash)	320	25	45		lvisc	-12.9165	25.44	698.9	-12.8007	52.94	915.8
1100 Can Max Ti (1 less wash)	417	25	48		lvisc	-12.3029	25.3	708.3	-12.2235	60.95	947.3
1100 Can Max Ti (1 less wash)	418	25	54		TL	-11.0485	27.22	738.6	-10.1446	90.99	1009.6
1100 Can Max Ti (1 less wash)	425	25	50		lvisc	-11.8478	26.2	718.1	-11.5306	69.9	969.2
1100 Can Max Ti (1 less wash)	426	25	53		lvisc	-11.4516	25.22	728.2	-10.8376	79.89	996.8
1100 Can Max Ti (1 less wash)	431	38	42	Del Gp	lvisc	-13.4141	25.17	843.5	-13.354	29.79	881.9
1100 Can Max Ti (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Baseline (1 less wash)	320	25	42		lvisc	-13.179	25.49	730.4	-13.1314	49.71	948
1200 Can Baseline (1 less wash)	417	25	45		lvisc	-12.6792	25.3	741.1	-12.4384	57.29	987.9
1200 Can Baseline (1 less wash)	418	25	44		TL	-11.1149	40.94	775.4	-10.3594	85.82	1006.1
1200 Can Baseline (1 less wash)	425	25	46		TL	-12.1923	27.73	752.1	-11.7454	65.79	1006.7

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1200 Can Baseline (1 less wash)	426	25	45		TL	-11.6628	33.8	763.5	-11.0524	75.27	1006.2
1200 Can Baseline (1 less wash)	431	.	.			.	.	.	.	.	.
1200 Can Baseline (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can 2nd Transfer, Baseline (1 less wash)	320	25	44		lvisc	-13.0329	24.79	736	-13.0114	51.37	974.7
1200 Can 2nd Transfer, Baseline (1 less wash)	417	25	46		TL lvisc	-12.5102	25.95	746.7	-12.3399	59.19	1003.3
1200 Can 2nd Transfer, Baseline (1 less wash)	418	25	43		TL	-10.9058	46.16	780.9	-10.261	88.55	1001.8
1200 Can 2nd Transfer, Baseline (1 less wash)	425	25	45		TL	-11.9939	31.65	757.7	-11.647	67.94	1002.5
1200 Can 2nd Transfer, Baseline (1 less wash)	426	25	44		TL	-11.4591	38.34	769.1	-10.954	77.7	1002
1200 Can 2nd Transfer, Baseline (1 less wash)	431	.	.			.	.	.	.	.	.
1200 Can 2nd Transfer, Baseline (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	320	25	30		Del Gp	-13.4256	38.44	737.6	-13.3649	46.25	813.7
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	417	25	42		lvisc	-13.0354	25.38	748.9	-12.6719	53.36	978.4
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	418	25	41		TL	-11.3785	41.17	785.4	-10.5929	80.17	999.5
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	425	25	43		TL	-12.5301	27.8	760.7	-11.9789	61.34	1000
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	426	25	42		TL	-11.9636	33.94	772.8	-11.2859	70.25	999.5
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	431	.	.			.	.	.	.	.	.
1200 Can Min Al, Na; Max Ce, Fe, Mn, U (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	320	25	51		lvisc	-12.5951	25.27	698.9	-12.1102	58.82	947.2
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	417	25	54		lvisc	-11.9021	25.13	707.9	-11.6293	67.63	972.1
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	418	26	57	hvisc	TL	-10.4091	32.37	749.5	-9.8414	98.42	1005
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	425	25	56		lvisc	-11.2091	25.97	717.2	-11.2039	77.46	989.2
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	426	25	58		TL lvisc	-10.8155	26.53	726.8	-10.5161	88.4	1005.3
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	431	25	48		lvisc	-13.2881	24.97	690.2	-12.6467	50.97	920.1
1200 Can Max Al, Na; Min Fe, Mn, Ni, U (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Max Ni (1 less wash)	320	25	42		TL lvisc	-13.3056	24.5	755.4	-13.2067	48.86	992.6
1200 Can Max Ni (1 less wash)	417	25	42		TL	-12.7697	28.47	766.9	-12.5138	56.34	1003
1200 Can Max Ni (1 less wash)	418	25	39		TL	-11.0337	50.31	804.1	-10.4348	84.5	1000.9
1200 Can Max Ni (1 less wash)	425	25	41		TL	-12.2095	34.64	778.9	-11.8208	64.72	1002
1200 Can Max Ni (1 less wash)	426	25	40		TL	-11.6308	41.87	791.3	-11.1278	74.08	1001.2
1200 Can Max Ni (1 less wash)	431	.	.			.	.	.	.	.	.

Type	Frit ID	Min WL	Max WL	Limited Below By	Limited Above By	Del Gp (min)	Visc (min)	TL (min)	Del Gp (max)	Visc (max)	TL (max)
1200 Can Max Ni (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Min Ce (1 less wash)	320	25	47		lvisc	-12.8408	25.28	735.7	-12.6467	55	994.2
1200 Can Min Ce (1 less wash)	417	25	47		TL	-12.157	29.32	746	-12.1478	63.31	1002.1
1200 Can Min Ce (1 less wash)	418	25	44		TL	-10.6034	51.16	779	-10.0688	94.45	1000.5
1200 Can Min Ce (1 less wash)	425	25	46		TL	-11.6576	35.51	756.6	-11.4548	72.6	1001.3
1200 Can Min Ce (1 less wash)	426	25	45		TL	-11.1398	42.75	767.6	-10.7618	82.95	1000.8
1200 Can Min Ce (1 less wash)	431	32	44	Del Gp	lvisc	-13.4073	24.99	823.1	-13.1906	39.06	957.7
1200 Can Min Ce (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Min Mg, Ti (1 less wash)	320	25	44		TL	-12.9563	26.55	751	-12.8765	52.94	997.5
1200 Can Min Mg, Ti (1 less wash)	417	25	43		TL	-12.354	32.28	762	-12.2633	60.98	996.1
1200 Can Min Mg, Ti (1 less wash)	418	25	40		TL	-10.6757	55.87	797.1	-10.1843	91.16	993.9
1200 Can Min Mg, Ti (1 less wash)	425	25	42		TL	-11.8131	38.99	773.3	-11.5703	69.98	995.1
1200 Can Min Mg, Ti (1 less wash)	426	25	41		TL	-11.2536	46.81	785	-10.8773	80.01	994.3
1200 Can Min Mg, Ti (1 less wash)	431	.	.			.	.	.	.	.	.
1200 Can Min Mg, Ti (1 less wash)	441	.	.			.	.	.	.	.	.
1200 Can Max Mg, Ti (1 less wash)	320	25	47		lvisc	-12.7979	25.46	699	-12.5661	55.06	927.7
1200 Can Max Mg, Ti (1 less wash)	417	25	50		lvisc	-12.1049	25.34	708.3	-12.0725	63.35	956.8
1200 Can Max Mg, Ti (1 less wash)	418	25	55		TL	-10.8187	29.04	738	-10.026	94.43	1008.2
1200 Can Max Mg, Ti (1 less wash)	425	25	52		lvisc	-11.6264	26.24	717.9	-11.4119	72.62	977.1
1200 Can Max Mg, Ti (1 less wash)	426	25	55		lvisc	-11.2345	25.25	727.8	-10.7189	82.95	1002.4
1200 Can Max Mg, Ti (1 less wash)	431	29	44	Del Gp	lvisc	-13.4118	25.16	742.1	-13.1152	42.79	896.2
1200 Can Max Mg, Ti (1 less wash)	441	.	.			.	.	.	.	.	.

Distribution:

J.E. Marra, 773-A
E.W. Holtzscheiter, 773-A
D.A. Crowley, 999-W
S.L. Marra, 999-W
T.B. Calloway, 999-W
N.E. Bibler, 773-A
C.M. Jantzen, 773-A
J.R. Harbour, 773-42A
G.G. Wicks, 773-A
D.K. Peeler, 999-W
T.B. Edwards, 773-42A
C.C. Herman, 773-42A
A.S. Choi, 999-W
M.E. Smith, 773-42A
M.E. Stone, 999-W
D.H. Miller, 999-W
T.M. Jones, 999-W
M.S. Miller, 704-S
T.H. Lorier, 999-W
J.E. Occhipinti, 704-S
R.M. Hoeppel, 704-27S
J.F. Iaukea, 704-30S
J.W. Ray, 704-S
F.A. Washburn, 704-27S
H.H. Elder, 766-H
G.R. Lilliston, 776-H
D.C. Bumgardner, 766-H
J.M. Gillam, 766-H
W.B. Van Pelt, 704-S
H. B. Shah, 766-H