

THE IMPACT OF ALTERNATIVE SORBENTS AS COMPARED TO MONOSODIUM TITANATE ON THE DEFENSE WASTE PROCESSING FACILITY

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May 2004

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EXECUTIVE SUMMARY

Several alternatives to the use of monosodium titanate (MST) are being examined to affect enhanced performance in both the Salt Waste Processing Facility (SWPF) and the Actinide Removal Process (ARP) facilities. The currently available (and baseline) material, MST, exhibits lower capacity and removal kinetics, particularly for plutonium, than that desired in the pretreatment of SRS waste solutions. An increase in the removal capacity and kinetics would reduce the risk of batches of decontaminated supernate not meeting saltstone waste acceptance criteria. Enhanced performance would also serve to increase processing throughput by decreasing the required batch contact time. However, the introduction of any actinide removal/sorbent stream results in downstream impacts to the Defense Waste Processing Facility's (DWPF) Chemical Process Cell (CPC) and projected operating windows – such impacts are the focus of this report. The specific alternative sorbent streams evaluated were: (1) optimized MST, (2) Engineered MST Case A (internal gelation process), (3) Engineered MST Case B (internal hydrolysis process), and (4) In-Situ Mixed Iron Oxide (IS-MIO). All of the alternative sorbents were compared to the baseline MST stream.

Based on the assessments performed and the assumptions made for this study, all of the options being considered are plausible from a DWPF CPC and glass formulation perspective. However, additional testing and evaluation is warranted to fully understand the impacts on DWPF processing.

Compared to the MST-baseline sorbent and process, no increase in acid addition demand is expected for the alternative sorbents. The IS-MIO stream introduces reduced iron as part of the incoming DWPF stream. This can impact glass REDOX in DWPF. However, the quantity is very small and can likely be accommodated. SRTC testing should be performed to demonstrate this hypothesis.

Of greatest concern are the potential impacts of the alternative sorbents on CPC processing, which can not be ascertained without actual testing of the sorbent materials. This includes rheology, antifoam effectiveness, potential generation of hydrogen, and processing time. Based on the limited data, Engineered MST Case B would appear to have a potential for the largest impact due to the high total and insoluble solids content.

With respect to projected operating windows, the Optimized MST, Engineered MST Case A, and IS-MIO options resulted in upper waste loadings (WLs) of 42, 42, and 40%, respectively, as compared to the MST baseline of 43% WL. The use of Frit 202 with the Engineered MST Case B sorbent resulted in complete elimination of the operating window. However, use of Frit 433 with the Engineered MST Case B sorbent result in a higher projected upper WL of 49% as compared to the MST baseline. Predictions of liquidus temperature restricted access to higher WLs for all systems evaluated. Although a potentially significant advantage in terms of the projected WL is shown for the Engineered MST Case B option with Frit 433 relative to the Frit 202-based systems, caution should be used given the projected operating windows for the other alternatives could possibly be improved through the use of strategic frit development approaches. In fact, a high probability exists that the “WL gap” between the different systems could be minimized by strategic frit development efforts. From a glass formulation perspective, the greatest concern is the potential impact on melter processing (i.e., melt rate and waste throughput).

Projections regarding the total number of cans produced suggested very little differences among the various options and negligible difference from the baseline MST. The maximum difference among the options in terms of annual canister count was an increase of approximately 26 for the IS-MIO case which are not viewed as significant given the assumptions made and the fact that specific frit development efforts were not undertaken.

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ACRONYMS

ARP	Actinide Removal Process
CPC	Chemical Processing Cell
DF	decontamination factor
DWPF	Defense Waste Processing Facility
ΔG_p	preliminary glass dissolution estimator based on free energy of hydration
IS-MIO	In-Situ Mixed Iron Oxide
ITP	In-Tank Precipitation
NL [B]	normalized boron release (in g/L)
MAR	Measurement Acceptability Region
MFT	Melter Feed Tank
MST	monosodium titanate
ORNL	Oak Ridge National Laboratory
PCCS	Product Composition Control System
PCT	product consistency test
PHA	precipitate hydrolysis aqueous
REDOX	<u>RED</u> uction/ <u>OX</u> idation
SB	sludge batch
SRAT	Sludge Receipt and Adjustment Tank
SRS	Savannah River Site
SRTC	Savannah River Technology Center
SWPF	Salt Waste Processing Facility
SME	Slurry Mix Evaporator
T_L	liquidus temperature
η	viscosity
WL	waste loading
WPT	Waste Processing Technology

1.0 INTRODUCTION

There are approximately 36 million gallons of high-level waste (HLW) stored in 49 tanks at the Savannah River Site (SRS) in South Carolina. This waste, which is a product of the cold-war era, contains a number of radioactive isotopes of a large number of elements such as cesium (Cs), strontium (Sr), and actinide elements (such as neptunium (Np), uranium (U), plutonium (Pu), and americium (Am)). The waste is composed of sludge (c. 10%) and alkaline water-based supernate (c. 90%). A portion of the supernate is stored as a saltcake resulting from the evaporation of water from the HLW supernates (Cathey 2003 and Caldwell et al. 2002). Upon retrieval of the saltcake by dissolution in inhibited waste, the total inventory of supernate and dissolved saltcake that will require pretreatment and disposal is expected to be about 80 million gallons.

The baseline plan for the waste treatment requires the sludge to be sent to the Defense Waste Processing Facility (DWPF) for vitrification into borosilicate glass, while all the remaining supernate (including the dissolved saltcake) processes through the Salt Waste Processing Facility (SWPF). The SWPF will separate Cs, Sr, and actinides into a high-level stream, to be vitrified in the DWPF, while the decontaminated solution will be disposed of in the Saltstone Production Facility. An alternative accelerated baseline approach (Cathey 2003 and Caldwell et al. 2002) would require only the high-curie portion of the supernate to be processed in the SWPF, while the remaining low-curie supernate would either be treated for Sr and actinide removal within the Actinide Removal Process (ARP) facility or sent directly to the Saltstone Grout Facility, if its curie content is sufficiently low. Acceleration of waste disposal at the SRS requires materials that exhibit increased loading capacities and removal kinetics for ^{90}Sr and alpha-emitting radionuclides compared to the baseline material, monosodium titanate (MST).

MST is the baseline material for Sr/actinide removal for the SRS SWPF and ARP facilities. MST is an inorganic sorbent originally developed for use in the In-Tank Precipitation (ITP) process. Key specifications of the MST for ITP included: (1) a high decontamination factor (DF) for strontium, (2) a relatively narrow particle size distribution (1 – 35.5 microns), and (3) supplied as an aqueous suspension containing sodium hydroxide and sodium nitrite as corrosion inhibitors. A high strontium DF requirement was specified to ensure adequate ^{90}Sr removal. An upper particle size constraint was specified to reduce rapid settling of the MST particles in the ITP processing tank. A lower particle size constraint was specified to reduce plugging of the cross flow filter from fine particles. The addition of sodium hydroxide and sodium nitrite was specified to prevent corrosion of the cold chemical storage tank and the ITP processing tank.

The proposed SWPF and existing ARP facilities have significantly different reactor configurations and process cycle times compared to those proposed for the now shutdown ITP operation. In particular, contact times between the MST and the alkaline waste solutions in the SWPF and ARP will be 24 hours versus approximately 2 weeks for the ITP process. Increased waste characterization data indicate that alpha removal characteristics (principally plutonium removal) represent a greater challenge than those for ^{90}Sr . Based on recent testing at Savannah River Technology Center (SRTC) (Hobbs 2002), the performance of MST to efficiently and rapidly remove alpha-emitting radionuclides serves as the limiting factor in sizing the equipment and determining the operational throughput. Even higher alpha activities are projected for the SWPF and ARP operations as a result of initiatives to accelerate the disposal of HLW at the SRS. Due to the limited solubility of titanium in HLW borosilicate glass (Lorier and Jantzen 2003), there may be limits on the amount of MST that can be used in SWPF and ARP facilities. Consequently, the need exists for an improved Sr/alpha removal material that exhibits increased actinide removal capacity and kinetics.

SRTC's Waste Processing Technology (WPT) Section is evaluating alternative sorbents to affect enhanced performance in both the SWPF and the ARP facilities. A four-fold or more increase in the removal capacity and more rapid sorption kinetics would reduce the risk that batches of decontaminated supernate would not meet saltstone waste acceptance criteria. Enhanced removal kinetics would also serve to increase processing throughput by decreasing the required batch contact time to less than 24 hours.

In this study, four alternative sorbents/cases are assessed with respect to potential downstream impacts to the DWPF and are compared to the MST-baseline process. These alternative sorbents/cases are: (1) optimized MST case, (2) Engineered MST sorbent - Case A, (3) Engineered MST sorbent - Case B, and (4), the In-Situ Mixed Iron Oxide (IS-MIO) case. The potential downstream impacts on the Chemical Process Cell (CPC), projected operating windows, and canister production totals for DWPF are the focus of this report. The impacts are assessed relative to the current MST baseline flowsheet. The CPC and operating window impacts are assessed by appealing to models that relate composition to process and product quality properties. Since there are currently no models relating composition to melt rate, the comparison of canister production rely more heavily on underlying assumptions. It should be noted that no experimental work was performed as part of this assessment.

2.0 OBJECTIVE

The objective of this report is to evaluate the relative impacts of the alternative sorbent materials/cases on the DWPF. The impacts are assessed relative to the baseline SWPF process using MST sorbent and include processing issues associated primarily with the CPC, projected glass operating windows (which are based on model predictions and are represented in terms of waste loading (WL) intervals), and canister production totals. The specific sorbent streams to be evaluated include: (1) optimized MST, (2) Engineered MST Case A (internal gelation process), (3) Engineered MST Case B (internal hydrolysis process), and (4) IS-MIO.

The primary focus of the CPC evaluations is the potential impact to the DWPF acid addition strategy and/or the influences of the SWPF streams on slurry rheology and other processing properties. In terms of the projected glass operating windows, current processing and product performance models are used to estimate the waste loading interval over which the various flowsheets could potentially be processed. The waste loadings presented provide a relative measure of the impact of each sorbent and associated volume on the operational flexibility and potential maximum waste loadings that could be attained in DWPF. Based on the projected operating windows, assessments are made with respect to potential impacts to canister production totals – without the impact of melt rate factored into this assessment.

3.0 DEFINITION OF BASELINE FLOWSHEET AND ALTERNATIVE WASTE STREAM COMPOSITIONS

To assess the impacts of the alternative sorbents on the DWPF process, one must first select a specific sludge/frit system. Once the sludge/frit system is selected, the MST baseline flowsheet can be established. For this assessment, the Frit 202 – Sludge Batch 3 (SB3) system with the SWPF stream containing MST will serve as the baseline flowsheet against which the relative impacts of the alternative sorbents will be evaluated. There are obvious advantages and potential disadvantages of selecting the Frit 202 – SB3 system. Advantages include a thorough knowledge of the sludge composition (since Click and Pareizs (2003) have reported measured compositions of the Tank 51 qualification sample). The use of Frit 202 is on firm technical ground given it was developed for “coupled operations” (i.e., HLW sludge plus high alkali from precipitate hydrolysis aqueous (PHA)) (Jantzen 1988). Although “coupled operations” is not anticipated during processing of SB3, the fact that the Tank 51 sludge was “underwashed” to provide higher sodium concentrations and anticipating the introduction of the MST or alternative sorbents from a compositional viewpoint, use of Frit 202 becomes a possible candidate.

The primary disadvantage of using this specific system is the fact that the SWPF streams being assessed may not be integrated into the DWPF process during actual processing of SB3. Therefore, one will be establishing or comparing the impacts of these secondary streams on a potentially “non-representative” sludge batch. However, consideration of other baseline flowsheets has potential issues about their use as well. For example, assume the introduction of the SWPF stream was known or projected to occur with SB4. Although there is historical information regarding the composition of SB4, frit development efforts have not been initiated to design a frit to maximize the operational windows, to produce acceptable melt rates and waste loadings, and to ultimately optimize the waste throughput of SB4 for DWPF. Developing a frit for SB4 may be rather time consuming and would require both model-based assessments and experimental work to be performed. In addition, the frit optimized for SB4 with the SWPF stream containing MST would perhaps be different. Therefore, the Frit 202 – SB3 with MST will serve as the baseline flowsheet from which the relative impacts of introducing the alternative sorbents can be assessed.

Four primary inputs are required to assess the impact on DWPF’s CPC and projected operational windows. These inputs are: (1) the SB3 sludge composition, (2) the frit composition, (3) composition(s) of the SWPF streams containing MST and alternative sorbents, and (4) the nominal process volumes in DWPF including the amount of sludge and SWPF stream to be processed in a year. The first three inputs are presented in the following subsections. Section 4.0 provides a detailed discussion of the anticipated process volumes and assumptions used to estimate the incoming SWPF stream composition to DWPF.

3.1 SB3 Sludge Composition

Based on the Tank 51 sample results and updated projections of when SB2 and SB3 may be combined, Lilliston and Elder provided revised compositional estimates.¹ Four estimates were provided based on two targeted SB3 wash endpoints (1.23M and 1.24M Na⁺) and two blending

¹ Personal communication with G.R. Lilliston. It is noted that SB2 and SB3 were blended in the late March 2004 timeframe with the blend referred to as SB3. Initial assessments of projected operating windows for the “sludge-only” system refers to the sludge as SB2/3. A review of the initial DWPF SRAT/SME products suggests no significant difference as compared to the compositional projections by Elder.

options in terms of timing (175 and 200 canisters). The elemental concentrations provided were converted to an oxide basis (by multiplying by the appropriate gravimetric factor) and these data are presented in Table 3-1. A review of the projected compositions suggests very little (if any) practical difference among the four sludge compositions. Assessments by Peeler and Edwards (2003) indicate that the projected operating windows (at the Measurement Acceptability Region (MAR)) for each of these SB3 streams when coupled with Frit 202 (the nominal SB3 frit) are essentially the same. More specifically, waste loadings of approximately 27 – 38% result in acceptable processing and product performance predictions for each sludge composition without considering or anticipation of the compositional impact of the MST baseline or alternative sorbent streams. Therefore, to select a base sludge for blending with the SWPF streams, the authors chose the 1.23M, 175-canister option as shown (and shaded) in Table 3-1.

It should be noted that anions were not reported as part of the calcined elemental concentrations – only as part of the supernate information. Therefore no assessment of the potential to exceed the anion solubility limits could be made as a function of WL for the Frit 202 – SB3 system.

Table 3-1. Projected SB2/SB3 Compositions (oxide basis, wt%).

Oxide	SB3 1.23M 175 cans	SB3 1.24M 175 cans	SB3 1.23M 200 cans	SB3 1.24M 200 cans
Al ₂ O ₃	15.33	15.33	15.41	15.40
BaO	0.15	0.15	0.15	0.15
CaO	2.95	2.95	2.93	2.93
Ce ₂ O ₃	0.24	0.24	0.24	0.24
Cr ₂ O ₃	0.25	0.25	0.24	0.24
CuO	0.08	0.08	0.08	0.08
Fe ₂ O ₃	32.54	32.53	32.41	32.39
K ₂ O	0.94	0.94	0.96	0.96
La ₂ O ₃	0.12	0.12	0.12	0.12
MgO	3.57	3.56	3.57	3.57
MnO	6.66	6.66	6.73	6.73
Na ₂ O	21.32	21.36	21.28	21.33
NiO	1.82	1.82	1.83	1.83
PbO	0.15	0.15	0.14	0.14
SiO ₂	2.84	2.84	2.88	2.88
ThO ₂	0.03	0.03	0.03	0.03
TiO ₂	0.03	0.03	0.03	0.03
U ₃ O ₈	10.26	10.25	10.29	10.28
ZnO	0.16	0.16	0.15	0.15
ZrO ₂	0.26	0.26	0.24	0.24
Total	99.68	99.68	99.69	99.69

3.2 Frit Composition

The nominal Frit 202 composition (with the acceptable tolerance values) is shown in Table 3-2. It should be noted that the nominal values (with no variation) shown in Table 3-2 were used in the

assessments. Based on previous glass formulation experience, the introduction of most, if not all, of alternative sorbents into the Frit 202 – SB3 systems should have a positive impact of the projected operating windows.

Although Frit 202 is used it should not be considered an optimized frit for any of the systems being assessed. Its use in this report is strictly for demonstrating the impact of the alternative sorbents relative to the baseline flowsheet. If negative impacts to the projected operating window result with Frit 202, there is a high probability that strategic glass formulation efforts (via designed frits with an integrated systems approach in mind) could mitigate these impacts and restore the projected operating windows. However, Frit 202 was developed for “coupled operations” and has been shown to be effective in providing relatively large operating windows for high alkali sludges.

Assessments of melt rate for the Frit 202 – SB3 system have not been performed. Prior to implementation of any frit into DWPF, laboratory assessments of melt rate should be made to ensure that what appears attractive on paper (projected operating windows based on model predictions) does not result in a difficult feed to process.

Table 3-2. Nominal Composition (with acceptable tolerance ranges) of Frit 202.

Oxide	wt%
B ₂ O ₃	8 ± 0.5
Li ₂ O	7 ± 0.5
Na ₂ O	6 ± 0.5
SiO ₂	77 ± 1.0
MgO	2 ± 0.25
Total	100

3.3 Alternative Sorbent Compositions/Cases

Table 3-3 summarizes the nominal compositions of the MST, (which is also the Optimized MST composition), Engineered MST Case A, Engineered MST Case B, and IS-MIO sorbents. The option known as Optimized MST uses the same MST material as the baseline MST process, and, therefore, the composition given in Table 3-3, represents the sorbent material for both cases. Table 3-3 also provides the nominal composition of the 1.23M, 175-canister SB3 blend (see Table 3-1), which serves as the common sludge composition for all of the assessments. A brief description of each sorbent is provided below.

3.3.1 MST

MST, NaTi₂O₅H, is the baseline material for Sr/actinide removal for the SRS SWPF and Actinide Removal Process (ARP) facilities. MST is an inorganic sorbent originally discovered by researchers at Sandia National Laboratory. SRTC researchers modified the synthesis of the MST to provide a material for use at SRS in the In-Tank Precipitation (ITP) process. SRTC transferred the synthesis technology to several vendors. The MST sorbent is comprised of TiO₂ and Na₂O and contains roughly 4.5 wt% bound water.

Table 3-3. Nominal Compositions of MST and the Alternative Sorbents.
(oxide wt%, calcined basis).

Oxide	1.23M, 175-canister option for SB3	MST Stream* (wt% in solids)	Engineered MST Case A (wt% in solids)	Engineered MST Case B (wt% in solids)	IS-MIO (wt% in solids)
Al ₂ O ₃	15.33	-	-	90.22	-
BaO	0.15	-	-	-	-
CaO	2.95	-	0.52	0.29	-
Ce ₂ O ₃	0.24	-	-	-	-
Cr ₂ O ₃	0.25	-	-	-	-
CuO	0.08	-	-	-	-
Fe ₂ O ₃	32.54	-	0.10	0.09	49.47
FeO	-	-	-	-	43.94
K ₂ O	0.94	-	-	-	-
La ₂ O ₃	0.12	-	-	-	-
MgO	3.57	-	-	-	-
MnO	6.66	-	-	-	-
Na ₂ O	21.32	16.24	-	-	-
NiO	1.82	-	-	-	-
PbO	0.15	-	-	-	-
SiO ₂	2.84	-	0.66	0.2	-
SO ₄ ²⁻	-	-	-	-	6.6
ThO ₂	0.03	-	-	-	-
TiO ₂	0.03	83.76	98.72	9.2	-
U ₃ O ₈	10.26	-	-	-	-
ZnO	0.16	-	-	-	-
ZrO ₂	0.26	-	-	-	-
Totals	99.68	100.0	100.0	100.0	100.0

*MST-baseline and Optimized MST both have the same chemical composition.

3.3.2 Optimized MST

As previously mentioned, the Optimized MST sorbent is assumed to have an identical composition to the MST-baseline sorbent. The optimized MST sorbent is prepared by the modified synthesis to that used for the baseline MST sorbent. The modification results in a material that exhibits higher capacity and removal kinetics for strontium and actinides. The increased capacity allows the use of less material in pretreatment operations to accomplish the same degree of radionuclide separation.

3.3.3 Engineered MST – Case A

The Engineered MST Case A sorbent, manufactured at Oak Ridge National Laboratory (ORNL) using an internal gelation process (Collins 1998), is enriched in TiO₂ with minor concentrations of CaO, Fe₂O₃, and SiO₂. The internal gelation process provides a unique method for the

preparation of composite microspheres in which the MST powder can be homogeneously dispersed. Collins (1998) indicates that variations in several process parameters can control the type and shape of the hydrous metal oxide gel-spheres. The process provides a unique means to make inorganic ion exchangers more usual as an engineered form. This material contains roughly 40% bound water.

3.3.4 Engineered MST – Case B

Al_2O_3 is the dominant oxide for the Engineered MST Case B sorbent as made in laboratory amounts at SRTC, using internal hydrolysis. The material is produced by precipitating MST into the pores of an inorganic porous substrate. Variations on the process have been tested using other substrates in the past (Bray and Hara (1991) and Schulz (1980)). The substrate chosen for current work was Dynocel 600(tm) particles.² These alumina particles were provided at the desired 30 x 60 mesh. Locally they were soaked in an anhydrous alcohol solution containing tetraisopropyl titanate and sodium methoxide. MST was then precipitated by exposing the particles to a water-alcohol solution. Excess MST forming outside of the particles was washed away. MST content in the alumina was 10 to 13 weight percent on a dry basis. The product contained trace levels of CaO , Fe_2O_3 , and SiO_2 in addition to the alumina and MST. This material contains roughly 14 wt% bound water.

3.3.5 IS-MIO

Testing completed by Argonne National Laboratory using SRS waste simulants showed that the IS-MIO process could be a viable alternative to MST with regards to sorption kinetics and actinide/fission product DF (Arafat et al., 2002). In previous IS-MIO development work, iron (II) was added as a sulfate salt and iron (III) was added as a nitrate salt. Sulfate is known to have a limited solubility in glass (typically $< 1 \text{ wt\% SO}_4^{2-}$), and although iron (II) could be added with an alternative counter anion (e.g., Cl^-), sulfate was assessed to be added to the process stream as a result of the IS-MIO process for this evaluation. The nominal IS-MIO sorbent additive that remains in the DWPF feed stream (i.e., the material that is not removed during the SWPF alpha strike processing steps) consists of mixed iron oxides, sulfate, and nitrate. Nitrate is roughly equivalent to 7.9% of the IS-MIO material that is transferred to DWPF.

² Dynocel 600(tm) particles are produced by Porocel Corp., Little Rock, AR.

4.0 MATERIAL BALANCE BLENDING STRATEGIES AND ASSUMPTIONS

The SWPF will generate two streams to be transferred to the DWPF. One stream will primarily contain the sorbent material, which is used to remove actinides and strontium from salt solutions. This stream is concentrated to increase solids content and also contains entrained sludge solids. It is washed to remove sodium salts before it is transferred to the DWPF. The second stream is generated during caustic side solvent extraction in the SWPF. The stream that is transferred to DWPF is slightly acidic and contains concentrated Cs.

Since the process flowsheet and associated material balances have not been finalized for the SWPF, official guidance from project management³ was used to generate potential SWPF flow rates and stream compositions. In all cases, it was assumed that the SWPF would achieve a nominal annual throughput of 3 million gallons of waste at 6.44 M Na. The facility was also assumed to operate at 75% utility, while DWPF operations were assumed to be limited by melter life. For the material balances, a melter (and DWPF) was assumed to operate for 24 months before requiring a 6 month replacement outage. Therefore the DWPF outage cycle time was 30 months. It was also assumed that the SWPF has a storage capacity for 1 week's worth of production. Given these assumptions, the design throughput bases (for SWPF and DWPF) are 4.948 Mgal/yr ($3\text{Mgal/yr} \div 75\% \text{ availability} \times \text{DWPF outage cycle time} / [\text{DWPF operating period} + \text{SWPF storage capacity}]$) of liquid waste at 6.44 M Na. This allows the SWPF to meet higher attainment if the SWPF availability is greater or if the DWPF melter does not have to be replaced as rapidly.

Two different MST concentrations have been proposed for SWPF processing. These are 0.4 and 0.8 g/l. For this evaluation, the DWPF feed stream was assumed to contain 80% of feed from processing at 0.4 g/l and 20% of feed from processing at 0.8 g/l. This guidance was provided in Painter (2003) and Edwards (2003).

Based on the guidance provided, concentrations of the materials in the alpha strike process liquid and solid streams and in the concentrated Cs stream were estimated. The composition estimates are given in Table 4-1. Baseline volume flow rates were also calculated for the three streams and are shown in Table 4-2.

³ Guidance provided by S.D. Fink via email on April 8, 2004.

Table 4-1. Composition of SWPF Streams to Be Transferred to DWPF

Alpha Strike Process				Concentrated Cs Stream	
Liquid Stream		Solid Stream			
Component	g/l	Component	g/l	Component	g/l
Al(OH) ₄	5.58	sludge solids	32.5	NO ₃	0.460
CO ₃	0.362	MST	30.3	Cs	0.853
NO ₂	1.44			Extractant	0.000402
NO ₃	5.03			Modifier	0.0127
OH	5.08			TOA	0.0000531
PO ₄	0.339				
SO ₄ ²⁻	0.471				
Cs	0.00508				
Cu	0.0121				
Hg	0.00410				
K	0.0959				
Na	11.5				

Table 4-2. Baseline MST SWPF Process Flow Rates to DWPF

Process Stream	Volume Flow (gal/yr)
Alpha Strike - Liquid Stream	8.92 E04
Alpha Strike - Solid Stream	4.17 E03
Concentrated Cs Stream	3.95 E05

The values in Table 4-2 were used to estimate the projected MST use per year in the SWPF actinide removal process. Projections for the annual use of the other sorbents were made using the baseline MST value and the known or estimated performance of the other sorbent options. Table 4-3 contains these projections.

Table 4-3. Sorbent Compositions Projected Annual Use

Sorbent Type	Sorbent Use (kg/yr)
MST	1.07 E04
Optimized MST	2.73 E03
Engineered MST Case A	8.20 E03
Engineered MST Case B	4.10 E04
IS-MIO	6.53 E03

For the Optimized MST case, it was assumed that improvements in performance could be made such that only ~25% of the MST sorbent material would be used in a year. Thus, the number in Table 4-3 for Optimized MST represents ~25% of the requirement for the baseline MST. The volumes of the liquid stream and the sludge solids associated with the actinide removal part of the

SWPF facility were assumed to remain constant for the Optimized MST case. Therefore, the only value from Table 4-2 that was adjusted was the “Alpha Strike – Solid Stream” (i.e., the sorbent and sludge solids), which was reduced to 2.30 E03 gal/yr. [Stated another way, no credit was assumed for improved batching strategy possible with use of less sorbent nor was credit taken for less frequent chemical cleaning of the filters as likely will occur with lower solids content.] The fresh waste number was estimated based on maintaining the throughput for the fresh waste containing the entrained sludge. This throughput was added to the adjusted throughput for the alternative sorbent stream. For the Optimized MST case, as well as all of the other cases, the throughput of the “MST” portion or sorbent portion of the “Alpha Strike – Solids Stream” was scaled to the associated increase or reduction in the amount of sorbent used per year (see Table 4-3). As an example, the Optimized MST case reduces the sorbent utilized per year by ~75%; therefore, the throughput of the sorbent portion of the stream was reduced by ~75% (i.e., 6.42 E02 gal/yr) and was added to the fresh waste throughput (i.e., 1.66 E02 gal/yr). Once again, this calculation was performed for each of the cases.

The two Engineered MST cases both use a different type of sorbent than the baseline process. They also rely on a packed column for performing the actinide removal as opposed to the baseline cross-flow filtration process. Due to this arrangement and the associated lower solids content, chemical cleaning of the filters in the SWPF will occur less frequently. However, since flush water is needed to sluice the Engineered MST from the column into the DWPF transfer stream, the assumption was made that this extra water is equal to or less than the water saved by reducing chemical cleaning frequency. This assumption also implies that the materials can be transferred at the resulting solids level and will not require further adjustment. Cycle time saved from cleaning is assumed to be balanced by the cycle time needed for column operations. Since the salt waste to be treated contains much higher quantities of uranium than plutonium, the column loading was assumed to be limited by uranium sorption. Assuming the waste (dilute 5.6 M Na waste) contains 10 mg/l U, then the projected usage would be 4.1 E03 kg/yr for MST material (Hobbs 2002). However, the Engineered MST materials do not have the same compositions or performance as the baseline MST sorbent. For Case A, the ORNL material is 50 wt% MST, so projections are that twice the mass of material (compared to the baseline MST) will have to be used per year in SWPF operations. This resulted in a change in the “Alpha Strike – Solid Stream” flow to 3.58 E03 gal/yr. Case B material assumes only 10 wt% MST loading, so a significantly larger fraction of material is necessary compared to the baseline MST process. The associated “Alpha Strike – Solid Stream” flow rate estimate was 1.13 E04 gal/yr.

Finally, the IS-MIO case was approached slightly differently than the other streams since it is not a sorbent but is instead chemical additives. For each gram of MST in the baseline MST material balance, it was assumed that 0.500 g Fe, 0.645 g SO_4^{2-} , and 0.833 g NO_3 would be needed to perform the necessary radiochemical separation (Pereira et al 2004). However, most of the sulfate and nitrate added remain soluble and are not carried forward to DWPF because of the washing performed in the SWPF. The estimated dilution factor for soluble species is ~13.4, which results in only 0.500 g Fe, 0.048 g SO_4^{2-} , and 0.062 g NO_3 being transferred to DWPF with the actinide removal portion of the stream. This results in an “Alpha Strike – Solid Stream” flow rate of 3.19 E03 gal/yr.

The information presented above, as well as compositional information provided in Table 3-3 and Table 4-1, was used to estimate the DWPF Sludge Receipt and Adjustment Tank (SRAT) receipt or feed stream compositions. The information was also used to estimate the total volume of material to be received at DWPF for each case. The assumption was then made that DWPF would process the material in 45 CPC batches per year. Currently, the DWPF is processing a CPC batch per week (excluding instances for outages), so this should be a reasonable assumption. It should also be conservative from a CPC processing and glass composition perspective, since a greater number of CPC batches per year would dilute the effects of the SWPF feed stream. Table 4-4 provides the projected annual quantity of material and estimated volume per CPC batch for each sorbent. Very little difference was seen among the five different options with respect to volume to be processed at DWPF. Once again, changes in the volume of the Alpha Strike stream do occur with sorbent changes, but the total SWPF volume changes are negligible when compared to the large volume associated with the concentrated Cs stream.

Table 4-4. Estimated Volume of SWPF Stream to Be Processed in DWPF

Sorbent	Volume (gal/yr)	Volume (gal/batch)
Baseline MST	4.89 E05	1.09 E04
Optimized MST	4.87 E05	1.08 E04
Engineered MST Case A	4.88 E05	1.08 E04
Engineered MST Case B	4.96 E05	1.10 E04
IS-MIO	4.88 E05	1.08 E04

Currently, the DWPF is operating on a sludge-only flowsheet. Coupled operations were planned for the incorporation of the Precipitate Hydrolysis Aqueous stream. However, since DWPF has become operational, the salt processing flowsheet has changed leading to revised approaches for incorporating the solids and radionuclides from the salt stream into the DWPF process. For the development of the flowsheet for DWPF processing of the ARP stream, several processing cases were considered, but the most advantageous to DWPF was to reduce the volume of the ARP stream through concentration before processing with HLW sludge. The DWPF SRAT can hold 11,000 gallons; however, its nominal operating volume is 6,000 gallons with a maximum operating volume of ~7,000 gallons. For the ARP process, all of the liquid associated with the ARP stream was evaporated to accommodate a full 6,000 gallon sludge batch (Baich et al. (2003)). Therefore, in this study, the assumption was made that DWPF would boil off the volume of each input stream before commencing SRAT processing with the nominal 6,000 gallons of sludge.

The assumptions identified above were used to estimate SRAT sludge compositions for each case. The contributions to each estimated SRAT composition include the base sludge (SB3) and the SWPF stream including the sorbent solids, entrained sludge solids from SWPF (assumed to be the same composition as the SB3 sludge), liquid portion of the actinide and Sr removal stream (alpha strike process), and concentrated Cs stream. Table 4-5 provides the estimated total solids, Na molarity, and volume for the baseline sludge and each of the SWPF stream cases. All of the properties for the SWPF streams include the contribution from the Alpha Strike Process streams and the concentrated Cs Streams. Table 4-6 summarizes the estimated SRAT sludge compositions for each of the cases.

Table 4-5. Estimated Properties of Baseline Sludge and SWPF Streams.

STREAM	TOTAL SOLIDS	NA (M)	VOLUME (GAL)
SB3 Sludge	23.9%	1.45	6.00 E03
MST	1.81%	0.151	4.15 E04
Optimized MST	1.41%	0.130	4.13 E04
Engineered Case A	1.53%	0.122	4.14 E04
Engineered Case B	3.10%	0.121	4.22 E04
IS-MIO	1.61%	0.149	4.14 E04

Table 4-6. Resulting SRAT Products for the MST and Alternative Sorbents.
(wt% calcined oxide basis)

Oxide	MST	Optimized MST	Engineered MST Case A	Engineered MST Case B	IS-MIO
Al ₂ O ₃	14.6	15.1	15.0	25.2	14.9
BaO	0.138	0.143	0.141	0.125	0.141
CaO	2.73	2.82	2.81	2.52	2.79
Ce ₂ O ₃	0.223	0.230	0.228	0.202	0.227
Cr ₂ O ₃	0.227	0.235	0.232	0.206	0.232
Cs ₂ O	0.563	0.581	0.575	0.510	0.574
CuO	0.0782	0.0808	0.0800	0.0708	0.0797
Fe ₂ O ₃	30.2	31.2	30.9	27.4	32.0
FeO	0.00	0.00	0.00	0.00	1.03
K ₂ O	0.886	0.915	0.907	0.803	0.904
La ₂ O ₃	0.114	0.118	0.117	0.103	0.116
MgO	3.31	3.42	3.38	3.00	3.37
MnO	6.18	6.38	6.32	5.60	6.30
Na ₂ O	22.6	22.8	22.4	19.9	22.4
NiO	1.69	1.74	1.73	1.53	1.72
P ₂ O ₅	0.0355	0.0367	0.0363	0.0322	0.0362
PbO	0.135	0.139	0.138	0.122	0.137
SO ₄ ²⁻	0.0660	0.0681	0.0675	0.0598	0.222
SiO ₂	2.64	2.72	2.71	2.41	2.69
ThO ₂	0.0315	0.0326	0.0323	0.0286	0.0322
TiO ₂	3.58	0.960	2.07	1.24	0.0237
U ₃ O ₈	9.52	9.83	9.73	8.62	9.70
ZnO	0.145	0.149	0.148	0.131	0.148
ZrO ₂	0.239	0.247	0.245	0.217	0.244
Total	100.0	100.0	100.0	100.0	100.0

5.0 IMPACTS TO CPC PROCESSING

The main objectives of the CPC stage in the DWPF are the destruction of nitrite, reduction of Hg and Mn, neutralization of the base equivalents in the sludge, and adjustment of the slurry rheology to facilitate processing in the DWPF melter. Currently, the DWPF calculates the amount of acid to be added to each CPC SRAT batch based on the composition of the material received in the SRAT process vessel. The applicability of the acid addition equation to include ARP process streams that include MST and sludge solids has already been demonstrated (Baich et al. 2003).

For each of the cases in this evaluation, the acid demand of the SWPF sorbent stream was individually estimated and then the acid demand of the combined sludge and SWPF sorbent stream was estimated. To determine the associated mass of the process volumes identified in Table 4-4, densities of the adjusted sorbent streams were necessary. This information was not readily available for each of the streams, so an estimate for density was made for each case. In the baseline MST case, the density of the MST stream (i.e., 9.59 lbs/gal) and the density of the fresh waste part of the stream (i.e., 15 lbs/gal) were scaled to the associated percentages of the throughput of each stream. As an example, if the fresh waste represented 55% of the throughput, then its density contributed 55% to the DWPF output feed stream density. This was done for each case, and the density of the sorbent stream itself was assumed to remain constant since actual densities were not available.

Since the flowsheets for processing of the sorbent materials in the SWPF and the DWPF are still being developed, several assumptions had to be made to estimate the impact parameters needed for the acid calculation. Key assumptions included the following:

- The information provided by project management and outlined in Section 4.0 was used to estimate the nitrite, hydroxide, carbonate, total solids, insoluble solids, nitrate, and density of the SWPF stream to be transferred to DWPF. Soluble solids were assumed to come only from the materials identified in Table 4-1, and the only other solids were assumed to come from the sorbent material and the entrained sludge solids. The resulting solids concentrations were assumed to meet transfer criteria, and it was assumed that no additional changes to the stream would be necessary for transfer.
- The amount of Hg and Mn in the incoming SWPF stream will depend greatly on the material being processed. For these calculations, the SB3 sludge concentrations were used in conjunction with the amount of entrained sludge solids and were assumed to be the only source of Hg and Mn.
- DWPF will reduce the volume associated with the SWPF streams through boiling/concentration before processing and the starting volume will be roughly equivalent to that currently being used in DWPF (~6,000 gallons). The volume to be removed should be adjusted for the solids remaining in the vessel.
- The input parameters for the acid calculation were based on the individual inputs of the sludge and SWPF streams. This assumes no loss during boiling. Based on earlier DWPF flowsheet testing, this is a reasonable approach and was found to be conservative for the ARP flowsheet cases (Baich et al. 2003).
- The density of the SRAT receipt material is a necessary input parameter and this was estimated by assuming that the mass of solids from the SWPF stream and the sludge solids remained in a ~6,000 gallon batch.

- The SWPF introduces organics as part of the concentrated Cs stream. The assumption was made that all organics transferred to the DWPF were accounted for in the material balance information provided by project management. In calculating the REDOX term of the acid calculation, it was assumed that the total quantity of material was present as carbon. This should be conservative since it is a greater amount of carbon than would actually be present, and, thus, a lower level should not present a processing issue.
- The IS-MIO stream introduces a small amount of reduced iron (Fe^{+2}). For evaluation purposes, it was assumed that the proper REDOX control could be obtained in the melter feed by adjusting the formic to nitric ratio. Since the amount of reduced iron is small, this should be a valid assumption.

In order to use the existing DWPF acid addition equation, the inputs have to be measured on the SRAT slurry as is currently performed in the DWPF. Based on the ARP flowsheet studies, minimal impact on the SRAT slurry receipt analysis is anticipated for the MST sorbent material. The other sorbent materials should also not present an analytical issue. However, the ability to analyze the materials in a sludge stream should be demonstrated before being introduced in the DWPF. Particularly, any component present at >0.5 wt% in the glass has to be reported to meet Waste Acceptance Product Specifications.

For the four alternatives, no significant variation was seen in the acid demand of the individual SWPF sorbent streams. This is because no substantial differences in the feed stream compositions were assumed other than the sorbent itself. Some differences were seen in the calculated values for the total and insoluble solids associated with each sorbent stream, which also affected the organics, Hg and Mn input parameters. However, the overall impact to the acid addition requirement was minimal. Also, the acid demand for the four alternatives was equivalent to the acid demand of the baseline MST SWPF stream.

Table 5-1 provides the inputs for the acid calculation in each of the cases when combined with nominal 6,000 gallons of sludge. Although the inputs change slightly for each case, the overall acid demand remained constant, as did the relative concentration of formic to nitric acid. Therefore, no impacts on acid demand are anticipated for any of the options relative to the baseline MST process.

Due to the presence of a small quantity of reduced iron in the IS-MIO stream, methods may have to be developed to quantify its concentration in DWPF. The existing acid addition equation and associated REDOX equation assume that all of the iron introduced into the SRAT process is oxidized; therefore, an iron term does not exist in the REDOX equation but a $\text{Fe}^{2+}/\Sigma\text{Fe}$ of 0.2 is targeted based on other input parameters. Studies will have to be performed to demonstrate that the contribution from the IS-MIO stream is insignificant when estimating the glass REDOX or the existing equation will have to be modified to account for its contribution. Until those studies are completed, it is not known whether the SRAT receipt analysis strategy will require modification. The IS-MIO stream is the only case that presents this problem.

Table 5-1. Inputs for the DWPF Acid Addition Calculation.

Input Parameter	MST	Optimized MST	Engineered MST Case A	Engineered MST Case B	IS-MIO
Sludge amount (gal)	6,000	6,000	6,000	6,000	6,000
SWPF stream amount (gal)	10,858	10,818	10,847	11,018	10,838
Estimated SWPF density (lb/gal)	11.7	13.5	12.1	10.4	12.4
SRAT Receipt Mass (kg)	28,233	28,064	28,114	28,790	28,150
Nitrite (mg/kg)	17,904	18,012	17,980	17,558	17,957
Hydroxide (Eq/l)	0.544	0.544	0.544	0.544	0.544
Total Inorganic Carbon (mg/kg)	1090	1097	1095	1069	1093
Hg (wt% in solids)	0.107	0.109	0.109	0.099	0.108
Mn (wt% in solids)	3.54	3.62	3.60	3.29	3.58
Total Solids (Wt%)	25.9	25.5	25.6	27.4	25.7
Insoluble Solids (Wt%)	18.0	17.5	17.6	19.6	17.7
Nitrate (mg/kg)	16,186	16,284	16,254	15,873	16,638
Density (g/ml)	1.24	1.24	1.24	1.27	1.24
Oxalate (mg/kg)	3202	3222	3216	3141	3212
Organics (wt% in solids)	0.074	0.104	0.093	0.038	0.090
Acid Demand (moles/l of slurry)	1.38	1.38	1.38	1.38	1.38
Formic Acid Percentage	94%	94%	94%	94%	94%

In addition to the acid addition strategy, the CPC must also consider the processing time associated with the additions of the various quantities and types of sorbents. Incoming sludge (~6000 gallons) is received in the CPC in the SRAT that contains a heel of treated sludge (~1500 gallons) from the previous batch. Flush water (~1500 gallons) is also transferred as part of the operations. The sludge is heated to below boiling and then nitric and formic acids are added. The vessel contents are then heated to boiling and the treated sludge is concentrated to obtain a nominal process volume of 6,000 gallons. After concentration, the contents are boiled in reflux conditions for 12 hours to complete the necessary reactions. Currently the DWPF's baseline boil-up rate is 5,000 pounds (of liquid) per hour, but recently a boil-up rate of ~2,500 pounds per hour is more prototypic. A typical sludge transfer takes 10 hours in DWPF with the entire SRAT cycle taking ~84 hours⁴. For the volume/mass of materials associated with the different SWPF sorbent streams (see Table 4-4), the DWPF processing time would be increased 18 – 36 hours assuming a boil-up rate between the prototypic and baseline could be obtained throughout the required boiling time which seems reasonable given the relatively small increase in total solids and the

⁴ Personal communication with P. Patel (DWPF Engineering).

composition of the solids. This time does not include any additional time required for material transfers (which traditionally take 10 hours) and time needed to cool and reheat the vessel, since all of the material cannot be transferred at once due to the volume limitations of the SRAT vessel and the transfers are not performed at elevated temperatures. As stated above the entire SRAT cycle usually takes ~84 hours; therefore, the cycle time in the SRAT would easily be increased ~50% with the SWPF stream incorporated. During ARP flowsheet development, the DWPF expressed the preference for performing these process steps sequentially instead of simultaneously. In other words, material would be transferred, concentration would be performed, and then additional material would be transferred or sampled depending on the stage of the process. Based on the listed assumptions, no real differences in processing time are evident between the baseline MST SWPF stream and the alternative streams.

DWPF CPC operations and melter feed processing both rely heavily on the rheological behavior of the sludge slurry. The DWPF's SB2 had significant problems with feed transfers and melter feeding. Problems in these areas can result in reduced melter production, which in turn reduces the number of canisters produced from DWPF. Therefore, any changes to the feed slurry must consider the impact on slurry rheology (e.g., slurry yield stress). Addition of a SWPF stream into the DWPF will increase the solids concentration and change the type of solids (composition and particle size) that are introduced. Based on the limited information available, the Engineered MST Case B would appear to be the feed most out of the range of existing DWPF processing. It has a total and insoluble solids content that is higher than the remaining cases. The SWPF waste streams may also change the chemical composition or pH of the slurry. All of these have the potential to negatively affect rheology. In addition, the rheology of the feed may change as a result of caustic boiling and concentration of the SWPF stream prior to acid addition. Caustic boiling of the slurry presents different processing issues than the current DWPF acid boiling process. In the ARP studies, caustic boiling was acceptable at solids concentrations similar to those used in the DWPF SRAT process.

To fully understand the effects of the SWPF streams on rheology, simulant studies should be performed. Included in these studies should be appropriately sized sorbent material so agglomeration effects during processing can be investigated. The studies should also provide the opportunity to test the current antifoam addition strategy, which is used to mitigate foaming in the process vessels, and acid addition strategies to assist with slurry rheological properties.

This section addressed the potential CPC processing impacts from the alternative sorbent streams and different volumes associated with these streams. Compared to the baseline MST sorbent and process, no increase in acid demand would be expected for the alternative sorbents. For the IS-MIO case, additional studies would have to be performed to account for the impacts of the reduced iron on the targeted REDOX. Of greater concern are the potential impacts on process rheology, which can not be ascertained without actual testing of the sorbent materials. The Engineered MST Case B appears to present the largest challenge with respect to rheology since it contains the highest total and insoluble solids content. It also has the greatest impact on sludge composition, which may also affect the sludge rheology.

6.0 IMPACTS TO GLASS PROPERTIES: THE STRATEGY OR APPROACH

Using the available Product Composition Control System (PCCS) models (Brown, Postles and Edwards (2002)), the alternative sorbents were assessed in terms of the predicted impacts and projected operating windows relative to the Frit 202 – SB3 with the baseline SWPF stream containing MST flowsheet. In this section, the approach or strategy to make such comparisons is presented. It should be noted that the assessments are solely model-based. That is, the operating windows (defined in terms of waste loadings over which acceptable glasses can be made) will be projected using compositional-property models that are currently defined in PCCS. No experimental work was performed as a part of this assessment.

Two stages of investigation have been proposed by Peeler and Edwards (2002) to assess various frit/sludge combinations: the Nominal Stage and the Variation Stage. In this study, the Nominal Stage utilizes nominal compositions representing the combination of Frit 202 and the various SRAT products resulting from the introduction of the MST baseline or alternative sorbent streams into the SB3 flowsheet. In general, this stage is used to provide or project the operational windows (in terms of waste loadings allowed) for the nominal compositions considered. It is important to note that during this stage, composition variation in the sludge is not accounted for – strictly nominal compositions are considered. Assessments are made using predictions from models currently implemented in the DWPF over the waste loading (WL) interval of interest (25 – 60 wt%). The primary property predictions assessed include those for liquidus temperature (T_L), viscosity (η), durability (e.g., normalized boron release – NL [B]), the constraints associated with durability (Al_2O_3 and sum of alkali), and specific solubility limits (e.g., SO_4^{2-} and TiO_2). It should be noted that the projected operating windows did not account for potential canister dose rates that could exceed acceptance levels due to high concentrations of Cs.

The intent or focus of the Variation Stage (Stage 2) assessment is to gain insight into the robustness of the system with respect to compositional variation. Although an extremely valuable tool, the Variation Stage was not used for this study. All assessments were performed on nominal compositions.

7.0 MEASUREMENT ACCEPTABILITY REGION (MAR) LIMITS USED FOR THE ASSESSMENTS

The glass 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 ($\eta_{1150^\circ\text{C}}$), T_L (new model), 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 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 are based on satisfying their respective (and most restrictive) MAR limit values. Brown, Postles, and Edwards (2002) provide a detailed discussion of how the MAR limits are utilized in PCCS. It should be noted that the MAR limits are compositionally dependent for some properties (i.e., will change as a function of glass composition); thus a table can not be shown with “standard or set” values. Although the models and acceptance limits are seemingly well-defined, some interesting technical issues result with the introduction of the baseline and alternative sorbents with respect to glass chemistry and model predictions. A brief discussion of the primary compositional concerns, potential model validity issues, and changes to various acceptance criteria is provided below.

The introduction of significant quantities of TiO_2 from the baseline MST, the Optimized MST, and the Engineered MST Case A sorbent cases presents interesting technical issues associated with the application of the compositional-based models and specific individual “solubility” limits within PCCS. Lorier and Jantzen (2003) have provided the technical basis for raising the current 1% TiO_2 limit in PCCS to 2%. The primary driver for this technical baseline change was that introduction of these TiO_2 -based sorbents could result in the individual TiO_2 solubility limit of 1% being exceeded; thus, waste loading would be artificially limited or significant impacts could occur to the projected operating windows. For these assessments, TiO_2 concentrations up to 2% (ignoring measurement uncertainties) were allowed (i.e., were classified as acceptable based on the Slurry Mix Evaporator (SME) acceptability process). For those glasses in which the TiO_2 concentrations exceed 2%, issues regarding the applicability of the T_L model surface as noted by Lorier and Jantzen (2003).

The Engineered MST Case B sorbent results in relatively high Al_2O_3 concentrations in glass (approximately 6.3 – 15.1 wt% over the 25 – 60% WL interval based on the SRAT product shown in Table 3-3. The development of the “new” DWPF T_L model (Brown et al. (2001)) covered a compositional range of Al_2O_3 concentrations of 0.99 to 14.162 wt%. Although the resulting Al_2O_3 concentrations for glasses based on the Engineered MST Case B option exceed the upper range over which the model was developed, the application of the model is valid over most of the WL interval. Although risk exists for using the T_L model to assess glasses whose Al_2O_3 concentrations exceed the 14.162 wt% limit, it is minimal for this extrapolation given other properties are limiting at these higher WLs.

For the IS-MIO based glasses, introduction of reduced and oxidized Fe (FeO and Fe_2O_3) as well as SO_4^{2-} into the flowsheet poses some interesting technical issues and solubility concerns. The introduction of reduced Fe (or FeO) into the flowsheet causes some uncertainties regarding the potential to reoxidize, if necessary, FeO to Fe_2O_3 during the CPC processing. In the development of the IS-MIO SRAT product compositions, the assumption was made that the acid addition strategy to be used would oxidize the necessary amount of iron to meet the DWPF REDOX target. This is a critical assumption (that will need to be confirmed through experimental work)

given that the durability model in PCCS has the potential for accounting for both FeO and Fe₂O₃ (if needed). In particular, the theory supporting the durability model suggests that as the Fe²⁺/ΣFe ratio shifts from a fully oxidized state toward the upper limit of 0.33, the durability of the glass should decrease due to the presence of FeO (Jantzen et al. (1995)). Assuming a targeted Reduction/Oxidation (REDOX) > 0, the durability model in theory partitions the REDOX of select species (e.g., Fe) based on assigned ΔG_i values (Jantzen et al. (1995)). The ΔG_i value for FeO is -21.33 kcal/mol compared to a +14.56 kcal/mol value for Fe₂O₃.⁵ Thus, there is a negative impact on the predicted durability response (via the ΔG_p model) as REDOX shifts from fully oxidized to the REDOX upper limit (for the same targeted glass composition) – the glass is predicted to become less durable. For those systems in which the upper or lower waste loading limit is defined by the ΔG_p SME acceptability criterion, as REDOX transitions from fully oxidized toward the more reduced state, the result will be to reduce the waste loading range over which acceptability would be classified. In theory, the extent or magnitude of the ΔG_p shift (and ultimately the potential impact on the projected operation window) is directly related to the total iron (Fe) concentration and the REDOX shift.

Peeler and Edwards (2003) have recently indicated that the impact of REDOX on durability within the SB3 region (with Frit 418) can be ignored. That is, there was no significant (or practical) effect of REDOX on the measured durability response of a fully oxidized glass and its reduced compositional counterpart for the Frit 418 – SB3 glass system. With Frit 202 being a more refractory frit (less alkali), predictions of durability should not be an issue within the Frit 202-based system with MST or the alternatives being considered. With this assumption, the assessments performed in this study will be based on a fully oxidized system (e.g., the REDOX term will not be activated). It should be noted that if systems become PCT limited based on the introduction of the sorbent waste streams, then there may be a need to reassess the impact of REDOX on durability.

In the assessment of the IS-MIO sorbent case, an evaluation of the Na₂SO₄ solubility limit in glass is also necessary. The current Na₂SO₄ limit in PCCS is 0.59 wt% in glass (or 0.4 wt% expressed as SO₄²⁻).⁶ Initial concerns center on the addition of excessive quantities of SO₄²⁻ (6.6 wt% in the IS-MIO sorbent alone) that would lead to exceeding this predefined glass limit. It should be noted that SO₄²⁻ was not included in the SB3 composition (see Table 3-3) since the actual level for SB3 was higher than the Na₂SO₄ limit given above. For SB3, glass studies were specifically performed to define the SO₄²⁻ limit since it is dependent on the overall glass composition. Since the resulting sludge and SWPF compositions would be different than the existing SB3 glass composition projections, using this experimentally determined limit would not have been technically justified. Therefore, the SB3 contribution was not included and the sorbent streams were compared against each other. Excessive SO₄²⁻ then only becomes a concern if the PCCS limit is exceeded or closely approaches the limit with no sludge SO₄²⁻ contribution. If the IS-MIO sorbent is introduced into a flowsheet with a high SO₄²⁻ content, the projected concentration of SO₄²⁻ could have a significant impact to the overall flowsheet.

⁵ More positive ΔG_i values enhance the predicted durability.

⁶ For the Frit 418 – SB3 system, Peeler et al. (2004) established a SO₄ limit in PCCS of 0.60 wt% in glass (or 0.88 wt% expressed as Na₂SO₄) assuming a portion of a Np-based stream from H-Canyon would be transferred. In that study, the SO₄ solubility was found to be a function of waste loading or overall glass composition and therefore the more conservative limit (0.4 wt%) will be used in this assessment. Application of this lower limit could restrict access to higher WLs (when appropriate this impact will be discussed). However, it should be noted that the SO₄ coming from the Np-based stream is not included in the SB3 base sludge which prompted the need to increase the solubility limit. Therefore, any additional SO₄ coming into this specific system could have a negative impact on the operating window.

8.0 NOMINAL STAGE ASSESSMENTS

Table 8-1 summarizes the MAR-based Nominal Stage assessments. In addition to the MAR-based projected WL interval, the property that restricts access to higher WLs is also provided in parenthesis. The primary objective is to assess the relative impact of the alternative sorbent streams to the projected operating window in relation to the Frit 202 – SB3, baseline SWPF stream containing MST system (shaded in Table 8-1).

Table 8-1. Nominal Stage Assessment Using MAR Criteria.

Option	WL range (limiting property)
MST-Baseline	27 – 43 (T _L)
Optimized MST	27 – 42 (T _L)
Engineered MST – Case A	27 – 42 (T _L)
Engineered MST – Case B	None
IS-MIO	26 – 40 (T _L)

Numerous comparisons can be made with respect to these systems and their impacts to the DWPF process (based on model assessments of projected operating windows and the data presented in the appendices). In general, with the exception of the Engineered MST Case B sorbent, the projected operating windows are relatively equivalent (mid-20's for a lower WL bound ranging to lower 40's for an upper WL bound). The most striking observation from Table 8-1 is the fact that the Engineered MST Case B sorbent results in the complete elimination of the projected operating window.

In the following sections, a more detailed discussion of the projected operating windows is provided for each option. Table A.1 in Appendix A provides a summary of the MAR-based assessments for the MST-baseline as well as the other systems of interest. Table A.2 provides various predicted glass properties for these systems. The nomenclature used in Appendix A is consistent with that used by Peeler and Edwards (2002), and for a detailed discussion, the reader is referred to that report. The following assessments are performed using Frit 202 (unless otherwise specified), the current PCCS models, and associated constraints without any attempt at “optimization”.

8.1 MST-Baseline

The projected operating window for the MST-baseline Frit 202 – SB3 system is 27 – 43% WL. Access to lower WLs is restricted (< 27%) by predictions of high viscosity (viscosity values exceeding the upper control limit of 110 Poise without uncertainties considered). Perhaps of more interest is the upper WL (43%) which this system can achieve based on model predictions. At 44% WL and higher, the glass system becomes T_L limited. As expected, as the sludge WL increases in the MST-baseline option, the predicted T_L increases until the predicted T_L value exceeds the MAR criterion at and above WLs of 44% (see Table A.2 in Appendix A for more details). Given the T_L model is dependent upon the concentration of TiO₂, one could conclude that the contribution of the MST has a significant impact on this predicted and limiting property. However, the DWPF T_L predictions are also a dependent upon Fe₂O₃, Cr₂O₃, NiO, SiO₂, ZrO₂, Na₂O, Li₂O, MgO, MnO, CaO, K₂O, and Al₂O₃ concentrations (Brown et al. 2001) with these

oxides having different impacts to the magnitude of the predicted value based on the associated “coefficients”. That is, the relative concentration and the associated “coefficient” ultimately dictate the predicted T_L value. Therefore, TiO_2 may have a role in determining the T_L value, but may not be the primary contributor given its concentration and “coefficient” product (see Section 8.2 for more discussion).

A primary concern with the addition of MST was the TiO_2 concentration and its impact to T_L or the potential to exceed the individual TiO_2 solubility limit. Concern regarding the individual solubility limit was one of the drivers for the report issued by Lorier and Jantzen (2003) which raised the TiO_2 solubility limit from 1 wt% to 2 wt% (in glass). With respect to the individual solubility limit, the 2% TiO_2 limit (as proposed by Lorier and Jantzen (2003)) is not exceeded until WLs of 53% or greater are reached (which can not be achieved due to predictions of T_L).

As mentioned in Section 7.0, the assessments are being made with the REDOX term in PCCS deactivated. However, predictions of durability are not an issue over the entire 25 – 60% WL interval for the Frit 202 – SB3 with MST baseline system under oxidizing conditions. Given recent DWPF operations have targeted a 0.2 REDOX, the impact of the more reduced system is suggested either through a paper study or experimental assessment.

Although no formal assessment of melt rate (via experimental study) was made, literature suggests that the presence of TiO_2 can have a detrimental effect on melt rate (Plodinec 1979, 1980). It should be noted that this latter statement is qualitative in nature and until quantified for the specific systems of interest should be used with caution (i.e., the option should not be withdrawn based on circumstantial evidence or the presence of relatively high TiO_2 concentrations). Melt rate impacts should be assessed regardless of the sorbent material selected.⁷ It is also noted that use of Frit 202 does provide a relatively large processing window but the predicted viscosities of the glasses within the 25 – 60% WL interval could have a negative effect on melt rate relative to a lower viscosity system via the use of a specifically designed frit.

8.2 Optimized MST

The overall projected operating window for this system is 27 – 42% with predictions of T_L still limiting access to higher WLs. As with the MST-baseline system, predictions of high viscosity restrict access to lower WLs (26% and lower). It is interesting to note that the Optimized MST SRAT product contains significantly less TiO_2 than the MST baseline flowsheet (0.96 versus 3.58 wt%, respectively). This is consistent with the ~75% reduction in MST use per year. Therefore, the TiO_2 concentrations in glass are lower at each WL for the Optimized MST option relative to the MST-baseline which would lead one to speculate that the T_L predictions would be lower. However, this is not the case (see Appendix A, Table A.2 for more details). For example, the T_L predictions at 43% WL for the MST-baseline and Optimized MST flowsheet are 1016.93°C and 1027.14°C, respectively. Given TiO_2 concentrations in glass (at 43% WL) are 1.54 and 0.41 wt%, respectively, this suggests that the concentrations of other components are the driver for T_L predictions in the two systems (i.e., the coefficient for TiO_2 is small within the new DWPF T_L model). Regardless, the introduction of the Optimized MST sorbent results in a 1% reduction in the upper WL that can be achieved relative to the MST-baseline flowsheet.

⁷ Experimental assessments of melt rate or waste throughput are not evaluated in this report. The reader should be aware that the melt rate program is a critical component of the integrated glass formulation strategy as it ensures that what appears attractive on paper (in terms of model-based WL ranges) does not result in a difficult feed to process. In fact, historical information indicates that the maximum waste throughput is not obtained at the maximum WL but at some lower, intermediate value within the projected operating window.

With respect to the 2% TiO_2 solubility limit, the assessment indicates that this limit is not exceeded over the entire WL range from 25 – 60%. The highest TiO_2 concentration in glass is 0.58 wt% at 60% WL – well below the current 1% limit or proposed 2% limit. In addition, predictions of durability are not an issue over the entire WL interval as would be expected for high viscosity or T_L limited systems.

The 1% decrease in WL for the optimized flowsheet (relative to the MST-baseline flowsheet) may be off-set by an assessment of melt rate or differences in the estimated process volumes of the sludge and SWPF stream which ultimately could dictate waste throughput issues. Previous testing has indicated that the maximum waste throughput is not achieved at the maximum WL obtained via model predictions but at some intermediate WL value (Smith et al. 2003, Lorier et al. 2003). Without a formal assessment of melt rate, the “breakpoint” in waste throughput can not be determined. Given the lower TiO_2 levels in the Optimized MST flowsheet, there may be an advantage in melt rate given the conclusion drawn by Plodinec (1979, 1980) that the presence of TiO_2 can have a detrimental effect on melt rate. It should be noted that this latter statement is qualitative in nature and until quantified for the specific systems of interest should be used with caution (i.e., the option should not be withdrawn based on circumstantial evidence). From a glass formulation and projected operational window perspective, there is not a significant difference between the MST and Optimized MST options. An advantage, however, may come from CPC process issues since smaller volumes of sorbent material would be processed in the CPC for the Optimized MST case.

8.3 Engineered MST Case A

Introduction of the Engineered MST Case A option has essentially no effect on the projected operational window relative to the MST-baseline case. More specifically, the projected operating window is 27 – 42% WL as compared to the 27 – 43% window for the MST-baseline process. As with the Optimized MST case, the 1% reduction in WL could be negligible (as compared to the baseline) given similar melt rates and sludge volumes to process. At WLs less than 27%, high viscosity predictions are limiting; while at WLs of 43% or greater, predictions of T_L are limiting. Again, the relatively high TiO_2 concentrations in the SRAT product (2.07 wt%) do not appear to have a significant impact on the upper WL that can be achieved. The 2% TiO_2 solubility limit is not exceeded over the entire 25 – 60% WL interval (1.24 wt% being the maximum amount in glass based on the 2.06 wt% in the SRAT at 60% WL). Predictions of durability are not an issue for this system.

8.4 Engineered MST Case B

Introduction of the Engineered MST Case B option has an extremely negative impact on the projected operating window (relative to the MST-baseline case). More specifically, an operating window is non-existent for this case. Predictions of high viscosity restrict processing from 25 – 37% WL; while predictions of T_L limit access to WLs of 38% or higher. The primary reason for the non-existent window is the fact that the Engineered MST Case B SRAT product is extremely high in Al_2O_3 (25.2 wt%) and low in Na_2O (19.88 wt%) as compared to the MST-baseline (as well as other alternative sorbent) SRAT products. The high Al_2O_3 content and low Na_2O content of the Frit 202 – SB3 system result in increased predicted values for viscosity and T_L . Thus, the Engineered MST Case B sorbent could not be processed with Frit 202 and SB3. However, this option should not be ruled out from further consideration (from a glass formulation perspective)

given the possible use of an alternative frit to restore the projected operating window (see Section 8.6).

8.5 IS-MIO

The overall projected operating window with the addition of the IS-MIO option is 26 – 40% WL. As with all systems, access to lower WLs is restricted by the predictions of high viscosity. At 41% WL, the IS-MIO-based flowsheet becomes T_L limited – again, similar to the other flowsheets. The 2% reduction in the maximum WL attainable relative to the MST-baseline flowsheet may be significant if melt rates are assumed to be equivalent at each WL and the maximum waste throughput is achieved at 41 or 42% WL.

A primary concern with the addition of IS-MIO process was the introduction of SO_4^{2-} to the overall flowsheet. Based on the assessments, the SO_4^{2-} concentrations in glass do not exceed the 0.4 wt% constraint in PCCS over the entire WL interval of 25 – 60%. The maximum amount of SO_4^{2-} in glass is 0.13 wt% which occurs at 60% WL with 0.222 wt% SO_4^{2-} in the IS-MIO SRAT product.⁸ Although the SO_4^{2-} solubility limit was not exceeded with the introduction of the IS-MIO process (i.e., did not limit the projected operating window), its introduction into a sludge batch with (or accounting for) SO_4^{2-} could make this single point solubility limit a constraining parameter.

8.6 Impact of Frit Composition Changes

In this section, Frit 433 (a less refractory (more alkali) containing frit as compared to Frit 202) is applied to each option to demonstrate the impact of frit composition on the projected operating windows. The primary interest is focused on the Engineered MST Case B flowsheet and the fact that Frit 202 was consistently used to assess each option without consideration of alternative frits to compensate for the compositional differences for the incoming SRAT products. Application of Frit 202 with the Engineered MST Case B sorbent resulted in the complete elimination of the projected operating window.

Frit 433 should not be considered an “optimized” frit for the Engineered MST Case B option. As with Frit 202, it is being used out of convenience, and based on previous glass formulation experience its composition should have a positive impact for the introduction of the Engineered MST Case B option into the DWPF process. In fact, its use may have negative impacts on the MST baseline and other alternative sorbents being considered relative to Frit 202.

Table 8-2 summarizes the projected operational windows for the MST-baseline and other alternative sorbents with the use of Frit 433. In this assessment, the same SRAT compositions (shown in Table 3-3) are used, with the difference being that the sludges are now coupled with Frit 433 instead of Frit 202.

The most striking feature about Table 8-2 is the fact that the only system that has an operating window is the Engineered MST Case B option. All other flowsheets (including the MST baseline) have no operational window – each being limited by predictions of durability over the entire 25 – 60% WL range. The application of Frit 433 converts the once T_L limited systems to durability limited systems resulting in complete closure of the projected operating windows. This

⁸ The SB3 sludge used in this assessment did not account for any SO_4 concentration associated with SB3 (see Table 3-3).

implies that a frit lying between Frit 202 and Frit 433 (in terms of composition) may be “optimal” with respect to the model-based projected operating windows.

For the Engineered MST Case B option and Frit 433, the projected operating window is 25 – 49% WL with the system being T_L limited at WLs of 50% or greater. This projected operating window shows a significant advantage over the MST-baseline and other alternative sorbents with the use of Frit 202 (where the highest WL attainable was 43% for the MST-baseline process). This demonstrates the ability of frit development efforts to compositionally compensate for the incoming sludge to develop larger operating windows.

Although a significant advantage in terms of the projected WL is shown for the Engineered MST Case B option with Frit 433 relative to the Frit 202 based systems, caution should be used to make the conclusion that the projected operating windows could not be altered through the use of strategic frit development approaches. In fact, a high probability exists that the “WL gap” between the different systems could be minimized by strategic frit development efforts.

Table 8-2. Comparison of Frit 202 and Frit 433.

Option	Frit 202	Frit 433
MST-Baseline	27 – 43 (T_L)	None
Optimized MST	27 – 42 (T_L)	None
Engineered MST – Case A	27 – 42 (T_L)	None
Engineered MST – Case B	None	25– 49 (T_L)
IS-MIO	26 – 40 (T_L)	None

The bottom line is that introduction of the SWPF waste stream should not be made in a vacuum ignoring the potential impacts to the overall process. In fact, if these streams are well characterized and blending strategies are known in advance, frit development efforts can account or compositionally compensate for these streams resulting in projected operating windows of relatively large size covering a WL range of interest to DWPF. The unknown factor is the assessment of melt rate which lowers the probability that what appears attractive on paper (based on model predictions only) does not result in a difficult feed to process.

8.7 Impact to Canister Production Total

In this section, the impact of the alternative sorbents on the projected DWPF canister count (i.e., the number of canisters resulting from the introduction of the sorbent) is made. This approach is independent of a canister production rate approach (i.e., no melter throughput considerations) which would require an assessment of melt rate for each system to determine the WL at which maximum waste throughput occurs.

The approach makes the assumptions that melt rates are constant among the various options at each WL and that melt rate increases with increased WL (a trend that has not been observed in previous tests but one that would drive DWPF to target the maximum WL achievable). Therefore, the system demonstrating access to higher WLs could have an advantage in terms of minimizing the number of canisters assuming sludge and SWPF volumes are comparable. This approach basically uses the maximum WLs shown in this report (with either Frit 202 or Frit 433) and draws general conclusions regarding the number of canisters that each system would produce (per year). Obviously, the fact that maximum WLs were not “optimized” for each system

provides a measure of uncertainty and potential bias in the projected number of canisters. The primary drivers for this assessment are the upper WL that can be achieved and the volume of sludge to be processed.

The total number of canisters that would be produced (per year) was calculated as follows:

$$\frac{\text{Total canisters}}{\text{year}} = \left(\frac{\text{kgs sludge}}{\text{year}} \right) \left(\frac{\text{lbs sludge}}{\text{kg sludge}} \right) \left(\frac{\text{lbs glass}}{\text{lbs sludge}} \right) \left(\frac{\text{canister}}{\text{lb glass}} \right)$$

The total mass (kgs) of sludge per year was obtained based on the mass of sludge per SRAT batch and assuming 45 SRAT batches were processed in a year (see discussion in Section 5.0 for more detail). The total mass (in kgs) was then converted to pounds of sludge (multiply by 2.2). To determine the amount of glass produced for each sorbent option, the total mass of sludge was divided by the maximum attainable WL based on model predictions. Assuming 4000 lbs of glass per DWPF canister, the total number of canisters produced per year was computed for each option.

Table 8-3 summarizes the total sludge mass per year, maximum achievable WL (per the model-based predictions), the kgs of glass produced per year, and the estimated total number of canisters for each option. The minimum number of canisters produced (299) within a year is based on the Engineered MST – Case B option. The maximum number of canisters produced (325) results from the IS-MIO process. The difference (26 canisters) is not viewed as significant given the assumptions made.

Table 8-3. Maximum WL, Sludge Volume, and Estimated # of Canisters for Each Option.

Option	Total Mass / Batch (kgs)	Total Mass / year⁹ (kgs)	Maximum WL (%, oxide basis)	kgs of glass produced / year¹⁰	# of Canisters / year¹¹
MST-Baseline	5353.9	240,926	43	560,293	308
Optimized MST	5184.7	233,311	42	555,502	306
Engineered MST – Case A	5235.1	235,581	42	560,908	309
Engineered MST – Case B ¹²	5911.0	265,997	49	542,851	299
IS-MIO	5250.1	236,253	40	590,633	325

⁹ Total mass per year assumes 45 SRAT batches are processed.

¹⁰ Kg of glass produced per year is the mass of SRAT product (sludge and sorbent) divided by the maximum WL.

¹¹ # of canisters is calculated by converting the kgs of glass produced per year to lbs of glass produced per year (multiply by 2.2) then dividing by 4000 lbs (estimated amount of glass in a DWPF canister).

¹² # of canisters for the Engineered MST – Case B option is based on the use of Frit 433; whereas all other options are based on the use of Frit 202.

9.0 SUMMARY

The objective of this report was to evaluate the relative impacts of alternative Sr/actinide removal process sorbents on the Defense Waste Processing Facility (DWPF). The specific processes evaluated included: (1) optimized MST, (2) Engineered MST Case A, (3) Engineered MST Case B, and (4) IS-MIO. The impacts were assessed relative to the Frit 202 – SB3 and SWPF stream containing MST flowsheet (the current baseline technology) and included processing issues associated primarily with the Chemical Processing Cell (CPC) and projected operating windows (which were based on model predictions and were represented in terms of a waste loading interval). In addition, the total number of canisters (per year) produced for each option was assessed.

Based on the limited assessments, all of the options being considered are still plausible from a DWPF CPC and glass formulation perspective. Compared to the baseline MST sorbent and process, no increase in acid demand would be expected for the alternative sorbents and no significant processing differences have been identified with any option based on the paper assessment. With respect to projected operating windows, the Optimized MST, Engineered MST Case A, and IS-MIO options resulted in upper WLs of 42, 42, and 40%, respectively, as compared to the MST baseline of 43% WL. The use of Frit 202 with the Engineered MST Case B sorbent resulted complete elimination of the operating window. However, use of Frit 433 with the Engineered MST Case B sorbent result in a higher projected upper WL of 49% as compared to the MST baseline. Although a potentially significant advantage in terms of the projected WL is shown for the Engineered MST Case B option with Frit 433 relative to the Frit 202-based systems, caution should be used in making the conclusion that the projected operating windows could not be altered through the use of strategic frit development approaches. In fact, a high probability exists that the “WL gap” among the different systems could be minimized by strategic frit development efforts.

Projections regarding the total number of cans produced annually suggested very little differences among the various options. The difference among the options in terms of canister count was approximately 26 per year, which is not viewed as significant given the assumptions made.

10.0 FUTURE WORK

Based on the limited assessments performed in this study, all of the sorbent options being considered are plausible from a DWPF CPC and glass formulation perspective. However, various issues regarding the processability of the feed through the CPC and melter have not been assessed. These open issues are outlined below and there is a need to:

- (1) Demonstrate processability of the sorbent streams with stimulant studies
 - with respect to the CPC, issues associated with rheology, particle size, anti-foam additions, H₂ generation, and SRAT processing time are of interest
 - a. the Engineered MST Case B appears to present the largest challenge with respect to rheology since it contains the highest total and insoluble solids content
 - with respect to the melter, issues associated with melt rate and cold cap behavior are of interest to reduce the risk that what appears attractive on paper (based on model-based predictions) does not result in a difficult feed to process
 - a. other potential processing issues associated with carry-over organics should be evaluated with respect to melter flammability concerns
- (2) Address potential analytical “needs” associated with the sorbent materials
- (3) Perform frit development activities to “optimize” the flowsheet with respect to projected operating windows and melt rate
- (4) Address potential REDOX issues associated with CPC processing and product performance (durability)
- (5) Assess SO₄²⁻ solubility limits with the IS-MIO process if it is being considered for implementation with a high SO₄²⁻-based sludge
- (6) Assess the potential for the projected operating window to be limited by canister dose rates instead of model predictions (especially at high WLs)

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APPENDIX A

MAR Results for Nominal Stage Assessments

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	MAR Status
MST Baseline Frit 202	25	hvisc
MST Baseline Frit 202	26	hvisc
MST Baseline Frit 202	27	-
MST Baseline Frit 202	28	-
MST Baseline Frit 202	29	-
MST Baseline Frit 202	30	-
MST Baseline Frit 202	31	-
MST Baseline Frit 202	32	-
MST Baseline Frit 202	33	-
MST Baseline Frit 202	34	-
MST Baseline Frit 202	35	-
MST Baseline Frit 202	36	-
MST Baseline Frit 202	37	-
MST Baseline Frit 202	38	-
MST Baseline Frit 202	39	-
MST Baseline Frit 202	40	-
MST Baseline Frit 202	41	-
MST Baseline Frit 202	42	-
MST Baseline Frit 202	43	-
MST Baseline Frit 202	44	T _L
MST Baseline Frit 202	45	T _L
MST Baseline Frit 202	46	T _L
MST Baseline Frit 202	47	T _L
MST Baseline Frit 202	48	T _L
MST Baseline Frit 202	49	T _L
MST Baseline Frit 202	50	T _L
MST Baseline Frit 202	51	T _L , lvisc
MST Baseline Frit 202	52	T _L , lvisc
MST Baseline Frit 202	53	T _L , lvisc
MST Baseline Frit 202	54	T _L , lvisc, TiO ₂
MST Baseline Frit 202	55	T _L , lvisc, TiO ₂
MST Baseline Frit 202	56	T _L , lvisc, TiO ₂
MST Baseline Frit 202	57	T _L , lvisc, TiO ₂
MST Baseline Frit 202	58	T _L , lvisc, TiO ₂
MST Baseline Frit 202	59	T _L , lvisc, TiO ₂
MST Baseline Frit 202	60	T _L , lvisc, TiO ₂

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	MAR Status
MST Optimized Frit 202	25	hvisc
MST Optimized Frit 202	26	hvisc
MST Optimized Frit 202	27	-
MST Optimized Frit 202	28	-
MST Optimized Frit 202	29	-
MST Optimized Frit 202	30	-
MST Optimized Frit 202	31	-
MST Optimized Frit 202	32	-
MST Optimized Frit 202	33	-
MST Optimized Frit 202	34	-
MST Optimized Frit 202	35	-
MST Optimized Frit 202	36	-
MST Optimized Frit 202	37	-
MST Optimized Frit 202	38	-
MST Optimized Frit 202	39	-
MST Optimized Frit 202	40	-
MST Optimized Frit 202	41	-
MST Optimized Frit 202	42	-
MST Optimized Frit 202	43	T _L
MST Optimized Frit 202	44	T _L
MST Optimized Frit 202	45	T _L
MST Optimized Frit 202	46	T _L
MST Optimized Frit 202	47	T _L
MST Optimized Frit 202	48	T _L
MST Optimized Frit 202	49	T _L
MST Optimized Frit 202	50	T _L
MST Optimized Frit 202	51	T _L , lvisc
MST Optimized Frit 202	52	T _L , lvisc
MST Optimized Frit 202	53	T _L , lvisc
MST Optimized Frit 202	54	T _L , lvisc
MST Optimized Frit 202	55	T _L , lvisc
MST Optimized Frit 202	56	T _L , lvisc
MST Optimized Frit 202	57	T _L , lvisc
MST Optimized Frit 202	58	T _L , lvisc
MST Optimized Frit 202	59	T _L , lvisc
MST Optimized Frit 202	60	T _L , lvisc
Engr MST Case A Frit 202	25	hvisc

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	MAR Status
Engr MST Case A Frit 202	26	hvisc
Engr MST Case A Frit 202	27	-
Engr MST Case A Frit 202	28	-
Engr MST Case A Frit 202	29	-
Engr MST Case A Frit 202	30	-
Engr MST Case A Frit 202	31	-
Engr MST Case A Frit 202	32	-
Engr MST Case A Frit 202	33	--
Engr MST Case A Frit 202	34	-
Engr MST Case A Frit 202	35	-
Engr MST Case A Frit 202	36	-
Engr MST Case A Frit 202	37	-
Engr MST Case A Frit 202	38	-
Engr MST Case A Frit 202	39	-
Engr MST Case A Frit 202	40	-
Engr MST Case A Frit 202	41	-
Engr MST Case A Frit 202	42	-
Engr MST Case A Frit 202	43	T _L
Engr MST Case A Frit 202	44	T _L
Engr MST Case A Frit 202	45	T _L
Engr MST Case A Frit 202	46	T _L
Engr MST Case A Frit 202	47	T _L
Engr MST Case A Frit 202	48	T _L
Engr MST Case A Frit 202	49	T _L
Engr MST Case A Frit 202	50	T _L
Engr MST Case A Frit 202	51	T _L , lvisc
Engr MST Case A Frit 202	52	T _L , lvisc
Engr MST Case A Frit 202	53	T _L , lvisc
Engr MST Case A Frit 202	54	T _L , lvisc
Engr MST Case A Frit 202	55	T _L , lvisc
Engr MST Case A Frit 202	56	T _L , lvisc
Engr MST Case A Frit 202	57	T _L , lvisc
Engr MST Case A Frit 202	58	T _L , lvisc
Engr MST Case A Frit 202	59	T _L , lvisc
Engr MST Case A Frit 202	60	T _L , lvisc
Engr MST Case B Frit 202	25	hvisc
Engr MST Case B Frit 202	26	hvisc

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	MAR Status
Engr MST Case B Frit 202	27	hvisc
Engr MST Case B Frit 202	28	hvisc
Engr MST Case B Frit 202	29	hvisc
Engr MST Case B Frit 202	30	hvisc
Engr MST Case B Frit 202	31	hvisc
Engr MST Case B Frit 202	32	hvisc
Engr MST Case B Frit 202	33	hvisc
Engr MST Case B Frit 202	34	hvisc
Engr MST Case B Frit 202	35	hvisc
Engr MST Case B Frit 202	36	hvisc
Engr MST Case B Frit 202	37	hvisc
Engr MST Case B Frit 202	38	T _L
Engr MST Case B Frit 202	39	T _L
Engr MST Case B Frit 202	40	T _L
Engr MST Case B Frit 202	41	T _L
Engr MST Case B Frit 202	42	T _L
Engr MST Case B Frit 202	43	T _L
Engr MST Case B Frit 202	44	T _L
Engr MST Case B Frit 202	45	T _L
Engr MST Case B Frit 202	46	T _L
Engr MST Case B Frit 202	47	T _L
Engr MST Case B Frit 202	48	T _L
Engr MST Case B Frit 202	49	T _L
Engr MST Case B Frit 202	50	T _L
Engr MST Case B Frit 202	51	T _L
Engr MST Case B Frit 202	52	T _L
Engr MST Case B Frit 202	53	T _L
Engr MST Case B Frit 202	54	T _L
Engr MST Case B Frit 202	55	T _L
Engr MST Case B Frit 202	56	T _L
Engr MST Case B Frit 202	57	T _L
Engr MST Case B Frit 202	58	T _L
Engr MST Case B Frit 202	59	T _L
Engr MST Case B Frit 202	60	T _L
ISMIO Frit 202	25	hvisc
ISMIO Frit 202	26	-
ISMIO Frit 202	27	-

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	MAR Status
ISMIO Frit 202	28	-
ISMIO Frit 202	29	-
ISMIO Frit 202	30	-
ISMIO Frit 202	31	-
ISMIO Frit 202	32	-
ISMIO Frit 202	33	-
ISMIO Frit 202	34	-
ISMIO Frit 202	35	-
ISMIO Frit 202	36	-
ISMIO Frit 202	37	-
ISMIO Frit 202	38	-
ISMIO Frit 202	39	-
ISMIO Frit 202	40	-
ISMIO Frit 202	41	T _L
ISMIO Frit 202	42	T _L
ISMIO Frit 202	43	T _L
ISMIO Frit 202	44	T _L
ISMIO Frit 202	45	T _L
ISMIO Frit 202	46	T _L
ISMIO Frit 202	47	T _L
ISMIO Frit 202	48	T _L
ISMIO Frit 202	49	T _L
ISMIO Frit 202	50	T _L , lvisc
ISMIO Frit 202	51	T _L , lvisc
ISMIO Frit 202	52	T _L , lvisc
ISMIO Frit 202	53	T _L , lvisc
ISMIO Frit 202	54	T _L , lvisc
ISMIO Frit 202	55	T _L , lvisc
ISMIO Frit 202	56	T _L , lvisc
ISMIO Frit 202	57	T _L , lvisc
ISMIO Frit 202	58	T _L , lvisc
ISMIO Frit 202	59	T _L , lvisc
ISMIO Frit 202	60	T _L , lvisc

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
MST Baseline Frit 202	25	-9.0326	833.88	106.14	3.66	0.8942	0.02	15.77	18.64
MST Baseline Frit 202	26	-9.1097	846.61	102.01	3.81	0.9300	0.03	15.88	18.64
MST Baseline Frit 202	27	-9.1867	858.97	97.94	3.95	0.9658	0.03	15.99	18.64
MST Baseline Frit 202	28	-9.2638	870.93	93.93	4.10	1.0015	0.03	16.10	18.64
MST Baseline Frit 202	29	-9.3409	882.59	89.98	4.25	1.0373	0.03	16.22	18.64
MST Baseline Frit 202	30	-9.4179	893.93	86.10	4.39	1.0731	0.03	16.33	18.64
MST Baseline Frit 202	31	-9.4950	904.95	82.29	4.54	1.1089	0.03	16.44	18.64
MST Baseline Frit 202	32	-9.5721	915.64	78.55	4.69	1.1446	0.03	16.55	18.64
MST Baseline Frit 202	33	-9.6491	926.07	74.88	4.83	1.1804	0.03	16.66	18.64
MST Baseline Frit 202	34	-9.7262	936.24	71.28	4.98	1.2162	0.03	16.77	18.64
MST Baseline Frit 202	35	-9.8033	946.14	67.75	5.13	1.2519	0.03	16.88	18.64
MST Baseline Frit 202	36	-9.8803	955.76	64.31	5.27	1.2877	0.04	16.99	18.64
MST Baseline Frit 202	37	-9.9574	965.17	60.94	5.42	1.3235	0.04	17.10	18.64
MST Baseline Frit 202	38	-10.0345	974.34	57.66	5.57	1.3592	0.04	17.21	18.64
MST Baseline Frit 202	39	-10.1115	983.29	54.46	5.71	1.3950	0.04	17.32	18.64
MST Baseline Frit 202	40	-10.1886	991.98	51.34	5.86	1.4308	0.04	17.44	18.64
MST Baseline Frit 202	41	-10.2656	1000.51	48.31	6.01	1.4666	0.04	17.55	18.64
MST Baseline Frit 202	42	-10.3427	1008.83	45.37	6.15	1.5023	0.04	17.66	18.64
MST Baseline Frit 202	43	-10.4197	1016.93	42.52	6.30	1.5381	0.04	17.77	18.64
MST Baseline Frit 202	44	-10.4968	1024.87	39.77	6.44	1.5739	0.04	17.88	18.64
MST Baseline Frit 202	45	-10.5738	1032.63	37.10	6.59	1.6096	0.04	17.99	18.64
MST Baseline Frit 202	46	-10.6509	1040.22	34.54	6.74	1.6454	0.04	18.10	18.64
MST Baseline Frit 202	47	-10.7280	1047.60	32.06	6.88	1.6812	0.05	18.21	18.63

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
MST Baseline Frit 202	48	-10.8051	1054.86	29.69	7.03	1.7169	0.05	18.32	18.63
MST Baseline Frit 202	49	-10.8821	1061.96	27.41	7.18	1.7527	0.05	18.43	18.62
MST Baseline Frit 202	50	-10.9592	1068.90	25.24	7.32	1.7885	0.05	18.54	18.62
MST Baseline Frit 202	51	-11.0363	1075.67	23.16	7.47	1.8242	0.05	18.66	18.61
MST Baseline Frit 202	52	-11.1133	1082.33	21.18	7.62	1.8600	0.05	18.77	18.61
MST Baseline Frit 202	53	-11.1904	1088.84	19.31	7.76	1.8958	0.05	18.88	18.61
MST Baseline Frit 202	54	-11.2675	1095.19	17.53	7.91	1.9316	0.05	18.99	18.60
MST Baseline Frit 202	55	-11.3446	1101.45	15.85	8.06	1.9673	0.05	19.10	18.60
MST Baseline Frit 202	56	-11.4216	1107.57	14.28	8.20	2.0031	0.05	19.21	18.59
MST Baseline Frit 202	57	-11.4985	1113.58	12.80	8.35	2.0389	0.06	19.32	18.59
MST Baseline Frit 202	58	-11.5756	1119.44	11.42	8.50	2.0746	0.06	19.43	18.58
MST Baseline Frit 202	59	-11.6527	1125.21	10.14	8.64	2.1104	0.06	19.54	18.58
MST Baseline Frit 202	60	-11.7298	1130.87	8.95	8.79	2.1462	0.06	19.65	18.57
MST Optimized Frit 202	25	-9.1792	837.00	105.24	3.78	0.2399	0.03	15.84	18.64
MST Optimized Frit 202	26	-9.2621	850.09	101.11	3.93	0.2495	0.03	15.95	18.64
MST Optimized Frit 202	27	-9.3450	862.84	97.03	4.08	0.2591	0.03	16.06	18.64
MST Optimized Frit 202	28	-9.4280	875.19	93.02	4.23	0.2687	0.03	16.18	18.64
MST Optimized Frit 202	29	-9.5109	887.25	89.07	4.39	0.2783	0.03	16.29	18.64
MST Optimized Frit 202	30	-9.5938	898.95	85.19	4.54	0.2879	0.03	16.40	18.64
MST Optimized Frit 202	31	-9.6768	910.38	81.38	4.69	0.2975	0.03	16.52	18.64
MST Optimized Frit 202	32	-9.7596	921.48	77.64	4.84	0.3071	0.03	16.63	18.64
MST Optimized Frit 202	33	-9.8426	932.32	73.97	4.99	0.3167	0.03	16.74	18.64
MST Optimized Frit 202	34	-9.9255	942.86	70.38	5.14	0.3263	0.03	16.86	18.64

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
MST Optimized Frit 202	35	-10.0084	953.17	66.86	5.29	0.3359	0.04	16.97	18.64
MST Optimized Frit 202	36	-10.0913	963.19	63.43	5.44	0.3455	0.04	17.08	18.64
MST Optimized Frit 202	37	-10.1743	973.01	60.07	5.60	0.3551	0.04	17.20	18.64
MST Optimized Frit 202	38	-10.2572	982.55	56.80	5.75	0.3647	0.04	17.31	18.64
MST Optimized Frit 202	39	-10.3401	991.88	53.62	5.90	0.3743	0.04	17.42	18.64
MST Optimized Frit 202	40	-10.4231	1001.01	50.52	6.05	0.3839	0.04	17.54	18.64
MST Optimized Frit 202	41	-10.5060	1009.91	47.51	6.20	0.3935	0.04	17.65	18.64
MST Optimized Frit 202	42	-10.5890	1018.64	44.59	6.35	0.4031	0.04	17.76	18.64
MST Optimized Frit 202	43	-10.6719	1027.14	41.76	6.50	0.4127	0.04	17.88	18.64
MST Optimized Frit 202	44	-10.7547	1035.48	39.03	6.65	0.4223	0.04	17.99	18.64
MST Optimized Frit 202	45	-10.8376	1043.61	36.39	6.81	0.4319	0.05	18.11	18.64
MST Optimized Frit 202	46	-10.9206	1051.60	33.85	6.96	0.4415	0.05	18.22	18.63
MST Optimized Frit 202	47	-11.0035	1059.39	31.40	7.11	0.4511	0.05	18.33	18.63
MST Optimized Frit 202	48	-11.0864	1067.03	29.05	7.26	0.4607	0.05	18.45	18.62
MST Optimized Frit 202	49	-11.1692	1074.49	26.81	7.41	0.4703	0.05	18.56	18.62
MST Optimized Frit 202	50	-11.2522	1081.83	24.66	7.56	0.4799	0.05	18.67	18.61
MST Optimized Frit 202	51	-11.3352	1088.99	22.61	7.71	0.4895	0.05	18.79	18.61
MST Optimized Frit 202	52	-11.4181	1096.02	20.66	7.86	0.4991	0.05	18.90	18.60
MST Optimized Frit 202	53	-11.5011	1102.90	18.82	8.02	0.5087	0.05	19.01	18.60
MST Optimized Frit 202	54	-11.5839	1109.66	17.07	8.17	0.5183	0.05	19.13	18.60
MST Optimized Frit 202	55	-11.6668	1116.27	15.42	8.32	0.5279	0.06	19.24	18.59
MST Optimized Frit 202	56	-11.7498	1122.76	13.88	8.47	0.5375	0.06	19.35	18.59
MST Optimized Frit 202	57	-11.8327	1129.11	12.43	8.62	0.5471	0.06	19.47	18.58

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
MST Optimized Frit 202	58	-11.9156	1135.34	11.08	8.77	0.5566	0.06	19.58	18.58
MST Optimized Frit 202	59	-11.9986	1141.48	9.83	8.92	0.5662	0.06	19.69	18.57
MST Optimized Frit 202	60	-12.0815	1147.48	8.67	9.07	0.5758	0.06	19.81	18.57
Engr MST Case A Frit 202	25	-9.0471	838.78	106.58	3.74	0.5169	0.02	15.73	18.64
Engr MST Case A Frit 202	26	-9.1248	851.81	102.45	3.89	0.5376	0.03	15.84	18.64
Engr MST Case A Frit 202	27	-9.2025	864.50	98.39	4.04	0.5582	0.03	15.95	18.64
Engr MST Case A Frit 202	28	-9.2800	876.79	94.39	4.19	0.5789	0.03	16.06	18.64
Engr MST Case A Frit 202	29	-9.3576	888.76	90.45	4.34	0.5996	0.03	16.17	18.64
Engr MST Case A Frit 202	30	-9.4353	900.39	86.57	4.49	0.6203	0.03	16.28	18.64
Engr MST Case A Frit 202	31	-9.5129	911.74	82.76	4.64	0.6409	0.03	16.39	18.64
Engr MST Case A Frit 202	32	-9.5906	922.76	79.02	4.79	0.6616	0.03	16.50	18.64
Engr MST Case A Frit 202	33	-9.6683	933.50	75.34	4.94	0.6823	0.03	16.61	18.64
Engr MST Case A Frit 202	34	-9.7458	943.96	71.75	5.09	0.7030	0.03	16.72	18.64
Engr MST Case A Frit 202	35	-9.8235	954.19	68.22	5.24	0.7236	0.03	16.83	18.64
Engr MST Case A Frit 202	36	-9.9012	964.13	64.77	5.39	0.7443	0.04	16.93	18.64
Engr MST Case A Frit 202	37	-9.9788	973.83	61.40	5.54	0.7650	0.04	17.04	18.64
Engr MST Case A Frit 202	38	-10.0565	983.29	58.11	5.69	0.7857	0.04	17.15	18.64
Engr MST Case A Frit 202	39	-10.1341	992.57	54.91	5.84	0.8064	0.04	17.26	18.64
Engr MST Case A Frit 202	40	-10.2117	1001.59	51.79	5.99	0.8270	0.04	17.37	18.64
Engr MST Case A Frit 202	41	-10.2894	1010.40	48.75	6.14	0.8477	0.04	17.48	18.64
Engr MST Case A Frit 202	42	-10.3670	1019.00	45.80	6.29	0.8684	0.04	17.59	18.64
Engr MST Case A Frit 202	43	-10.4446	1027.45	42.95	6.44	0.8891	0.04	17.70	18.64
Engr MST Case A Frit 202	44	-10.5223	1035.67	40.18	6.59	0.9097	0.04	17.81	18.64

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
Engr MST Case A Frit 202	45	-10.6000	1043.71	37.51	6.74	0.9304	0.04	17.92	18.64
Engr MST Case A Frit 202	46	-10.6775	1051.58	34.93	6.89	0.9511	0.05	18.03	18.64
Engr MST Case A Frit 202	47	-10.7552	1059.31	32.44	7.04	0.9718	0.05	18.14	18.64
Engr MST Case A Frit 202	48	-10.8329	1066.83	30.06	7.19	0.9924	0.05	18.25	18.63
Engr MST Case A Frit 202	49	-10.9105	1074.20	27.77	7.34	1.0131	0.05	18.36	18.63
Engr MST Case A Frit 202	50	-10.9881	1081.41	25.58	7.49	1.0338	0.05	18.47	18.62
Engr MST Case A Frit 202	51	-11.0658	1088.51	23.49	7.64	1.0545	0.05	18.57	18.62
Engr MST Case A Frit 202	52	-11.1434	1095.43	21.50	7.79	1.0751	0.05	18.68	18.61
Engr MST Case A Frit 202	53	-11.2210	1102.21	19.61	7.94	1.0958	0.05	18.79	18.61
Engr MST Case A Frit 202	54	-11.2986	1108.85	17.81	8.09	1.1165	0.05	18.90	18.60
Engr MST Case A Frit 202	55	-11.3763	1115.39	16.12	8.24	1.1372	0.05	19.01	18.60
Engr MST Case A Frit 202	56	-11.4540	1121.77	14.53	8.39	1.1578	0.06	19.12	18.59
Engr MST Case A Frit 202	57	-11.5316	1128.02	13.04	8.54	1.1785	0.06	19.23	18.59
Engr MST Case A Frit 202	58	-11.6092	1134.17	11.65	8.69	1.1992	0.06	19.34	18.59
Engr MST Case A Frit 202	59	-11.6869	1140.21	10.35	8.84	1.2199	0.06	19.45	18.58
Engr MST Case A Frit 202	60	-11.7644	1146.12	9.14	8.99	1.2405	0.06	19.56	18.58
Engr MST Case B Frit 202	25	-7.5474	872.91	143.46	6.31	0.3104	0.02	15.05	18.64
Engr MST Case B Frit 202	26	-7.5652	886.04	140.11	6.56	0.3228	0.02	15.13	18.64
Engr MST Case B Frit 202	27	-7.5828	898.80	136.76	6.81	0.3353	0.02	15.21	18.64
Engr MST Case B Frit 202	28	-7.6003	911.11	133.40	7.07	0.3477	0.02	15.29	18.64
Engr MST Case B Frit 202	29	-7.6180	923.07	130.03	7.32	0.3601	0.03	15.38	18.64
Engr MST Case B Frit 202	30	-7.6357	934.67	126.67	7.57	0.3725	0.03	15.46	18.64
Engr MST Case B Frit 202	31	-7.6534	945.88	123.30	7.82	0.3849	0.03	15.54	18.64

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
Engr MST Case B Frit 202	32	-7.6710	956.79	119.93	8.08	0.3973	0.03	15.62	18.64
Engr MST Case B Frit 202	33	-7.6887	967.34	116.56	8.33	0.4098	0.03	15.70	18.64
Engr MST Case B Frit 202	34	-7.7063	977.63	113.19	8.58	0.4222	0.03	15.79	18.64
Engr MST Case B Frit 202	35	-7.7240	987.61	109.82	8.83	0.4346	0.03	15.87	18.64
Engr MST Case B Frit 202	36	-7.7415	997.28	106.46	9.09	0.4470	0.03	15.95	18.64
Engr MST Case B Frit 202	37	-7.7592	1006.71	103.10	9.34	0.4594	0.03	16.03	18.64
Engr MST Case B Frit 202	38	-7.7769	1015.85	99.76	9.59	0.4718	0.03	16.11	18.64
Engr MST Case B Frit 202	39	-7.7945	1024.77	96.42	9.84	0.4843	0.03	16.20	18.64
Engr MST Case B Frit 202	40	-7.8122	1033.45	93.09	10.09	0.4967	0.04	16.28	18.64
Engr MST Case B Frit 202	41	-7.8299	1041.87	89.78	10.35	0.5091	0.04	16.36	18.64
Engr MST Case B Frit 202	42	-7.8475	1050.10	86.48	10.60	0.5215	0.04	16.44	18.64
Engr MST Case B Frit 202	43	-7.8651	1058.08	83.20	10.85	0.5339	0.04	16.52	18.64
Engr MST Case B Frit 202	44	-7.8829	1065.89	79.94	11.10	0.5463	0.04	16.61	18.64
Engr MST Case B Frit 202	45	-7.9005	1073.47	76.70	11.36	0.5588	0.04	16.69	18.64
Engr MST Case B Frit 202	46	-7.9181	1080.88	73.49	11.61	0.5712	0.04	16.77	18.64
Engr MST Case B Frit 202	47	-7.9358	1088.11	70.30	11.86	0.5836	0.04	16.85	18.64
Engr MST Case B Frit 202	48	-7.9534	1095.14	67.15	12.11	0.5960	0.04	16.93	18.64
Engr MST Case B Frit 202	49	-7.9710	1102.02	64.03	12.37	0.6084	0.04	17.02	18.64
Engr MST Case B Frit 202	50	-7.9888	1108.71	60.94	12.62	0.6208	0.04	17.10	18.64
Engr MST Case B Frit 202	51	-8.0064	1115.26	57.89	12.87	0.6333	0.05	17.18	18.64
Engr MST Case B Frit 202	52	-8.0240	1121.67	54.89	13.12	0.6457	0.05	17.26	18.64
Engr MST Case B Frit 202	53	-8.0417	1127.89	51.93	13.38	0.6581	0.05	17.34	18.64
Engr MST Case B Frit 202	54	-8.0593	1134.00	49.02	13.63	0.6705	0.05	17.42	18.64

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
Engr MST Case B Frit 202	55	-8.0770	1139.94	46.16	13.88	0.6829	0.05	17.51	18.64
Engr MST Case B Frit 202	56	-8.0946	1145.78	43.36	14.13	0.6953	0.05	17.59	18.64
Engr MST Case B Frit 202	57	-8.1123	1151.49	40.62	14.38	0.7078	0.05	17.67	18.64
Engr MST Case B Frit 202	58	-8.1299	1157.03	37.94	14.64	0.7202	0.05	17.75	18.64
Engr MST Case B Frit 202	59	-8.1476	1162.49	35.33	14.89	0.7326	0.05	17.83	18.64
Engr MST Case B Frit 202	60	-8.1652	1167.80	32.79	15.14	0.7450	0.05	17.92	18.64
ISMIO Frit 202	25	-9.0829	846.30	104.10	3.73	0.0059	0.08	15.71	18.64
ISMIO Frit 202	26	-9.1621	859.70	99.95	3.88	0.0061	0.09	15.82	18.64
ISMIO Frit 202	27	-9.2411	872.73	95.86	4.03	0.0064	0.09	15.93	18.64
ISMIO Frit 202	28	-9.3202	885.40	91.84	4.18	0.0066	0.09	16.03	18.64
ISMIO Frit 202	29	-9.3994	897.73	87.89	4.33	0.0069	0.10	16.14	18.64
ISMIO Frit 202	30	-9.4783	909.77	84.00	4.48	0.0071	0.10	16.25	18.64
ISMIO Frit 202	31	-9.5574	921.46	80.19	4.63	0.0073	0.10	16.36	18.64
ISMIO Frit 202	32	-9.6365	932.85	76.45	4.77	0.0076	0.11	16.47	18.64
ISMIO Frit 202	33	-9.7156	943.95	72.79	4.92	0.0078	0.11	16.58	18.64
ISMIO Frit 202	34	-9.7946	954.78	69.20	5.07	0.0080	0.11	16.68	18.64
ISMIO Frit 202	35	-9.8737	965.34	65.70	5.22	0.0083	0.11	16.79	18.64
ISMIO Frit 202	36	-9.9528	975.68	62.27	5.37	0.0085	0.12	16.90	18.64
ISMIO Frit 202	37	-10.0319	985.73	58.93	5.52	0.0087	0.12	17.01	18.64
ISMIO Frit 202	38	-10.1110	995.56	55.68	5.67	0.0090	0.12	17.12	18.64
ISMIO Frit 202	39	-10.1900	1005.15	52.51	5.82	0.0092	0.13	17.23	18.64
ISMIO Frit 202	40	-10.2691	1014.52	49.43	5.97	0.0095	0.13	17.33	18.64
ISMIO Frit 202	41	-10.3481	1023.68	46.44	6.12	0.0097	0.13	17.44	18.64

**Table A.2. Various Property Predictions for the Frit 418 – SB2/3 System
(Baseline and Secondary Streams)**

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	Ti2O wt%	Na2SO4 wt%	R2O wt%	R2O MAR
ISMIO Frit 202	42	-10.4272	1032.63	43.55	6.27	0.0099	0.14	17.55	18.64
ISMIO Frit 202	43	-10.5064	1041.42	40.75	6.42	0.0102	0.14	17.66	18.64
ISMIO Frit 202	44	-10.5854	1049.98	38.04	6.56	0.0104	0.14	17.77	18.64
ISMIO Frit 202	45	-10.6645	1058.36	35.43	6.71	0.0106	0.15	17.88	18.64
ISMIO Frit 202	46	-10.7436	1066.56	32.92	6.86	0.0109	0.15	17.98	18.64
ISMIO Frit 202	47	-10.8226	1074.59	30.51	7.01	0.0111	0.15	18.09	18.64
ISMIO Frit 202	48	-10.9017	1082.44	28.19	7.16	0.0113	0.16	18.20	18.63
ISMIO Frit 202	49	-10.9807	1090.17	25.98	7.31	0.0116	0.16	18.31	18.63
ISMIO Frit 202	50	-11.0599	1097.71	23.87	7.46	0.0118	0.16	18.42	18.62
ISMIO Frit 202	51	-11.1389	1105.09	21.86	7.61	0.0120	0.17	18.53	18.62
ISMIO Frit 202	52	-11.2180	1112.33	19.95	7.76	0.0123	0.17	18.63	18.61
ISMIO Frit 202	53	-11.2971	1119.42	18.14	7.91	0.0125	0.17	18.74	18.61
ISMIO Frit 202	54	-11.3762	1126.38	16.43	8.06	0.0128	0.18	18.85	18.61
ISMIO Frit 202	55	-11.4551	1133.20	14.82	8.21	0.0130	0.18	18.96	18.60
ISMIO Frit 202	56	-11.5343	1139.91	13.31	8.35	0.0132	0.18	19.07	18.60
ISMIO Frit 202	57	-11.6134	1146.47	11.90	8.50	0.0135	0.19	19.18	18.59
ISMIO Frit 202	58	-11.6924	1152.91	10.59	8.65	0.0137	0.19	19.28	18.59
ISMIO Frit 202	59	-11.7715	1159.22	9.38	8.80	0.0139	0.19	19.39	18.58
ISMIO Frit 202	60	-11.8506	1165.42	8.25	8.95	0.0142	0.20	19.50	18.58

APPENDIX B

MAR Results for Nominal Stage Assessments Using Frit 433

Table B.1 MAR-Based Assessment Using Frit 433

Glass System	WL (%)	Fails MAR
MST Baseline Frit 433	25	ΔG_p R ₂ O
MST Baseline Frit 433	26	ΔG_p R ₂ O
MST Baseline Frit 433	27	ΔG_p R ₂ O
MST Baseline Frit 433	28	ΔG_p R ₂ O
MST Baseline Frit 433	29	ΔG_p
MST Baseline Frit 433	30	ΔG_p
MST Baseline Frit 433	31	ΔG_p
MST Baseline Frit 433	32	ΔG_p
MST Baseline Frit 433	33	ΔG_p
MST Baseline Frit 433	34	ΔG_p
MST Baseline Frit 433	35	ΔG_p
MST Baseline Frit 433	36	ΔG_p
MST Baseline Frit 433	37	ΔG_p
MST Baseline Frit 433	38	ΔG_p
MST Baseline Frit 433	39	ΔG_p
MST Baseline Frit 433	40	ΔG_p
MST Baseline Frit 433	41	ΔG_p lvisc
MST Baseline Frit 433	42	ΔG_p lvisc
MST Baseline Frit 433	43	ΔG_p lvisc
MST Baseline Frit 433	44	ΔG_p lvisc
MST Baseline Frit 433	45	ΔG_p lvisc
MST Baseline Frit 433	46	ΔG_p lvisc
MST Baseline Frit 433	47	ΔG_p lvisc
MST Baseline Frit 433	48	ΔG_p lvisc
MST Baseline Frit 433	49	ΔG_p lvisc
MST Baseline Frit 433	50	ΔG_p lvisc
MST Baseline Frit 433	51	ΔG_p lvisc
MST Baseline Frit 433	52	ΔG_p lvisc
MST Baseline Frit 433	53	ΔG_p lvisc
MST Baseline Frit 433	54	ΔG_p lvisc TiO ₂
MST Baseline Frit 433	55	ΔG_p T _L lvisc TiO ₂
MST Baseline Frit 433	56	ΔG_p T _L lvisc TiO ₂
MST Baseline Frit 433	57	ΔG_p T _L lvisc TiO ₂
MST Baseline Frit 433	58	ΔG_p T _L lvisc TiO ₂
MST Baseline Frit 433	59	ΔG_p T _L lvisc TiO ₂
MST Baseline Frit 433	60	ΔG_p T _L lvisc TiO ₂

Table B.1 MAR-Based Assessment Using Frit 433

Glass System	WL (%)	Fails MAR
MST Optimized Frit 433	25	$\Delta G_p R_2O$
MST Optimized Frit 433	26	$\Delta G_p R_2O$
MST Optimized Frit 433	27	$\Delta G_p R_2O$
MST Optimized Frit 433	28	ΔG_p
MST Optimized Frit 433	29	ΔG_p
MST Optimized Frit 433	30	ΔG_p
MST Optimized Frit 433	31	ΔG_p
MST Optimized Frit 433	32	ΔG_p
MST Optimized Frit 433	33	ΔG_p
MST Optimized Frit 433	34	ΔG_p
MST Optimized Frit 433	35	ΔG_p
MST Optimized Frit 433	36	ΔG_p
MST Optimized Frit 433	37	ΔG_p
MST Optimized Frit 433	38	ΔG_p
MST Optimized Frit 433	39	ΔG_p
MST Optimized Frit 433	40	ΔG_p
MST Optimized Frit 433	41	ΔG_p lvisc
MST Optimized Frit 433	42	ΔG_p lvisc
MST Optimized Frit 433	43	ΔG_p lvisc
MST Optimized Frit 433	44	ΔG_p lvisc
MST Optimized Frit 433	45	ΔG_p lvisc
MST Optimized Frit 433	46	ΔG_p lvisc
MST Optimized Frit 433	47	ΔG_p lvisc
MST Optimized Frit 433	48	ΔG_p lvisc
MST Optimized Frit 433	49	ΔG_p lvisc
MST Optimized Frit 433	50	ΔG_p lvisc
MST Optimized Frit 433	51	ΔG_p lvisc
MST Optimized Frit 433	52	ΔG_p lvisc
MST Optimized Frit 433	53	ΔG_p lvisc
MST Optimized Frit 433	54	ΔG_p T _L lvisc
MST Optimized Frit 433	55	ΔG_p T _L lvisc
MST Optimized Frit 433	56	ΔG_p T _L lvisc
MST Optimized Frit 433	57	ΔG_p T _L lvisc
MST Optimized Frit 433	58	ΔG_p T _L lvisc
MST Optimized Frit 433	59	ΔG_p T _L lvisc
MST Optimized Frit 433	60	ΔG_p T _L lvisc
Engr MST Case A Frit 433	25	$\Delta G_p R_2O$

Table B.1 MAR-Based Assessment Using Frit 433

Glass System	WL (%)	Fails MAR
Engr MST Case A Frit 433	26	$\Delta G_p R_2O$
Engr MST Case A Frit 433	27	$\Delta G_p R_2O$
Engr MST Case A Frit 433	28	ΔG_p
Engr MST Case A Frit 433	29	ΔG_p
Engr MST Case A Frit 433	30	ΔG_p
Engr MST Case A Frit 433	31	ΔG_p
Engr MST Case A Frit 433	32	ΔG_p
Engr MST Case A Frit 433	33	ΔG_p
Engr MST Case A Frit 433	34	ΔG_p
Engr MST Case A Frit 433	35	ΔG_p
Engr MST Case A Frit 433	36	ΔG_p
Engr MST Case A Frit 433	37	ΔG_p
Engr MST Case A Frit 433	38	ΔG_p
Engr MST Case A Frit 433	39	ΔG_p
Engr MST Case A Frit 433	40	ΔG_p
Engr MST Case A Frit 433	41	ΔG_p lvisc
Engr MST Case A Frit 433	42	ΔG_p lvisc
Engr MST Case A Frit 433	43	ΔG_p lvisc
Engr MST Case A Frit 433	44	ΔG_p lvisc
Engr MST Case A Frit 433	45	ΔG_p lvisc
Engr MST Case A Frit 433	46	ΔG_p lvisc
Engr MST Case A Frit 433	47	ΔG_p lvisc
Engr MST Case A Frit 433	48	ΔG_p lvisc
Engr MST Case A Frit 433	49	ΔG_p lvisc
Engr MST Case A Frit 433	50	ΔG_p lvisc
Engr MST Case A Frit 433	51	ΔG_p lvisc
Engr MST Case A Frit 433	52	ΔG_p lvisc
Engr MST Case A Frit 433	53	ΔG_p lvisc
Engr MST Case A Frit 433	54	$\Delta G_p T_L$ lvisc
Engr MST Case A Frit 433	55	$\Delta G_p T_L$ lvisc
Engr MST Case A Frit 433	56	$\Delta G_p T_L$ lvisc
Engr MST Case A Frit 433	57	$\Delta G_p T_L$ lvisc
Engr MST Case A Frit 433	58	$\Delta G_p T_L$ lvisc
Engr MST Case A Frit 433	59	$\Delta G_p T_L$ lvisc
Engr MST Case A Frit 433	60	$\Delta G_p T_L$ lvisc
Engr MST Case B Frit 433	25	-
Engr MST Case B Frit 433	26	-

Table B.1 MAR-Based Assessment Using Frit 433

Glass System	WL (%)	Fails MAR
Engr MST Case B Frit 433	27	-
Engr MST Case B Frit 433	28	-
Engr MST Case B Frit 433	29	-
Engr MST Case B Frit 433	30	-
Engr MST Case B Frit 433	31	-
Engr MST Case B Frit 433	32	-
Engr MST Case B Frit 433	33	-
Engr MST Case B Frit 433	34	-
Engr MST Case B Frit 433	35	-
Engr MST Case B Frit 433	36	-
Engr MST Case B Frit 433	37	-
Engr MST Case B Frit 433	38	-
Engr MST Case B Frit 433	39	-
Engr MST Case B Frit 433	40	-
Engr MST Case B Frit 433	41	-
Engr MST Case B Frit 433	42	-
Engr MST Case B Frit 433	43	-
Engr MST Case B Frit 433	44	-
Engr MST Case B Frit 433	45	-
Engr MST Case B Frit 433	46	-
Engr MST Case B Frit 433	47	-
Engr MST Case B Frit 433	48	-
Engr MST Case B Frit 433	49	-
Engr MST Case B Frit 433	50	T _L
Engr MST Case B Frit 433	51	T _L
Engr MST Case B Frit 433	52	T _L
Engr MST Case B Frit 433	53	T _L
Engr MST Case B Frit 433	54	T _L lvisc
Engr MST Case B Frit 433	55	T _L lvisc
Engr MST Case B Frit 433	56	T _L lvisc
Engr MST Case B Frit 433	57	T _L lvisc
Engr MST Case B Frit 433	58	T _L lvisc
Engr MST Case B Frit 433	59	T _L lvisc
Engr MST Case B Frit 433	60	T _L lvisc
ISMIO Frit 433	25	ΔG_p R ₂ O
ISMIO Frit 433	26	ΔG_p R ₂ O
ISMIO Frit 433	27	ΔG_p R ₂ O

Table B.1 MAR-Based Assessment Using Frit 433

Glass System	WL (%)	Fails MAR
ISMIO Frit 433	28	ΔG_p R ₂ O
ISMIO Frit 433	29	ΔG_p
ISMIO Frit 433	30	ΔG_p
ISMIO Frit 433	31	ΔG_p
ISMIO Frit 433	32	ΔG_p
ISMIO Frit 433	33	ΔG_p
ISMIO Frit 433	34	ΔG_p
ISMIO Frit 433	35	ΔG_p
ISMIO Frit 433	36	ΔG_p
ISMIO Frit 433	37	ΔG_p
ISMIO Frit 433	38	ΔG_p
ISMIO Frit 433	39	ΔG_p
ISMIO Frit 433	40	ΔG_p
ISMIO Frit 433	41	ΔG_p lvisc
ISMIO Frit 433	42	ΔG_p lvisc
ISMIO Frit 433	43	ΔG_p lvisc
ISMIO Frit 433	44	ΔG_p lvisc
ISMIO Frit 433	45	ΔG_p lvisc
ISMIO Frit 433	46	ΔG_p lvisc
ISMIO Frit 433	47	ΔG_p lvisc
ISMIO Frit 433	48	ΔG_p lvisc
ISMIO Frit 433	49	ΔG_p lvisc
ISMIO Frit 433	50	ΔG_p lvisc
ISMIO Frit 433	51	ΔG_p lvisc
ISMIO Frit 433	52	ΔG_p T _L lvisc
ISMIO Frit 433	53	ΔG_p T _L lvisc
ISMIO Frit 433	54	ΔG_p T _L lvisc
ISMIO Frit 433	55	ΔG_p T _L lvisc
ISMIO Frit 433	56	ΔG_p T _L lvisc
ISMIO Frit 433	57	ΔG_p T _L lvisc
ISMIO Frit 433	58	ΔG_p T _L lvisc
ISMIO Frit 433	59	ΔG_p T _L lvisc
ISMIO Frit 433	60	ΔG_p T _L lvisc

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	TiO2 wt%	Na2SO4 wt%	R2O wt%
MST Baseline Frit 433	25	-13.6159	697.64	55.20	3.66	0.89	0.02	21.02
MST Baseline Frit 433	26	-13.6319	711.93	52.93	3.81	0.93	0.03	21.06
MST Baseline Frit 433	27	-13.6478	725.90	50.70	3.95	0.97	0.03	21.10
MST Baseline Frit 433	28	-13.6638	739.51	48.50	4.10	1.00	0.03	21.14
MST Baseline Frit 433	29	-13.6798	752.85	46.35	4.25	1.04	0.03	21.19
MST Baseline Frit 433	30	-13.6957	765.90	44.24	4.39	1.07	0.03	21.23
MST Baseline Frit 433	31	-13.7116	778.66	42.17	4.54	1.11	0.03	21.27
MST Baseline Frit 433	32	-13.7276	791.12	40.15	4.69	1.14	0.03	21.31
MST Baseline Frit 433	33	-13.7435	803.35	38.17	4.83	1.18	0.03	21.35
MST Baseline Frit 433	34	-13.7595	815.34	36.23	4.98	1.22	0.03	21.39
MST Baseline Frit 433	35	-13.7755	827.08	34.34	5.13	1.25	0.03	21.43
MST Baseline Frit 433	36	-13.7914	838.57	32.50	5.27	1.29	0.04	21.47
MST Baseline Frit 433	37	-13.8073	849.85	30.70	5.42	1.32	0.04	21.51
MST Baseline Frit 433	38	-13.8234	860.92	28.96	5.57	1.36	0.04	21.55
MST Baseline Frit 433	39	-13.8393	871.78	27.26	5.71	1.40	0.04	21.59
MST Baseline Frit 433	40	-13.8553	882.40	25.62	5.86	1.43	0.04	21.64
MST Baseline Frit 433	41	-13.8711	892.86	24.02	6.01	1.47	0.04	21.68
MST Baseline Frit 433	42	-13.8871	903.13	22.48	6.15	1.50	0.04	21.72
MST Baseline Frit 433	43	-13.9030	913.19	20.99	6.30	1.54	0.04	21.76
MST Baseline Frit 433	44	-13.9189	923.09	19.56	6.44	1.57	0.04	21.80
MST Baseline Frit 433	45	-13.9349	932.81	18.18	6.59	1.61	0.04	21.84
MST Baseline Frit 433	46	-13.9509	942.37	16.85	6.74	1.65	0.04	21.88
MST Baseline Frit 433	47	-13.9668	951.73	15.58	6.88	1.68	0.05	21.92

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al ₂ O ₃ wt%	TiO ₂ wt%	Na ₂ SO ₄ wt%	R ₂ O wt%
MST Baseline Frit 433	48	-13.9828	960.97	14.37	7.03	1.72	0.05	21.96
MST Baseline Frit 433	49	-13.9987	970.04	13.21	7.18	1.75	0.05	22.00
MST Baseline Frit 433	50	-14.0147	978.97	12.10	7.32	1.79	0.05	22.04
MST Baseline Frit 433	51	-14.0307	987.72	11.06	7.47	1.82	0.05	22.09
MST Baseline Frit 433	52	-14.0466	996.35	10.06	7.62	1.86	0.05	22.13
MST Baseline Frit 433	53	-14.0626	1004.84	9.13	7.76	1.90	0.05	22.17
MST Baseline Frit 433	54	-14.0786	1013.17	8.24	7.91	1.93	0.05	22.21
MST Baseline Frit 433	55	-14.0945	1021.39	7.42	8.06	1.97	0.05	22.25
MST Baseline Frit 433	56	-14.1105	1029.49	6.64	8.20	2.00	0.05	22.29
MST Baseline Frit 433	57	-14.1263	1037.46	5.92	8.35	2.04	0.06	22.33
MST Baseline Frit 433	58	-14.1422	1045.27	5.25	8.50	2.07	0.06	22.37
MST Baseline Frit 433	59	-14.1582	1053.00	4.63	8.64	2.11	0.06	22.41
MST Baseline Frit 433	60	-14.1742	1060.60	4.06	8.79	2.15	0.06	22.45
MST Optimized Frit 433	25	-13.7625	698.45	54.71	3.78	0.24	0.03	21.09
MST Optimized Frit 433	26	-13.7842	713.03	52.44	3.93	0.25	0.03	21.13
MST Optimized Frit 433	27	-13.8061	727.30	50.21	4.08	0.26	0.03	21.17
MST Optimized Frit 433	28	-13.8279	741.23	48.01	4.23	0.27	0.03	21.22
MST Optimized Frit 433	29	-13.8498	754.90	45.86	4.39	0.28	0.03	21.26
MST Optimized Frit 433	30	-13.8716	768.25	43.75	4.54	0.29	0.03	21.30
MST Optimized Frit 433	31	-13.8934	781.35	41.69	4.69	0.30	0.03	21.35
MST Optimized Frit 433	32	-13.9151	794.17	39.66	4.84	0.31	0.03	21.39
MST Optimized Frit 433	33	-13.9370	806.75	37.69	4.99	0.32	0.03	21.43
MST Optimized Frit 433	34	-13.9588	819.06	35.75	5.14	0.33	0.03	21.48
MST Optimized Frit 433	35	-13.9806	831.17	33.87	5.29	0.34	0.04	21.52

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al ₂ O ₃ wt%	TiO ₂ wt%	Na ₂ SO ₄ wt%	R ₂ O wt%
MST Optimized Frit 433	36	-14.0024	843.01	32.03	5.44	0.35	0.04	21.56
MST Optimized Frit 433	37	-14.0243	854.67	30.25	5.60	0.36	0.04	21.61
MST Optimized Frit 433	38	-14.0460	866.08	28.51	5.75	0.36	0.04	21.65
MST Optimized Frit 433	39	-14.0678	877.29	26.83	5.90	0.37	0.04	21.69
MST Optimized Frit 433	40	-14.0897	888.32	25.19	6.05	0.38	0.04	21.74
MST Optimized Frit 433	41	-14.1115	899.13	23.61	6.20	0.39	0.04	21.78
MST Optimized Frit 433	42	-14.1334	909.79	22.08	6.35	0.40	0.04	21.82
MST Optimized Frit 433	43	-14.1552	920.23	20.61	6.50	0.41	0.04	21.87
MST Optimized Frit 433	44	-14.1769	930.52	19.18	6.65	0.42	0.04	21.91
MST Optimized Frit 433	45	-14.1987	940.61	17.82	6.81	0.43	0.05	21.96
MST Optimized Frit 433	46	-14.2205	950.56	16.51	6.96	0.44	0.05	22.00
MST Optimized Frit 433	47	-14.2423	960.32	15.25	7.11	0.45	0.05	22.04
MST Optimized Frit 433	48	-14.2642	969.95	14.05	7.26	0.46	0.05	22.09
MST Optimized Frit 433	49	-14.2859	979.39	12.91	7.41	0.47	0.05	22.13
MST Optimized Frit 433	50	-14.3077	988.72	11.82	7.56	0.48	0.05	22.17
MST Optimized Frit 433	51	-14.3296	997.87	10.79	7.71	0.49	0.05	22.22
MST Optimized Frit 433	52	-14.3514	1006.90	9.81	7.86	0.50	0.05	22.26
MST Optimized Frit 433	53	-14.3733	1015.77	8.89	8.02	0.51	0.05	22.30
MST Optimized Frit 433	54	-14.3950	1024.53	8.02	8.17	0.52	0.05	22.35
MST Optimized Frit 433	55	-14.4168	1033.13	7.21	8.32	0.53	0.06	22.39
MST Optimized Frit 433	56	-14.4386	1041.62	6.45	8.47	0.54	0.06	22.43
MST Optimized Frit 433	57	-14.4605	1049.96	5.74	8.62	0.55	0.06	22.48
MST Optimized Frit 433	58	-14.4823	1058.19	5.09	8.77	0.56	0.06	22.52
MST Optimized Frit 433	59	-14.5041	1066.31	4.48	8.92	0.57	0.06	22.56

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al ₂ O ₃ wt%	TiO ₂ wt%	Na ₂ SO ₄ wt%	R ₂ O wt%
MST Optimized Frit 433	60	-14.5259	1074.29	3.93	9.07	0.58	0.06	22.61
Engr MST Case A Frit 433	25	-13.6304	700.64	55.45	3.74	0.52	0.02	20.98
Engr MST Case A Frit 433	26	-13.6469	715.18	53.19	3.89	0.54	0.03	21.02
Engr MST Case A Frit 433	27	-13.6635	729.42	50.96	4.04	0.56	0.03	21.06
Engr MST Case A Frit 433	28	-13.6800	743.31	48.77	4.19	0.58	0.03	21.10
Engr MST Case A Frit 433	29	-13.6965	756.90	46.62	4.34	0.60	0.03	21.14
Engr MST Case A Frit 433	30	-13.7131	770.21	44.51	4.49	0.62	0.03	21.18
Engr MST Case A Frit 433	31	-13.7296	783.26	42.44	4.64	0.64	0.03	21.22
Engr MST Case A Frit 433	32	-13.7461	796.02	40.42	4.79	0.66	0.03	21.26
Engr MST Case A Frit 433	33	-13.7627	808.52	38.43	4.94	0.68	0.03	21.30
Engr MST Case A Frit 433	34	-13.7791	820.77	36.50	5.09	0.70	0.03	21.34
Engr MST Case A Frit 433	35	-13.7957	832.81	34.60	5.24	0.72	0.03	21.38
Engr MST Case A Frit 433	36	-13.8123	844.59	32.76	5.39	0.74	0.04	21.41
Engr MST Case A Frit 433	37	-13.8288	856.15	30.96	5.54	0.77	0.04	21.45
Engr MST Case A Frit 433	38	-13.8453	867.49	29.21	5.69	0.79	0.04	21.49
Engr MST Case A Frit 433	39	-13.8619	878.66	27.51	5.84	0.81	0.04	21.53
Engr MST Case A Frit 433	40	-13.8783	889.60	25.86	5.99	0.83	0.04	21.57
Engr MST Case A Frit 433	41	-13.8949	900.33	24.27	6.14	0.85	0.04	21.61
Engr MST Case A Frit 433	42	-13.9114	910.87	22.72	6.29	0.87	0.04	21.65
Engr MST Case A Frit 433	43	-13.9279	921.27	21.23	6.44	0.89	0.04	21.69
Engr MST Case A Frit 433	44	-13.9445	931.44	19.79	6.59	0.91	0.04	21.73
Engr MST Case A Frit 433	45	-13.9611	941.45	18.40	6.74	0.93	0.04	21.77
Engr MST Case A Frit 433	46	-13.9774	951.29	17.07	6.89	0.95	0.05	21.81
Engr MST Case A Frit 433	47	-13.9940	961.00	15.79	7.04	0.97	0.05	21.85

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al ₂ O ₃ wt%	TiO ₂ wt%	Na ₂ SO ₄ wt%	R ₂ O wt%
Engr MST Case A Frit 433	48	-14.0106	970.51	14.57	7.19	0.99	0.05	21.89
Engr MST Case A Frit 433	49	-14.0271	979.87	13.40	7.34	1.01	0.05	21.93
Engr MST Case A Frit 433	50	-14.0437	989.08	12.29	7.49	1.03	0.05	21.97
Engr MST Case A Frit 433	51	-14.0602	998.16	11.23	7.64	1.05	0.05	22.00
Engr MST Case A Frit 433	52	-14.0767	1007.08	10.23	7.79	1.08	0.05	22.04
Engr MST Case A Frit 433	53	-14.0932	1015.85	9.29	7.94	1.10	0.05	22.08
Engr MST Case A Frit 433	54	-14.1097	1024.49	8.39	8.09	1.12	0.05	22.12
Engr MST Case A Frit 433	55	-14.1263	1033.02	7.56	8.24	1.14	0.05	22.16
Engr MST Case A Frit 433	56	-14.1429	1041.40	6.77	8.39	1.16	0.06	22.20
Engr MST Case A Frit 433	57	-14.1594	1049.64	6.04	8.54	1.18	0.06	22.24
Engr MST Case A Frit 433	58	-14.1758	1057.77	5.37	8.69	1.20	0.06	22.28
Engr MST Case A Frit 433	59	-14.1924	1065.80	4.74	8.84	1.22	0.06	22.32
Engr MST Case A Frit 433	60	-14.2089	1073.69	4.16	8.99	1.24	0.06	22.36
Engr MST Case B Frit 433	25	-12.1307	736.55	76.11	6.31	0.31	0.02	20.30
Engr MST Case B Frit 433	26	-12.0873	751.46	74.24	6.56	0.32	0.02	20.31
Engr MST Case B Frit 433	27	-12.0438	766.02	72.38	6.81	0.34	0.02	20.32
Engr MST Case B Frit 433	28	-12.0003	780.18	70.51	7.07	0.35	0.02	20.33
Engr MST Case B Frit 433	29	-11.9568	794.03	68.64	7.32	0.36	0.03	20.35
Engr MST Case B Frit 433	30	-11.9134	807.54	66.77	7.57	0.37	0.03	20.36
Engr MST Case B Frit 433	31	-11.8700	820.69	64.90	7.82	0.38	0.03	20.37
Engr MST Case B Frit 433	32	-11.8265	833.56	63.03	8.08	0.40	0.03	20.38
Engr MST Case B Frit 433	33	-11.7831	846.11	61.17	8.33	0.41	0.03	20.39
Engr MST Case B Frit 433	34	-11.7396	858.40	59.31	8.58	0.42	0.03	20.41
Engr MST Case B Frit 433	35	-11.6961	870.40	57.46	8.83	0.43	0.03	20.42

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al ₂ O ₃ wt%	TiO ₂ wt%	Na ₂ SO ₄ wt%	R ₂ O wt%
Engr MST Case B Frit 433	36	-11.6526	882.11	55.61	9.09	0.45	0.03	20.43
Engr MST Case B Frit 433	37	-11.6092	893.59	53.77	9.34	0.46	0.03	20.44
Engr MST Case B Frit 433	38	-11.5658	904.79	51.94	9.59	0.47	0.03	20.45
Engr MST Case B Frit 433	39	-11.5223	915.78	50.11	9.84	0.48	0.03	20.47
Engr MST Case B Frit 433	40	-11.4789	926.54	48.29	10.09	0.50	0.04	20.48
Engr MST Case B Frit 433	41	-11.4354	937.03	46.49	10.35	0.51	0.04	20.49
Engr MST Case B Frit 433	42	-11.3919	947.34	44.70	10.60	0.52	0.04	20.50
Engr MST Case B Frit 433	43	-11.3484	957.41	42.92	10.85	0.53	0.04	20.51
Engr MST Case B Frit 433	44	-11.3051	967.29	41.15	11.10	0.55	0.04	20.53
Engr MST Case B Frit 433	45	-11.2616	976.95	39.40	11.36	0.56	0.04	20.54
Engr MST Case B Frit 433	46	-11.2180	986.44	37.67	11.61	0.57	0.04	20.55
Engr MST Case B Frit 433	47	-11.1747	995.75	35.96	11.86	0.58	0.04	20.56
Engr MST Case B Frit 433	48	-11.1312	1004.84	34.26	12.11	0.60	0.04	20.57
Engr MST Case B Frit 433	49	-11.0877	1013.79	32.59	12.37	0.61	0.04	20.59
Engr MST Case B Frit 433	50	-11.0443	1022.53	30.95	12.62	0.62	0.04	20.60
Engr MST Case B Frit 433	51	-11.0008	1031.14	29.32	12.87	0.63	0.05	20.61
Engr MST Case B Frit 433	52	-10.9573	1039.58	27.73	13.12	0.65	0.05	20.62
Engr MST Case B Frit 433	53	-10.9139	1047.83	26.16	13.38	0.66	0.05	20.63
Engr MST Case B Frit 433	54	-10.8704	1055.96	24.63	13.63	0.67	0.05	20.64
Engr MST Case B Frit 433	55	-10.8269	1063.91	23.12	13.88	0.68	0.05	20.66
Engr MST Case B Frit 433	56	-10.7835	1071.75	21.65	14.13	0.70	0.05	20.67
Engr MST Case B Frit 433	57	-10.7400	1079.44	20.22	14.38	0.71	0.05	20.68
Engr MST Case B Frit 433	58	-10.6966	1086.97	18.83	14.64	0.72	0.05	20.69
Engr MST Case B Frit 433	59	-10.6531	1094.38	17.47	14.89	0.73	0.05	20.70

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	TiO2 wt%	Na2SO4 wt%	R2O wt%
Engr MST Case B Frit 433	60	-10.6096	1101.64	16.16	15.14	0.75	0.05	20.72
ISMIO Frit 433	25	-13.6662	705.70	54.07	3.73	0.01	0.08	20.96
ISMIO Frit 433	26	-13.6843	720.54	51.80	3.88	0.01	0.09	21.00
ISMIO Frit 433	27	-13.7022	735.07	49.56	4.03	0.01	0.09	21.04
ISMIO Frit 433	28	-13.7201	749.27	47.36	4.18	0.01	0.09	21.07
ISMIO Frit 433	29	-13.7382	763.19	45.21	4.33	0.01	0.10	21.11
ISMIO Frit 433	30	-13.7561	776.84	43.10	4.48	0.01	0.10	21.15
ISMIO Frit 433	31	-13.7740	790.19	41.03	4.63	0.01	0.10	21.19
ISMIO Frit 433	32	-13.7920	803.27	39.01	4.77	0.01	0.11	21.23
ISMIO Frit 433	33	-13.8100	816.10	37.04	4.92	0.01	0.11	21.27
ISMIO Frit 433	34	-13.8279	828.69	35.11	5.07	0.01	0.11	21.30
ISMIO Frit 433	35	-13.8459	841.03	33.23	5.22	0.01	0.11	21.34
ISMIO Frit 433	36	-13.8639	853.18	31.41	5.37	0.01	0.12	21.38
ISMIO Frit 433	37	-13.8819	865.07	29.63	5.52	0.01	0.12	21.42
ISMIO Frit 433	38	-13.8998	876.76	27.90	5.67	0.01	0.12	21.46
ISMIO Frit 433	39	-13.9178	888.23	26.23	5.82	0.01	0.13	21.50
ISMIO Frit 433	40	-13.9357	899.50	24.61	5.97	0.01	0.13	21.53
ISMIO Frit 433	41	-13.9536	910.58	23.04	6.12	0.01	0.13	21.57
ISMIO Frit 433	42	-13.9716	921.46	21.52	6.27	0.01	0.14	21.61
ISMIO Frit 433	43	-13.9897	932.19	20.07	6.42	0.01	0.14	21.65
ISMIO Frit 433	44	-14.0076	942.72	18.66	6.56	0.01	0.14	21.69
ISMIO Frit 433	45	-14.0256	953.06	17.31	6.71	0.01	0.15	21.73
ISMIO Frit 433	46	-14.0436	963.25	16.02	6.86	0.01	0.15	21.76
ISMIO Frit 433	47	-14.0615	973.26	14.78	7.01	0.01	0.15	21.80

Table B.2 Property Predictions Using Frit 433

Glass System	WL (%)	B Del Gp Value	TL Pred (°C)	Visc Pred (P)	Al2O3 wt%	TiO2 wt%	Na2SO4 wt%	R2O wt%
ISMIO Frit 433	48	-14.0794	983.12	13.60	7.16	0.01	0.16	21.84
ISMIO Frit 433	49	-14.0974	992.85	12.48	7.31	0.01	0.16	21.88
ISMIO Frit 433	50	-14.1154	1002.40	11.41	7.46	0.01	0.16	21.92
ISMIO Frit 433	51	-14.1333	1011.80	10.40	7.61	0.01	0.17	21.96
ISMIO Frit 433	52	-14.1513	1021.05	9.44	7.76	0.01	0.17	21.99
ISMIO Frit 433	53	-14.1693	1030.17	8.54	7.91	0.01	0.17	22.03
ISMIO Frit 433	54	-14.1872	1039.15	7.70	8.06	0.01	0.18	22.07
ISMIO Frit 433	55	-14.2051	1047.99	6.91	8.21	0.01	0.18	22.11
ISMIO Frit 433	56	-14.2231	1056.73	6.17	8.35	0.01	0.18	22.15
ISMIO Frit 433	57	-14.2411	1065.31	5.48	8.50	0.01	0.19	22.19
ISMIO Frit 433	58	-14.2591	1073.77	4.85	8.65	0.01	0.19	22.22
ISMIO Frit 433	59	-14.2770	1082.11	4.26	8.80	0.01	0.19	22.26
ISMIO Frit 433	60	-14.2950	1090.33	3.73	8.95	0.01	0.20	22.30