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Sludge Batch 10 Frit Development and Variability Study Matrix Design

F.C. Johnson

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EXECUTIVE SUMMARY

The Defense Waste Processing Facility (DWPF) is currently preparing to initiate processing of Sludge Batch 10 (SB10), which is comprised of material from Tanks 11H, 13H, 15H, and 26H, and Alternate Feed Stock-2 (AFS-2). H-Canyon also had a need to discard Sodium Reactor Experiment (SRE) material that was stored in Tanks 16.3 and 16.4. Savannah River Remediation (SRR) added a portion of the SRE material to Sludge Batch 9 (SB9) in Tank 40 and the remainder was added to SB10 that is currently being prepared in Tank 51. In support of sludge batch preparation and qualification efforts, SRR requested that the Savannah River National Laboratory (SRNL) complete the following tasks based on the SB10 projections provided by the SRR System Planning group.

- Recommend a frit for SB10 processing that allows for a waste loading (WL) of 36% to be targeted (yet to be finalized and will be documented separately).
- Evaluate the acceptability of frit leaching in the frit slurry as compared to previously studied frit matrices.
- Perform a variability study.
- Determine a bounding glass density that will be used to support fissile mass loading calculations for SB10 (to be documented separately).
- Perform a sulfate solubility evaluation (to be documented separately).

To evaluate frit compositions for SB10 processing, calculation-only frit assessments were performed that used the DWPF Product Composition Control System (PCCS) glass property models and their associated Measurement Acceptance Region (MAR) constraints. This report summarizes the results of these assessments that support the frit development, frit leaching assessment, and development of a test matrix that will support the variability study.

The variability study has been designed to account for variation in the SB10 composition and for flexibility in the frit composition. Depending on the composition of SB10, Frit 473 ($8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (weight percent (wt.%)) or Frit 209 ($11B_2O_3$-$8Li_2O$-$5Na_2O$-$76SiO_2$ (wt.%)) allow for sludge-only processing or coupled operation with the Salt Waste Processing Facility (SWPF) at 36% WL. No issues are expected for leaching of either of these frits in the DWPF frit slurry with water. The SB10 frit recommendation will be finalized and documented separately in the future once more information is known about the composition of SB10 after washing.

The SB10 glass region for the variability study was developed based on the following SB10 projections.

- 0.7M and 0.85M Na wash endpoint projections with Frit 473 for sludge-only operation and coupled operation with SWPF (with monosodium titanate (MST))
    - With and without SRE material
- 0.95M wash endpoint projections with Frit 209 for sludge-only operation and coupled operation with SWPF (with and without MST)
    - With SRE material

This glass region overlaps compositions previously evaluated for the SB6, SB7a, and SB7b variability studies. Thus, only a minimal number of glasses are needed to supplement the existing durability data in the SB10 glass region. SRNL recommends that eight variability study glasses be fabricated, tested, and analyzed to confirm that the glasses are acceptable relative to the chemical durability of the Environmental Assessment (EA) benchmark glass and predictable by the current PCCS models for durability.

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AFS-2	Alternate Feed Stock-2
CCC	canister centerline cooling
CPC	Chemical Process Cell
DUO	depleted uranium oxide
DWPF	Defense Waste Processing Facility
EA	Environmental Assessment
EVs	extreme vertices
MAR	Measurement Acceptance Region
MST	monosodium titanate
NC	normalized concentration
PCCS	Product Composition Control System
PCT	Product Consistency Test
SB	Sludge Batch
SME	Slurry Mix Evaporator
SO	sludge-only
SRAT	Sludge Receipt and Adjustment Tank
SRE	Sodium Reactor Experiment
SRNL	Savannah River National Laboratory
SRR	Savannah River Remediation
SSRT	Sludge Solids Receipt Tank
SWPF	Salt Waste Processing Facility
TTQAP	Task Technical and Quality Assurance Plan
TTR	Technical Task Request
WL	waste loading

1.0 Introduction

The Defense Waste Processing Facility (DWPF) is currently preparing to initiate processing of Sludge Batch 10 (SB10), which is comprised of material from Tanks 11H, 13H, 15H, and 26H, and Alternate Feed Stock-2 (AFS-2). H-Canyon also had a need to discard Sodium Reactor Experiment (SRE) material that was stored in Tanks 16.3 and 16.4. Savannah River Remediation (SRR) added a portion of the SRE material to Sludge Batch 9 (SB9) in Tank 40 and the remainder was added to SB10 that is currently being prepared in Tank 51. In support of sludge batch preparation and qualification efforts, SRR requested that the Savannah River National Laboratory (SRNL) complete the following tasks.[1]

- Recommend a frit for SB10 processing that allows for a waste loading (WL) of 36% to be targeted.
- Evaluate the acceptability of frit leaching in the frit slurry as compared to previously studied frit matrices.[2-4]
- Perform a variability study.
- Determine a bounding glass density that will be used to support fissile mass loading calculations for SB10 (to be documented separately).[5]
- Perform a sulfate solubility evaluation (to be documented separately).

The objective of this task was to identify a viable frit for SB10 sludge-only (SO) and coupled operation with the Salt Waste Processing Facility (SWPF) based on the most recent Tank 40 blend projections. This report documents the results of calculation-only frit assessments that used the DWPF Product Composition Control System (PCCS) glass property models and their associated Measurement Acceptance Region (MAR) constraints. This report also summarizes the frit leaching assessment and development of a test matrix that will support the variability study.

2.0 Quality Assurance

This work was requested via a Technical Task Request (TTR)[1] and directed by a Task Technical and Quality Assurance Plan (TTQAP).[6] The functional classification of the tasks covered by this report is Production Support. The variability study is waste form affecting and needs to follow the quality assurance requirements of RW-0333P.[7] Microsoft Excel, JMP Version 14.3.0,[8] and SAS Version 8.2[9] were used to support this work.[10] Requirements for performing reviews of technical reports and the extent of review are established in Manual E7, Procedure 2.60. This document, including calculations, was reviewed by a Design Check. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.[11] The Design Checklists for this report are stored in electronic laboratory notebook experiment C7592-00311-35. Hence, all work was performed commensurate with the applicable quality assurance requirements.

3.0 Initial SB10 Frit Development

3.1 Inputs and Assumptions

In May 2020 SRR System Planning provided SB10 Tank 40 blend projections with SRE material on a calcine basis representing the following SO and coupled operation scenarios:

- 1M Na wash endpoint[12]
- 0.85M Na wash endpoint[13,14]
- 0.7M Na wash endpoint[13,14]

The projections assume no addition of depleted uranium oxide (DUO) and include the amount of manganous oxide required SB10 as required by the DWPF Waste Acceptance Criteria.[15] Projections representing coupled operation include the contribution of the monosodium titanate (MST) stream from

SWPF. The elemental concentrations were converted to oxides and normalized to 100 wt.% as shown in Appendix Table A-1.

3.2 Methodology for the Variation Stage MAR Assessments

The approach taken for the Variation Stage MAR assessment[16] was to evaluate how robust candidate frit compositions were relative to expected variation in the composition of the SB10 Sludge Receipt and Adjustment Tank (SRAT) material and the uncertainty in targeting the desired WL. These uncertainties take effect as DWPF (i) conducts the blending process[a] to target the desired WL for the next Slurry Mix Evaporator (SME) batch, and (ii) subsequently judges the new SME batch for MAR acceptability via the PCCS process, which is driven by the analysis of samples of the new SME batch.

Compositional variation (±) was applied to SRAT compositions to account for likely, but not necessarily bounding, differences that may be seen in the material that is transferred from Tank 40 and SWPF into the SRAT during the processing of SB10. The compositional variation for the individually tracked oxides was represented by the larger of 0.5 wt.% or 7.5% of the nominal concentration. Those oxides not tracked individually were grouped into an "Others" component.[b] The resulting SRAT oxide intervals are summarized in Appendix Table A-2 through Table A-4 and represent the minimum and maximum oxide concentrations for the various cases of SO and coupled operation. Extreme vertices (EVs) were generated using the oxide intervals for the SB10 scenarios and were combined with a large array of frits covering the B_2O_3-Li_2O-Na_2O-SiO_2 region in the interval of 24-42% WL. Any frits currently in the frit procurement specification were also included.[17] Each of the resulting glass compositions was evaluated against the PCCS MAR criteria to determine whether the composition would pass the SME acceptability process. An operating window of at least 9 percentage points (target WL ± 4 percentage points) was the primary success metric used to select a frit for SB10 processing.

3.3 Variation Stage MAR Assessment Results

3.3.1 1M Na Wash Endpoint

Table 3-1 presents a summary of the results from the initial coupled operation MAR assessment results. More detailed results are provided in Appendix Table A-5. The frit compositions and number of EVs are shown for reference. Consider the middle column as an example for the interpretation of the information provided. The operating window (WL interval over which all EVs pass the SME acceptability process) is 27-40%. At 26% WL, 24% of the EVs fail the high viscosity constraint and at 41% WL, 19% of the EVs fail the low viscosity constraint. These initial coupled operation MAR assessment results demonstrated that frits with low Na_2O concentrations and low total alkali concentrations were necessary to achieve the highest WL as shown in the middle column of Table 3-1. Frits having these compositions may be more challenging for the vendor to fabricate due to increased viscosity and may reduce the melting rate in the DWPF melter. Previous SB3 testing showed that laboratory scale melting rate is significantly reduced when the Na_2O concentration in the frit is less than or equal to 4 wt.%.[18] Thus, the SB10 frits were rescreened to determine whether frits with a higher total alkali concentration and Na_2O concentration greater than 4 wt.% were viable. The right column of Table 3-1 shows that frits with higher total Na_2O and total alkali concentrations are possible but result in a lower WL. Based on these results, SRNL recommended that additional SB10 projections representing lower Na wash endpoints be evaluated to determine whether a more desirable balance between Na_2O and total alkali in the frit, and WL could be achieved.

[a] Combining SRAT material with frit and the heel of the SME.
[b] The "Others" components include B_2O_3, BaO, Ce_2O_3, Cr_2O_3, CuO, K_2O, La_2O_3, Li_2O, MgO, PbO, SO_4^{2-}, ZnO, and ZrO_2.

Table 3-1. 1M Na Wash Endpoint MAR Assessment Results During Coupled Operation

Goal	Highest WL	Increased Frit Alkali
Frit (wt.%)	$10B_2O_3$-$8Li_2O$-$2Na_2O$-$80SiO_2$	Frit 625*
Number of EVs	1948	1948
Operating Window	27-40	25-36
Lower WL Limiting Constraint	26% WL *highv* (24%)	24% WL *highv* (5.3%)
Upper WL Limiting Constraint	41% WL *lowv* (19%)	37% WL ΔG_p (7.5%)

highv = high viscosity *lowv* = low viscosity ΔG_p (del G_p) = related to durability
*Frit 625 composition (wt.%): $1Al_2O_3$-$8B_2O_3$-$7Li_2O$-$6Na_2O$-$78SiO_2$

3.3.2 Results for the 0.7M and 0.85M Na Wash Endpoints with SRE Material

As shown in Appendix Table A-1, additional Tank 40 blend projections containing SRE material were received for 0.7M and 0.85M wash endpoints. MAR assessments were completed using the methodology presented in Section 3.2. The following two criteria were requested by SRR to select frits for SB10 processing.

- Goal #1: Select frit based only on coupled operation (with MST case) and evaluate the candidate frit for SO operation recognizing that it may not have a 9-percentage point operating window
- Goal #2: Select frit based on SO and coupled operations

Table 3-2 and Table 3-3 present summaries of the SO and coupled operations MAR assessment results for the 0.7M and 0.85M Na wash endpoints. More detailed results are provided in Appendix Table A-6 and Table A-7. The following three frits were identified for the various scenarios for SB10 processing:

- $8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%) satisfies Goal #1 for the 0.7M and 0.85M Na wash endpoints
- $9B_2O_3$-$8Li_2O$-$6Na_2O$-$77SiO_2$ (wt.%) satisfies Goal #2 for the 0.7M Na wash endpoint
- $9B_2O_3$-$8Li_2O$-$5Na_2O$-$78SiO_2$ (wt.%) satisfies Goal #2 for the 0.85M Na wash endpoint

The failed nepheline constraint at higher waste loadings for some of the EVs is waste form affecting as it reduces the chemical durability of the waste form. Nepheline ($NaAlSiO_4$) is a crystalline phase that is prone to form in glass during slow cooling when higher concentrations of Al_2O_3 and Na_2O are present.[19] The formation of nepheline is controlled in the DWPF PCCS by the following expression:[20,21]

$$\frac{SiO_2}{Al_2O_3+Na_2O+SiO_2} > 0.62$$

where SiO_2, Na_2O, and Al_2O_3 are the concentrations in the glass as mass fractions. Nepheline is *not* predicted to form when the value is greater than 0.62.

Due to the Cr_2O_3 concentration in the sludge and additional compositional variation applied for the MAR assessments, the solubility constraint for Cr_2O_3 fails for some of the SO EVs at higher waste loadings. The PCCS limit for Cr_2O_3 is 0.3 wt.% minus measurement uncertainty.[20] Compositions exceeding this constraint were also observed in previous SB10 MAR assessments.[22]

The primary difference in the results for Goal #1 and Goal #2 is the SO operating window, which is 4-7 percentage points for Goal #1 and at least 9 percentage points for Goal #2. Compared to the 1M Na wash endpoint results, a 0.85M Na wash endpoint is sufficient to find a viable frit with increased Na_2O and total alkali concentrations; however, the projected SO_4^{2-} concentration in glass at 36% WL is still near or exceeds the current SB9 limit of 0.65 wt.% (Table 3-4). The SO_4^{2-} concentration is only slightly reduced for the

0.7M Na wash endpoint and still has the potential to exceed the current 0.65 wt.% limit. Based on a previous discussion with SRR, they believe that the sulfate concentration in the projections are conservative and could be lower in the feed after washing.

Table 3-2. 0.7M Na Wash Endpoint MAR Assessment Results with SRE Material

Goal	**#1 Coupled Operation Only**		**#2 SO and Coupled Operations**	
Frit (wt.%)	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$		$9B_2O_3$-$8Li_2O$-$6Na_2O$-$77SiO_2$	
Projection	Coupled	SO	Coupled	SO
Number of EVs	2256	2056	2256	2056
Operating Window	27-40	36-39	24-39	29-38
Lower WL Limiting Constraint	26% WL *highv* (7.5%)	35% WL *highv* (7.9%)	23% WL not evaluated	28% WL *highv* (4.6%)
Upper WL Limiting Constraint	41% WL *neph* (2.7%)	40% WL Cr_2O_3 (49%)	40% WL *lowv* (11%) *neph* (5.1%)	39% WL *neph* (0.7%)

highv = high viscosity *lowv* = low viscosity *neph* = nepheline

Table 3-3. 0.85M Na Wash Endpoint MAR Assessment Results with SRE Material

Goal	**#1 Coupled Operation Only**		**#2 SO and Coupled Operations**	
Frit (wt.%)	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$		$9B_2O_3$-$8Li_2O$-$5Na_2O$-$78SiO_2$	
Projection	Coupled	SO	Coupled	SO
Number of EVs	2144	2077	2144	2077
Operating Window	26-40	33-39	24-39	31-39
Lower WL Limiting Constraint	25% WL *highv* (0.05%)	32% WL *highv* (9.6%)	23% WL not evaluated	30% WL *highv* (2.9%)
Upper WL Limiting Constraint	41% WL *lowv* (1.6%) *neph* (3.9%)	40% WL *neph* (1.3%)	40% WL *lowv* (6.7%) *neph* (1.0%)	40% WL *neph* (3.6%)

highv = high viscosity *lowv* = low viscosity *neph* = nepheline

Table 3-4. Sulfate (SO_4^{2-}) Concentration in Glass with SRE Material at 36% WL (wt.%)

Na Wash Endpoint	**0.7M**	**0.85M**
Case		
SO	0.69	0.72
Coupled	0.58	0.61

As an independent verification of the coupled operation results, an additional MAR assessment was performed using the SRNL-developed inputs for the SWPF Sludge Solids Receipt Tank (SSRT) stream that have been used for previous SB9 and SB10 evaluations. Details of the inputs used for this assessment of the 0.85M Na wash endpoint case are provided in Appendix B. A summary of the MAR assessment results is shown in Table 3-5. While the coupled operation projections are slightly different between the SRR and SRNL-developed versions of the 0.85M Na wash endpoint case (see Appendix Table B-1), the projected operating windows are the same as those shown in Table 3-3.

Table 3-5. Coupled Operation MAR Assessment Results for the 0.85M Na Wash Endpoint Case Based on SRNL-Developed Inputs for the SSRT Stream

Goal	#1 Coupled Operation Only	#2 SO and Coupled Operations
Frit (wt.%)	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$	$9B_2O_3$-$8Li_2O$-$5Na_2O$-$78SiO_2$
Number of EVs	2214	2214
Operating Window	26-40	24-39
Lower WL Limiting Constraint	25% WL *highv* (0.2%)	23% WL not evaluated
Upper WL Limiting Constraint	41% WL *lowv* (1.1%) *neph* (2.7%)	40% WL *lowv* (3.3%)

highv = high viscosity *lowv* = low viscosity *neph* = nepheline

3.3.3 Verification of the 0.7M and 0.85M Na Wash Endpoints without SRE Material

In case the SRE material transfer could not be made to SB10, SRR System Planning provided a final set of Tank 40 blend projections without SRE material representing SO and coupled operations (on a calcine basis) in May 2020.[23,24] SRNL was requested to evaluate the three frits identified in Section 3.3.2 (projections with SRE material) against these corresponding projections for the 0.7M and 0.85M Na wash endpoint projections without SRE material. The elemental concentrations were converted to oxides and normalized to 100 wt.% as shown in Appendix Table C-1. The methodology used for the MAR assessment is summarized in Section 3.2. SRAT oxide intervals are summarized in Appendix Table C-2 and Table C-3.

Table 3-6 and Table 3-7 present summaries of the SO and coupled-operations MAR assessment results for the 0.7M and 0.85M Na wash endpoints without SRE material. More detailed results are provided in Appendix Table C-4 and Table C-5. The projected operating windows are generally the same as those shown in Table 3-2 and Table 3-3 for the projections with SRE material and slight differences are highlighted in yellow. Thus, the three frits developed for projections with SRE material are also viable if SB10 does not contain any SRE material.

As shown in Table 3-8, the projected SO_4^{2-} concentrations in glass are higher than the projections in Table 3-4 for glasses with SRE material.

Table 3-6. 0.7M Na Wash Endpoint MAR Assessment Results without SRE Material

Goal	#1 Coupled Operation Only		#2 SO and Coupled Operations	
Frit (wt.%)	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$		$9B_2O_3$-$8Li_2O$-$6Na_2O$-$77SiO_2$	
Projection	Coupled	SO	Coupled	SO
Number of EVs	2256	2056	2256	2056
Operating Window	27-40	36-39	24-38*	28-38*
Lower WL Limiting Constraint	26% WL *highv* (1.9%)	35% WL *highv* (3.6%)	23% WL not evaluated	27% WL *highv* (13%)
Upper WL Limiting Constraint	41% WL *neph* (5.2%)	40% WL *neph* (1.4%)	39% WL *lowv* (1.9%) *neph* (2.2%)	39% WL *neph* (3.5%)

highv = high viscosity *lowv* = low viscosity *neph* = nepheline

*Yellow highlighting denotes slight differences between the operating window with SRE (Table 3-2)

Table 3-7. 0.85M Na Wash Endpoint MAR Assessment Results without SRE Material

Goal	#1 Coupled Operation Only		#2 SO and Coupled Operations	
Frit (wt.%)	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$		$9B_2O_3$-$8Li_2O$-$5Na_2O$-$78SiO_2$	
Projection	Coupled	SO	Coupled	SO
Number of EVs	2144	2037	2144	2037
Operating Window	25-39*	33-39	24-39	30-38*
Lower WL Limiting Constraint	24% WL *highv* (9.1%)	32% WL *highv* (2.9%)	23% WL not evaluated	29% WL *highv* (12%)
Upper WL Limiting Constraint	40% WL *neph* (1.0%)	40% WL *Cr_2O_3*(47%) *Cr_2O_3 Neph*(0.69%) *neph* (2.7%)	40% WL *lowv* (15%) *neph* (3.1%)	39% WL *neph* (0.5%)

highv = high viscosity *lowv* = low viscosity *neph* = nepheline

*Yellow highlighting denotes slight differences between the operating window with SRE (Table 3-3)

Table 3-8. Sulfate (SO_4^{2-}) Concentration in Glass without SRE Material at 36% WL (wt.%)

Na Wash Endpoint	0.7M	0.85M
Case		
SO	0.75	0.79
Coupled	0.63	0.66

3.4 Initial Frit Recommendation

In July 2020, SRR finalized the decision to proceed with the 0.85M Na wash endpoint for SB10[25] and communicated that the preferred frit for SB10 was the one selected for coupled operation only (Goal #1).[26] The composition of this frit is $8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%), which will be identified as Frit 473 from this point forward.

Just prior to issuing this report in September 2020, SRR Engineering was concerned with low total solids in the SRAT feed and requested that System Planning revise the SB10 projections with increased solids. Section 4.0 summarizes these MAR assessment results.

4.0 Subsequent SB10 MAR Assessments and Frit Development

The methodology used for the MAR assessments is described in Section 3.2.

4.1 Verification of Frit 473 with 0.85-0.95M Na Wash Endpoint Projections for Coupled Operation

In September 2020 SRR System Planning provided SB10 Tank 40 blend projections with SRE material on a calcine basis representing the following coupled operation scenarios.

- 0.85M Na wash endpoint[27] – Note that due to the increased solids, this projection is different than the previous 0.85M Na wash endpoint projection received in May 2020 (discussed in Section 3.3)
- 0.90M Na wash endpoint[28]
- 0.95M Na wash endpoint[28]

These coupled operation projections include the contribution of MST stream from SWPF. The elemental concentrations were converted to oxides and normalized to 100 wt.% as shown in Table D-1. SRNL was requested to evaluate Frit 473 against these three projections. SRAT oxide intervals used to generate the EVs are provided in Appendix Table D-2.

Table 4-1 presents a summary of the coupled-operations MAR assessment results for the 0.85-0.95M Na wash endpoint projections with Frit 473. More detailed results are provided in Appendix Table D-3. The change in Na wash endpoint from 0.85M to 0.95M has no impact on the projected operating window, which remains constant at 28-40% WL.

Table 4-1. 0.85-0.95M Na Wash Endpoint MAR Assessment Results with Frit 473 for Coupled Operation

Na Wash Endpoint	**0.85M**	**0.90M**	**0.95M**
Frit (wt.%)	Frit 473	Frit 473	Frit 473
Projection	Coupled	Coupled	Coupled
Number of EVs	2224	2266	2256
Operating Window	28-40	28-40	28-40
Lower WL Limiting Constraint	27% WL *highv* (12%)	27% WL *highv* (6.4%)	27% WL *highv* (1.6%)
Upper WL Limiting Constraint	41% WL *neph* (2.6%)	41% WL *neph* (2.5%)	41% WL *neph* (4.0%)

highv = high viscosity *neph* = nepheline

4.2 Verification of Frit 473 with 0.95M Na Wash Endpoint Projections for SO Operation

Based on the MAR assessment results for coupled operation presented in Section 4.1, SRR selected the 0.95M wash endpoint for further evaluation. In October 2020 SRR System Planning provided the Tank 40 blend projection for the 0.95M Na wash endpoint for SO operation (with SRE material).[29] The elemental concentrations were converted to oxides and normalized to 100 wt.% as shown in Table D-4. SRNL was requested to evaluate this projection with Frit 473. SRAT oxide intervals used to generate the EVs are provided in Appendix Table D-5.

Table 4-2 presents a summary of the SO MAR assessment results for the 0.95M Na wash endpoint projection with Frit 473. More detailed results are provided in Appendix Table D-6. The SO operating window is reduced to 3 percentage points (38-40% WL), which is less than the typical acceptability criterion of 9 percentage points.

Table 4-2. 0.95M Na Wash Endpoint MAR Assessment Results with Frit 473 for SO Operation

Na Wash Endpoint	**0.95M**
Frit (wt.%)	Frit 473
Projection	SO
Number of EVs	2077
Operating Window	38-40
Lower WL Limiting Constraint	37% WL *highv* (4.3%)
Upper WL Limiting Constraint	41% WL *neph* (5.6%)

highv = high viscosity *neph* = nepheline

4.3 Alternative Frit Development

Due to the reduced operating window of Frit 473 for SO operation, SRR Engineering requested that SRNL determine whether an alternative frit composition would provide a sufficient operating window for both SO and coupled operation.[30] The 0.95M Na wash endpoint projections shown in Appendix Table D-1 and Table D-4 were utilized and combined with a large array of frits covering the B_2O_3-Li_2O-Na_2O-SiO_2 region in the interval of 24-42% WL. SRAT oxide intervals used to generate the EVs are provided in Appendix Table D-2 and Table D-5.

Table 4-3 presents a summary of the SO MAR assessment results for the 0.95M Na wash endpoint projection with the alternative frit, $11B_2O_3$-$8Li_2O$-$5Na_2O$-$76SiO_2$ (wt.%), which will be referred to as Frit 209 from this point forward. More detailed results are provided in Appendix Table D-7. The operating windows for Frit 209 for SO and coupled operations are greater than 9 percentage points. A targeted WL of 36% is achievable for both operating scenarios. Frit 209 has 3 wt.% more B_2O_3 than Frit 473, which could potentially be beneficial for melting rate.

Table 4-3. 0.95M Na Wash Endpoint MAR Assessment Results with Frit 209 for SO and Coupled Operations

Na Wash Endpoint	**0.95M**	**0.95M**
Frit (wt.%)	Frit 209	Frit 209
Projection	Coupled	SO
Number of EVs	2256	2077
Operating Window	24-39	29-39
Lower WL Limiting Constraint	not evaluated	28% WL *highv* (8.4%)
Upper WL Limiting Constraint	40% WL *lowv* (15%) *neph* (4.5%)	40% WL *neph* (5.6%)

highv = high viscosity *lowv* = low viscosity *neph* = nepheline

4.4 <u>Evaluation of 0.95M Na Wash Endpoint Projection for Coupled Operation without MST</u>

In the event that SWPF reduces or eliminates the MST addition during SB10 processing, SRR System Planning provided a 0.95M Na wash endpoint projection for coupled operation case without MST solids.[31] The elemental concentrations were converted to oxides and normalized to 100 wt.% as shown in Appendix Table D-8. SRAT oxide intervals used to generate the EVs are provided in Appendix Table D-9.

Table 4-4 presents a summary of the MAR assessment results for the 0.95M Na wash endpoint projection for coupled operation without MST for both Frit 209 and Frit 473. More detailed results are provided in Appendix Table D-10.

Table 4-4. 0.95M Na Wash Endpoint MAR Assessment Results for Coupled Operation without MST

Na Wash Endpoint	**0.95M**	**0.95M**
Frit (wt.%)	Frit 473	Frit 209
Projection	Coupled without MST	
Number of EVs	2037	2037
Operating Window	29-38	24-37
Lower WL Limiting Constraint	28% WL *highv* (13%)	not evaluated
Upper WL Limiting Constraint	39% WL *neph* (0.5%)	38% WL *neph* (0.5%)

highv = high viscosity *neph* = nepheline

5.0 Frit Leaching Assessment

Previous testing has been performed to assess the potential for gel formation in the frit slurry (without formic acid) for frits within the B_2O_3-Li_2O-Na_2O-SiO_2 system as shown in Table 5-1.[2-4] The composition of Frit 473 and Frit 209 are within the composition region shown in Table 5-1 and gel formation in the frit slurry is not expected to occur. Thus, additional experimental testing is not needed.

Table 5-1. Oxide Intervals of Previous Frit Slurry Gel Testing

Oxide	Interval (wt.%)
B_2O_3	8-17
Li_2O	2-8
Na_2O	1-14
SiO_2	69-84

6.0 SB10 Variability Study

The objective of the variability study is to demonstrate that the Product Consistency Test (PCT) responses of the glass compositions *within* (not necessarily bounding) the glass system based on the projected sludge and selected frits are:

- Acceptable relative to the chemical durability of the Environmental Assessment (EA) benchmark glass, and
- Predictable by the current DWPF PCCS models for durability.

The variability study has been designed to account for variation in the SB10 composition and for flexibility in the frit composition based on the MAR assessment results discussed in Sections 3.0 and 4.0. The SB10 frit recommendation will be finalized and documented separately in the future once more information is known about the composition of SB10 after the sludge washing demonstration in the SRNL Shielded Cells.

6.1 Development of the Overall SB10 Glass Composition Region

Using the SRAT oxide intervals developed for the MAR assessments,[c] the overall minimum and maximum concentrations of the major sludge components were determined for the following SB10 cases. Compositional variation of ±7.5% was included in the concentrations of the SRAT components (as used for the MAR assessments).

- 0.7M and 0.85M Na wash endpoints (May 2020)
  - SO operation and coupled operation with SWPF (with MST)
  - With and without SRE material
- 0.95M wash endpoint (September and October 2020)
  - SO operation and coupled operation with SWPF (with and without MST)
  - With SRE material

To generate glass compositions, the three SB10 frits of interest (including Frit 473) from Section 3.3.2 and Frit 209 were combined with the minimum and maximum SRAT oxide concentrations from the corresponding Na wash endpoints at 32% and 40% WL. The overall minimum and maximum concentrations of the major glass oxides were determined and are shown in Appendix Table E-1.

6.2 Review of the ComPro™ Database

Prior to developing the variability study glasses, the ComPro™ database[32-34] was used to determine whether glasses from previous studies were already within the SB10 glass composition region of interest. This database contains chemical composition and PCT data compiled from previous glass studies at SRNL and across the Department of Energy (DOE) complex. It is used as a tool during glass matrix development since identifying glasses in the frit-sludge region of interest would reduce the number of glasses required for the variability study.

To enhance the potential for identifying glasses, the intervals for the oxides shown in Appendix Table E-1 were expanded by ±1 wt.%, except for SiO_2, which was expanded by ±2 wt.% since it has the highest

[c] See Appendix Table A-4, Table A-4, Table C-3, Table C-3, Table D-2, Table D-5, and Table D-9.

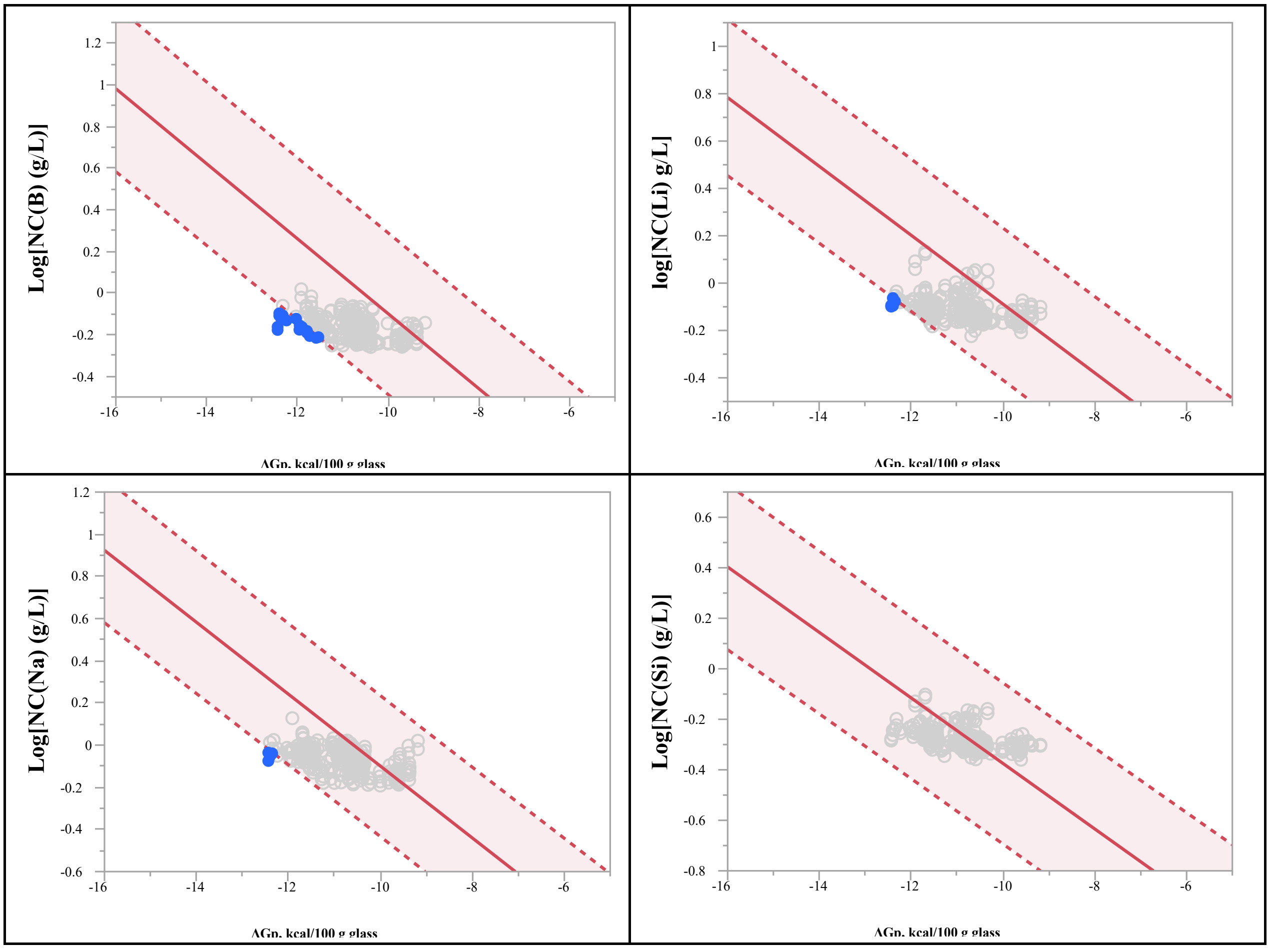
concentration in glass. Any of the minor oxides[d] not included in Appendix Table E-1 were limited to less than 0.5 wt.% in glass, which would force the elemental concentrations to be below the reportable limit. Per the DWPF Waste Form Compliance Plan,[35] components in the glass having an elemental concentration greater than 0.5 wt.% shall be reported. Limiting the minor oxide concentrations to less than 0.5 wt.% eliminated the possibility of identifying glass compositions that have unique minor oxides (e.g. Nb_2O_5), which are not representative of previous DWPF sludge batches.

Eighty-five "model" entries were found to have compositions that simultaneously satisfy the oxide intervals of the search criteria.[e] A list of the glasses is shown in Appendix Table E-2 and includes compositions from SB6,[36] SB7a,[37-39] and SB7b.[40] The compositions may represent target or measured compositions, or both.

Each of these glasses identified from previous variability studies underwent a heat treatment representing canister centerline cooling (CCC). For each composition, samples of both the quenched glass (cooled in air) and glass subjected to the CCC were evaluated by the PCT. The normalized concentrations (NC_i) of B, Li, Na, and Si were calculated using both the targeted and measured compositions. These results were reported previously and will not be repeated in this report.

Figure 6-1 provides plots of the DWPF durability models that relate the NCi to a linear function of a free energy of hydration term (ΔGp, kcal/100 g glass) for each of the glasses listed in Appendix Table E-2. Prediction limits at a 95% confidence for an individual PCT result (- - - -) are plotted along with the linear fit (——). All of the variability study glasses are predictable with respect to the PCCS models for durability except for some of the SB7a variability study glasses shown by a solid blue circle (●) in Figure 6-1, which are slightly outside of the lower 95% confidence band. A list of these glasses is provided in Appendix Table E-3. The durability models are conservative for the PCT responses of these glasses since the measured results indicate better durability values than predicted by the models.

[d] The minor oxides include BaO, Ce_2O_3, Cr_2O_3, CuO, K_2O, La_2O_3, MgO, PbO, SO_4^{2-}, ZnO and ZrO_2.
[e] "Model" entries are results from studies that were conducted under quality assurance criteria that were RW-0333P compliant or criteria determined to be RW-0333P equivalent.



○	Variability glasses *within* the 95% confidence bands
●	SB7a variability glasses *outside* the 95% confidence bands

Figure 6-1. ΔGp predictions (kcal/ 100 g glass) versus the log of the normalized concentrations (NC) of B, Li, Na, and Si.

6.3 Glass Selection

Due to the presence of ComPro™ glasses within the projected glass composition region for SB10, only a minimal number of glasses are necessary for the variability study to confirm durability model predictability. Using the Space Filling routine of the Design of Experiments platform in JMP 14.3.0,[8] 1000 compositions were generated within the oxide intervals shown in Appendix Table E-1 for the anticipated SB10 glass composition region. An interval of 0.77-1.99 wt.% was used for the minor oxides which included BaO, Ce_2O_3, Cr_2O_3, CuO, K_2O, La_2O_3, MgO, PbO, SO_4^{2-}, ZnO, and ZrO_2. Note that the maximum potential SO_4^{2-} concentration in glass was fixed at 0.65 wt.% since sulfate solubility behavior will be studied separately. Each of the compositions was evaluated against the PCCS MAR criteria to determine whether the composition would pass the SME acceptability process. Of the original 1000 compositions, 809 compositions passed the MAR constraints. Compositions that failed the MAR constraints were excluded from further evaluation.

To down-select from the 809 space filling glasses, the minimum and maximum oxide concentrations for the overall SB10 glass region were compared to glasses found in the ComPro™ database as shown in

Table 6-1. Only differences that fall outside of the intervals based on the ComPro™ glasses are noted. Otherwise, "---" is used to denote that the SB10 minimum and/or maximum value is within the ComPro™ interval for a particular oxide. Of the major glass oxides listed in Table 6-1, the concentrations of Al_2O_3, B_2O_3, Fe_2O_3, MnO, Na_2O, NiO, SiO_2, and TiO_2 in glass are more than 0.5 wt.% different than those represented by the ComPro™ glasses. Only Al_2O_3, B_2O_3, Fe_2O_3, Na_2O, SiO_2, and TiO_2 were of interest for generating the variability study glass compositions. MnO and NiO were ignored since lower concentrations of these oxides (as compared to the ComPro™ glasses) would not result in irregular durability behavior. The remaining components from Table 6-1 (CaO, Li_2O, ThO_2, and U_3O_8) were also not considered since the concentrations were either just outside or within the intervals based on the ComPro™ glasses.

Table 6-1. Comparison of Glass Oxide Intervals for the ComPro™ Glasses and SB10 Glass Region (wt.%)

Oxide	ComPro™ Glasses		SB10 Glass Region		Difference*	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Al_2O_3	7.01	11.34	7.15	12.92	---	1.6
B_2O_3	4.37	5.44	4.80	7.48	---	2.0
CaO	0.27	0.84	0.19	0.74	-0.1	---
Fe_2O_3	7.24	10.09	5.02	9.09	-2.2	---
Li_2O	4.59	6.40	4.80	5.44	---	---
MnO	1.67	2.67	1.01	2.83	-0.7	0.2
Na_2O	12.44	16.24	11.36	18.17	-1.1	1.9
NiO	0.84	1.50	0.05	0.52	-0.8	---
SiO_2	45.22	54.07	45.92	54.63	---	0.6
ThO_2	0.14	1.26	0.45	1.16	---	---
TiO_2	0.01	0.71	0.00	3.30	---	2.6
U_3O_8	1.43	2.88	1.01	1.91	-0.4	---

*Difference = SB10 Glass Region – ComPro™ Glasses

Using the OPTEX routine in SAS®,[9] seven glass compositions were D-optimally selected from the 809 space filling compositions based on the intervals of Al_2O_3, B_2O_3, Fe_2O_3, Na_2O, SiO_2, and TiO_2. One glass composition was manually selected to represent the center point of the SB10 glass region based on the oxides in Table 6-1. Six is the minimum number of glasses that represents the compositional variation of the major components of interest (Al_2O_3, B_2O_3, Fe_2O_3, Na_2O, SiO_2, and TiO_2) and two additional glasses were included to have two full PCT oven runs (i.e., 4 unique glasses per oven run). The durability results for these eight compositions will supplement the existing ComPro™ durability data already within the SB10 glass composition region.

Target compositions of the eight variability study glasses are shown in Table 6-2. SB10-01 through SB10- 07 are the D-optimally selected compositions and SB10-08 represents the center point.

Table 6-2. Target Compositions for the SB10 Variability Study Glasses (wt.%)

Glass ID	SB10-01	SB10-02	SB10-03	SB10-04	SB10-05	SB10-06	SB10-07	SB10-08
Al_2O_3	7.379	7.516	7.578	10.977	11.613	11.983	12.687	9.864
B_2O_3	5.120	6.946	7.291	7.450	5.003	7.191	5.210	6.095
BaO	0.035	0.049	0.046	0.066	0.040	0.067	0.041	0.050
CaO	0.673	0.604	0.522	0.443	0.718	0.642	0.535	0.465
Ce_2O_3	0.089	0.126	0.116	0.168	0.101	0.170	0.105	0.127
Cr_2O_3	0.098	0.138	0.128	0.185	0.111	0.187	0.115	0.139
CuO	0.022	0.032	0.029	0.042	0.025	0.043	0.026	0.032
Fe_2O_3	8.257	6.230	5.798	8.673	5.084	5.158	8.796	6.855
K_2O	0.043	0.060	0.055	0.080	0.048	0.081	0.050	0.060
La_2O_3	0.021	0.029	0.027	0.039	0.024	0.040	0.025	0.030
Li_2O	5.236	5.058	4.903	4.946	4.963	5.264	5.267	5.117
MgO	0.198	0.278	0.257	0.371	0.223	0.377	0.232	0.280
MnO	1.371	2.595	2.458	1.660	1.069	2.337	1.214	1.906
Na_2O	11.363	16.049	13.160	15.706	17.069	11.647	12.349	14.616
NiO	0.506	0.271	0.416	0.360	0.469	0.198	0.420	0.283
PbO	0.025	0.035	0.032	0.047	0.028	0.047	0.029	0.035
SO_4^{2-}	0.316	0.444	0.411	0.593	0.356	0.603	0.371	0.448
SiO_2	54.478	47.926	54.491	45.919	50.286	48.584	49.670	49.555
ThO_2	1.064	0.830	0.578	0.917	1.088	1.033	0.838	0.804
TiO_2	2.097	3.279	0.056	0.025	0.089	2.868	0.815	1.614
U_3O_8	1.488	1.337	1.492	1.107	1.459	1.253	1.065	1.455
ZnO	0.012	0.016	0.015	0.022	0.013	0.022	0.014	0.016
ZrO_2	0.108	0.151	0.140	0.202	0.121	0.205	0.127	0.153

7.0 Recommendations

The variability study has been designed to account for variation in the SB10 composition and for flexibility in the frit composition. Depending on the composition of SB10, Frit 473 ($8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%) or Frit 209 ($11B_2O_3$-$8Li_2O$-$5Na_2O$-$76SiO_2$ (wt.%)) allow for the flexibility of SO processing or coupled operation with SWPF at 36% WL. No issues are expected for leaching of either of these frits in the DWPF frit slurry with water. The SB10 frit recommendation will be finalized and documented separately in the future once more information is known about the composition of SB10 after the sludge washing demonstration in the SRNL Shielded Cells.

The SB10 glass region for the variability study was developed based on the following SB10 projections.

- 0.7M and 0.85M Na wash endpoint projections with Frit 473 for SO operation and coupled operation with SWPF (with MST)
    - With and without SRE material
- 0.95M wash endpoint projections with Frit 209 for SO operation and coupled operation with SWPF (with and without MST)
    - With SRE material

This glass region overlaps compositions previously evaluated for the SB6, SB7a, and SB7b variability studies. Thus, only a minimal number of glasses are needed to supplement the existing durability data in the SB10 glass region. SRNL recommends that eight variability study glasses be fabricated, tested, and analyzed to confirm that the glasses are acceptable relative to the chemical durability of the EA benchmark glass and predictable by the current PCCS models for durability.

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Appendix A. Supplementary Information for MAR Assessments with SRE Material

Table A-1. 0.7-1M Normalized SB10 Tank 40 Blend Projections with SRE Material (wt.%)

Na Wash Endpoint	1M		0.85M		0.7M	
Projection	Coupled	SO	Coupled	SO	Coupled	SO
Oxide						
Al_2O_3	22.55	26.79	24.17	28.65	24.87	29.38
B_2O_3	0.26	0.29	0.27	0.32	0.28	0.33
BaO	0.07	0.08	0.07	0.09	0.08	0.09
CaO	0.99	1.17	1.08	1.28	1.12	1.32
Ce_2O_3	0.16	0.20	0.18	0.22	0.19	0.23
Cr_2O_3	0.39	0.48	0.44	0.52	0.45	0.53
CuO	0.04	0.05	0.05	0.06	0.05	0.06
Fe_2O_3	15.52	18.43	16.95	20.08	17.55	20.73
K_2O	0.10	0.12	0.09	0.10	0.09	0.10
La_2O_3	0.04	0.05	0.04	0.05	0.04	0.05
Li_2O	0.04	0.04	0.04	0.05	0.05	0.05
MgO	0.38	0.45	0.41	0.48	0.42	0.50
MnO	4.63	5.51	5.28	6.25	5.46	6.46
Na_2O	38.00	35.68	33.75	30.68	32.08	28.78
NiO	0.58	0.70	0.64	0.76	0.67	0.79
PbO	0.04	0.05	0.05	0.06	0.05	0.06
SO_4^{2-}	1.88	2.24	1.68	1.99	1.62	1.91
SiO_2	1.30	1.56	1.42	1.69	1.47	1.74
ThO_2	1.76	2.09	1.92	2.28	1.99	2.35
TiO_2	7.63	0.03	7.55	0.03	7.41	0.04
U_3O_8	3.40	3.74	3.67	4.06	3.80	4.19
ZnO	0.02	0.02	0.02	0.03	0.02	0.03
ZrO_2	0.20	0.24	0.22	0.26	0.23	0.27

Table A-2. SRAT Oxide Intervals for the 1M Na Wash Endpoint with SRE Material (wt.%)

Case	Coupled			SO		
Al_2O_3	20.86	-	24.24	24.78	-	28.80
CaO	0.49	-	1.49	0.67	-	1.67
Fe_2O_3	14.36	-	16.69	17.05	-	19.81
MnO	4.13	-	5.13	5.01	-	6.01
Na_2O	35.15	-	40.85	33.01	-	38.36
NiO	0.08	-	1.08	0.20	-	1.20
SiO_2	0.80	-	1.80	1.06	-	2.06
ThO_2	1.26	-	2.26	1.59	-	2.59
TiO_2	7.06	-	8.21	0.00	-	0.53
U_3O_8	2.90	-	3.90	3.24	-	4.24
Others	3.12	-	4.12	3.81	-	4.81

Table A-3. SRAT Oxide Intervals for the 0.85M Na Wash Endpoint with SRE Material (wt.%)

Case	Coupled			SO		
Al_2O_3	22.36	-	25.98	26.50	-	30.79
CaO	0.58	-	1.58	0.78	-	1.78
Fe_2O_3	15.67	-	18.22	18.58	-	21.59
MnO	4.78	-	5.78	5.75	-	6.75
Na_2O	31.22	-	36.28	28.38	-	32.98
NiO	0.14	-	1.14	0.26	-	1.26
SiO_2	0.92	-	1.92	1.19	-	2.19
ThO_2	1.42	-	2.42	1.78	-	2.78
TiO_2	6.98	-	8.11	0.00	-	0.53
U_3O_8	3.17	-	4.17	3.56	-	4.56
Others	3.07	-	4.07	3.74	-	4.74

Table A-4. SRAT Oxide Intervals for the 0.7M Na Wash Endpoint with SRE Material (wt.%)

Case	Coupled			SO		
Al_2O_3	23.01	-	26.74	27.18	-	31.59
CaO	0.62	-	1.62	0.82	-	1.82
Fe_2O_3	16.23	-	18.87	19.18	-	22.29
MnO	4.96	-	5.96	5.96	-	6.96
Na_2O	29.68	-	34.49	26.62	-	30.94
NiO	0.17	-	1.17	0.29	-	1.29
SiO_2	0.97	-	1.97	1.24	-	2.24
ThO_2	1.49	-	2.49	1.85	-	2.85
TiO_2	6.86	-	7.97	0.00	-	0.54
U_3O_8	3.30	-	4.30	3.69	-	4.69
Others	3.07	-	4.07	3.72	-	4.72

Table A-5. Complete 1M Na Wash Endpoint MAR Assessment Results with SRE Material

Goal	Highest WL		Increased Frit Alkali	
Frit	$10B_2O_3$-$8Li_2O$-$2Na_2O$-$80SiO_2$ (wt.%)		Frit 625 [$1Al_2O_3$-$8B_2O_3$-$7Li_2O$-$6Na_2O$-$78SiO_2$ (wt.%)]	
Case	Coupled	SO	Coupled	SO
Number of EVs	1948	2009	1948	2009
%WL, 24	highv(51%)	highv(100%)	highv(5.3%)	highv(65%)
25	highv(42%)	highv(100%)		highv(54%)
26	highv(24%)	highv(81%)		highv(50%)
27		highv(57%)		highv(45%)
28		highv(51%)		highv(34%)
29		highv(48%)		highv(11%)
30		highv(42%)		
31		highv(28%)		
32		highv(7.4%)		
33				
34				
35				
36				
37			Del Gp(7.5%)	
38			Neph(1.2%) Del Gp(27%)	Neph(7.6%)
39			lowv(0.24%) Neph(20%) Del Gp(33%) Del Gp lowv(2.6%) Del Gp lowv Neph(9.5%) Del Gp Neph(35%)	Neph(63%)
40			lowv Neph(2.0%) Neph(32%) Del Gp lowv Neph(34%) Del Gp Neph(4.6%)	Neph(94%)
41	lowv(19%)	Neph(1.8%)	lowv Neph(4.8%) Neph(52%) Del Gp lowv Neph(41%) Del Gp Neph(0.46%)	Neph(94%) Del Gp Neph(6.4%)
42	lowv(39%) lowv Neph(1.2%) Neph(3.0%)	Neph(28%)	lowv Neph(7.0%) Neph(49%) Del Gp lowv Neph(44%) Del Gp Neph(0.05%)	Neph(76%) Del Gp Neph(24%)

Table A-6. Complete 0.7M Na Wash Endpoint MAR Assessment Results with SRE Material

Goal	#1 Coupled Operation Only		#2 SO and Coupled Operations	
Frit	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%)		$9B_2O_3$-$8Li_2O$-$6Na_2O$-$77SiO_2$ (wt.%)	
Case	Coupled	SO	Coupled	SO
Number of EVs	2256	2056	2256	2056
%WL, 24	highv(43%)	highv(100%)		highv(44%)
25	highv(29%)	highv(100%)		highv(38%)
26	highv(7.5%)	highv(89%)		highv(28%)
27		highv(70%)		highv(17%)
28		highv(57%)		highv(4.6%)
29		highv(52%)		
30		highv(49%)		
31		highv(43%)		
32		highv(38%)		
33		highv(29%)		
34		highv(18%)		
35		highv(7.9%)		
36				
37				
38				
39				Neph(0.73%)
40		Cr_2O_3(49%)	lowv(11%) Neph(5.1%)	Cr_2O_3(46%) Cr_2O_3 Neph(2.3%) Neph(5.9%)
41	Neph(2.7%)	Cr_2O_3(48%) Cr_2O_3 Neph(1.3%) Neph(4.4%)	lowv(18%) lowv Neph(18%) Neph(16%)	Cr_2O_3(15%) Cr_2O_3 Neph(34%) Neph(41%)
42	Neph(14%)	Cr_2O_3(36%) Cr_2O_3 Neph(14%) Neph(18%)	lowv(0.93%) lowv Neph(43%) Neph(46%)	Cr_2O_3(6.7%) Cr_2O_3 Neph(42%) Neph(48%)

Table A-7. Complete 0.85M Na Wash Endpoint MAR Assessment Results with SRE Material

Goal	#1 Coupled Operation Only		#2 SO and Coupled Operations	
Frit	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%)		$9B_2O_3$-$8Li_2O$-$5Na_2O$-$78SiO_2$ (wt.%)	
Case	Coupled	SO	Coupled	SO
Number of EVs	2144	2077	2144	2077
%WL, 24	highv(19%)	highv(95%)		highv(59%)
25	highv(0.05%)	highv(75%)		highv(53%)
26		highv(60%)		highv(48%)
27		highv(54%)		highv(41%)
28		highv(49%)		highv(32%)
29		highv(44%)		highv(17%)
30		highv(35%)		highv(2.9%)
31		highv(22%)		
32		highv(9.6%)		
33				
34				
35				
36				
37				
38				
39				
40		Neph(1.3%)	lowv(6.7%) Neph(1.0%)	Neph(3.6%)
41	lowv(1.6%) Neph(3.9%)	Cr_2O_3(45%) Cr_2O_3 Neph(3.8%) Neph(7.9%)	lowv(29%) lowv Neph(0.61%) Neph(9.1%)	Cr_2O_3(41%) Cr_2O_3 Neph(7.3%) Neph(12%)
42	lowv(1.7%) lowv Neph(24%) Neph(23%)	Cr_2O_3(13%) Cr_2O_3 Neph(36%) Neph(43%)	lowv(4.9%) lowv Neph(40%) Neph(27%)	Cr_2O_3(10%) Cr_2O_3 Neph(39%) Neph(45%)

Appendix B. Supplementary Information for MAR Assessment Using SRNL-Developed Input for SSRT Stream

The normalized SO projection from the 0.85M Na wash endpoint case in Appendix Table A-1 was used as the basis for this evaluation. SRNL performed subsequent calculations to estimate the composition of strip effluent (SE) and the SSRT effluent stream[41] for a single MST strike during coupled operation with SWPF. Other pertinent inputs include:

- DWPF receives 6000 gallons of sludge slurry from Tank 40 per SRAT batch,[42]
- A nominal single MST strike represents 2800 gallons of the SSRT effluent stream per SRAT batch,[43]
- DWPF receives 12,800 gallons of SE per SRAT batch based on the Next Generation Solvent (NGS),[a,43] and
- SE has a Cs-137 concentration of 66 curies/gallon.[43]

The resulting projection in the SRAT for coupled operation is shown in Table B-1 and the difference from the corresponding values in Appendix Table A-1 are also provided. The methodology used for the MAR assessment is summarized in Section 3.2. Note that Cs_2O was included with the "Others" components.

Table B-1. Coupled Operation Projection for the 0.85M Na Wash Endpoint Case Based on SRNL-Developed Input for the SSRT Stream

Oxide	Concentration (wt.%)	Difference from Appendix Table A-1 (wt.%)
Al_2O_3	23.96	-0.2
B_2O_3	0.81	0.5
BaO	0.07	0.0
CaO	1.04	0.0
Ce_2O_3	0.18	0.0
Cr_2O_3	0.42	0.0
Cs_2O	1.35	1.4
CuO	0.04	0.0
Fe_2O_3	16.24	-0.7
K_2O	0.26	0.2
La_2O_3	0.04	0.0
Li_2O	0.04	0.0
MgO	0.39	0.0
MnO	5.06	-0.2
Na_2O	32.99	-0.8
NiO	0.62	0.0
PbO	0.05	0.0
SO_4^{2-}	1.65	0.0
SiO_2	1.36	-0.1
ThO_2	1.84	-0.1
TiO_2	8.07	0.5
U_3O_8	3.28	-0.4
ZnO	0.02	0.0
ZrO_2	0.21	0.0

[a] NGS contains the extractant MaxCalix (1,3-alt-25,27-bis(3,7- dimethyloctyl-1-oxy) calix[4]arene-benzocrown-6), which uses a boric acid strip solution.

Appendix C. Supplementary Information for MAR Assessments without SRE Material

Table C-1. 0.7M -0.85M Normalized SB10 Tank 40 Blend Projections without SRE Material (wt.%)

Na Wash Endpoint	0.85M		0.7M	
Projection	Coupled	SO	Coupled	SO
Oxide				
Al_2O_3	24.57	29.21	25.32	30.02
B_2O_3	0.27	0.33	0.28	0.34
BaO	0.07	0.09	0.08	0.09
CaO	1.10	1.30	1.14	1.35
Ce_2O_3	0.19	0.22	0.19	0.23
Cr_2O_3	0.44	0.52	0.46	0.54
CuO	0.05	0.06	0.05	0.06
Fe_2O_3	17.18	20.43	17.84	21.15
K_2O	0.09	0.11	0.09	0.10
La_2O_3	0.04	0.05	0.05	0.05
Li_2O	0.05	0.05	0.05	0.06
MgO	0.41	0.49	0.43	0.51
MnO	3.65	4.34	3.79	4.50
Na_2O	34.35	31.33	32.62	29.33
NiO	0.65	0.78	0.68	0.80
PbO	0.05	0.06	0.05	0.06
SO_4^{2-}	1.84	2.19	1.75	2.08
SiO_2	1.44	1.72	1.50	1.78
ThO_2	1.95	2.31	2.02	2.40
TiO_2	7.68	0.03	7.56	0.04
U_3O_8	3.67	4.07	3.80	4.21
ZnO	0.02	0.03	0.03	0.03
ZrO_2	0.23	0.27	0.23	0.28

Table C-2. SRAT Oxide Intervals for the 0.85M Na Wash Endpoint without SRE Material (wt.%)

Case	Coupled			SO		
Al_2O_3	22.73	-	26.41	27.02	-	31.40
CaO	0.60	-	1.60	0.80	-	1.80
Fe_2O_3	15.89	-	18.47	18.90	-	21.96
MnO	3.15	-	4.15	3.84	-	4.84
Na_2O	31.78	-	36.93	28.98	-	33.68
NiO	0.15	-	1.15	0.28	-	1.28
SiO_2	0.94	-	1.94	1.22	-	2.22
ThO_2	1.45	-	2.45	1.81	-	2.81
TiO_2	7.10	-	8.25	0.00	-	0.53
U_3O_8	3.17	-	4.17	3.57	-	4.57
Others	3.26	-	4.26	3.97	-	4.97

Table C-3. SRAT Oxide Intervals for the 0.7M Na Wash Endpoint without SRE Material (wt.%)

Case	Coupled			SO		
Al_2O_3	23.42	-	27.21	27.77	-	32.27
CaO	0.64	-	1.64	0.85	-	1.85
Fe_2O_3	16.50	-	19.17	19.56	-	22.74
MnO	3.29	-	4.29	4.00	-	5.00
Na_2O	30.17	-	35.07	27.13	-	31.53
NiO	0.18	-	1.18	0.30	-	1.30
SiO_2	1.00	-	2.00	1.28	-	2.28
ThO_2	1.52	-	2.52	1.90	-	2.90
TiO_2	7.00	-	8.13	0.00	-	0.54
U_3O_8	3.30	-	4.30	3.71	-	4.71
Others	3.24	-	4.24	3.94	-	4.94

Table C-4. Complete 0.7M Na Wash Endpoint MAR Assessment Results without SRE Material

Goal	#1 Coupled Operation Only		#2 SO and Coupled Operations	
Frit	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%)		$9B_2O_3$-$8Li_2O$-$6Na_2O$-$77SiO_2$ (wt.%)	
Case	Coupled	SO	Coupled	SO
Number of EVs	2256	2056	2256	2056
%WL, 24	highv(41%)	highv(100%)		highv(43%)
25	highv(23%)	highv(100%)		highv(34%)
26	highv(1.9%)	highv(84%)		highv(23%)
27		highv(64%)		highv(13%)
28		highv(55%)		
29		highv(50%)		
30		highv(46%)		
31		highv(41%)		
32		highv(34%)		
33		highv(24%)		
34		highv(16%)		
35		highv(3.6%)		
36				
37				
38				
39			lowv(1.9%) Neph(2.2%)	Neph(3.5%)
40		Neph(1.4%)	lowv(21%) Neph(9.7%)	Neph(19%)
41	Neph(5.2%)	Cr_2O_3(45%) Cr_2O_3 Neph(3.8%) Neph(8.0%)	lowv(3.4%) lowv Neph(36%) Neph(29%)	Cr_2O_3(11%) Cr_2O_3 Neph(38%) Neph(45%)
42	lowv Neph(1.9%) Neph(34%)	Cr_2O_3(13%) Cr_2O_3 Neph(36%) Neph(43%)	lowv Neph(48%) Neph(47%)	Cr_2O_3(3.2%) Cr_2O_3 Neph(46%) Neph(50%)

Note that Frit 473 is $8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%).

Table C-5. Complete 0.85M Na Wash Endpoint MAR Assessment Results without SRE Material

Goal	#1 Coupled Operation Only		#2 SO and Coupled Operations	
Frit	$8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%)		$9B_2O_3$-$8Li_2O$-$5Na_2O$-$78SiO_2$ (wt.%)	
Case	Coupled	SO	Coupled	SO
Number of EVs	2144	2037	2144	2037
%WL, 24	highv(9.1%)	highv(89%)		highv(55%)
25		highv(66%)		highv(51%)
26		highv(55%)		highv(47%)
27		highv(52%)		highv(40%)
28		highv(49%)		highv(24%)
29		highv(41%)		highv(12%)
30		highv(32%)		
31		highv(16%)		
32		highv(2.9%)		
33				
34				
35				
36				
37				
38				
39				Neph(0.49%)
40	Neph(1.0%)	Cr_2O_3(47%) Cr_2O_3 Neph(0.69%) Neph(2.7%)	lowv(15%) Neph(3.1%)	Cr_2O_3(45%) Cr_2O_3 Neph(2.4%) Neph(5.7%)
41	lowv(8.8%) lowv Neph(0.05%) Neph(9.7%)	Cr_2O_3(35%) Cr_2O_3 Neph(13%) Neph(18%)	lowv(20%) lowv Neph(19%) Neph(12%)	Cr_2O_3(14%) Cr_2O_3 Neph(34%) Neph(42%)
42	lowv(0.93%) lowv Neph(35%) Neph(32%)	Cr_2O_3(8.0%) Cr_2O_3 Neph(41%) Neph(47%)	lowv(2.1%) lowv Neph(45%) Neph(44%)	Cr_2O_3(4.3%) Cr_2O_3 Neph(45%) Neph(50%)

Note that Frit 473 is $8B_2O_3$-$8Li_2O$-$5Na_2O$-$79SiO_2$ (wt.%).

Appendix D. Supplementary Information for Subsequent SB10 MAR Assessments

Table D-1. 0.85-0.95M Normalized SB10 Tank 40 Blend Projections for Coupled Operation (wt.%)

Na Wash Endpoint	0.85M	0.90M	0.95M
Projection	Coupled	Coupled	Coupled
Oxide			
Al_2O_3	25.64	25.50	25.34
B_2O_3	0.03	0.03	0.03
BaO	0.08	0.08	0.08
CaO	1.15	1.15	1.14
Ce_2O_3	0.20	0.20	0.19
Cr_2O_3	0.29	0.29	0.29
CuO	0.05	0.05	0.05
Fe_2O_3	18.06	17.94	17.79
K_2O	0.09	0.09	0.09
La_2O_3	0.05	0.05	0.05
Li_2O	0.05	0.05	0.05
MgO	0.44	0.43	0.43
MnO	5.63	5.59	5.54
Na_2O	30.83	31.22	31.70
NiO	0.69	0.68	0.68
PbO	0.05	0.05	0.05
SO_4^{2-}	1.27	1.30	1.33
SiO_2	1.52	1.51	1.50
ThO_2	2.04	2.03	2.01
TiO_2	7.69	7.64	7.58
U_3O_8	3.90	3.87	3.84
ZnO	0.03	0.03	0.03
ZrO_2	0.24	0.24	0.23

Table D-2. SRAT Oxide Intervals for the 0.85-0.95M Na Wash Endpoints for Coupled Operation (wt.%)

Na Wash Endpoint	0.85M	0.90M	0.95M
Al_2O_3	23.72 - 27.57	23.59 - 27.42	23.44 - 27.24
CaO	0.65 - 1.65	0.65 - 1.65	0.64 - 1.64
Fe_2O_3	16.71 - 19.42	16.59 - 19.28	16.45 - 19.12
MnO	5.13 - 6.13	5.09 - 6.09	5.04 - 6.04
Na_2O	28.52 - 33.14	28.88 - 33.57	29.33 - 34.08
NiO	0.19 - 1.19	0.18 - 1.18	0.18 - 1.18
SiO_2	1.02 - 2.02	1.01 - 2.01	1.00 - 2.00
ThO_2	1.54 - 2.54	1.53 - 2.53	1.51 - 2.51
TiO_2	7.11 - 8.27	7.07 - 8.21	7.01 - 8.15
U_3O_8	3.40 - 4.40	3.37 - 4.37	3.34 - 4.34
Others	2.36 - 3.36	2.37 - 3.37	2.39 - 3.39

Table D-3. Complete 0.85-0.95M Na Wash Endpoint MAR Assessment Results for Frit 473 and Coupled Operation

Na Wash Endpoint	0.85M	0.90M	0.95M
Frit	Frit 473	Frit 473	Frit 473
Case	Coupled	Coupled	Coupled
Number of EVs	2224	2266	2256
%WL, 24	highv(51%)	highv(49%)	highv(46%)
25	highv(44%)	highv(42%)	highv(38%)
26	highv(35%)	highv(29%)	highv(19%)
27	highv(12%)	highv(6.4%)	highv(1.6%)
28			
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			
41	Neph(2.6%)	Neph(2.5%)	Neph(4.0%)
42	Neph(11%)	Neph(14%)	Neph(14%)

Table D-4. 0.95M Normalized SB10 Tank 40 Blend Projections for SO Operation (wt.%)

Na Wash Endpoint	0.95M
Projection	SO
Oxide	
Al_2O_3	30.05
B_2O_3	0.04
BaO	0.09
CaO	1.35
Ce_2O_3	0.23
Cr_2O_3	0.34
CuO	0.06
Fe_2O_3	21.10
K_2O	0.11
La_2O_3	0.05
Li_2O	0.06
MgO	0.51
MnO	6.57
Na_2O	28.24
NiO	0.80
PbO	0.06
SO_4^{2-}	1.58
SiO_2	1.77
ThO_2	2.39
TiO_2	0.04
U_3O_8	4.26
ZnO	0.03
ZrO_2	0.28

Table D-5. SRAT Oxide Intervals for the 0.95M Na Wash Endpoint for SO Operation (wt.%)

Na Wash Endpoint	0.95M		
Al_2O_3	27.80	-	32.31
CaO	0.85	-	1.85
Fe_2O_3	19.52	-	22.68
MnO	6.07	-	7.07
Na_2O	26.12	-	30.35
NiO	0.30	-	1.30
SiO_2	1.27	-	2.27
ThO_2	1.89	-	2.89
TiO_2	0.00	-	0.54
U_3O_8	3.76	-	4.76
Others	2.93	-	3.93

Table D-6. Complete 0.95M Na Wash Endpoint MAR Assessment Results for Frit 473 and SO Operation

Na Wash Endpoint	0.95M
Frit	Frit 473
Case	SO
Number of EVs	2077
%WL, 24	highv(100%)
25	highv(100%)
26	highv(100%)
27	highv(87%)
28	highv(68%)
29	highv(58%)
30	highv(53%)
31	highv(49%)
32	highv(44%)
33	highv(39%)
34	highv(32%)
35	highv(24%)
36	highv(15%)
37	highv(4.3%)
38	
39	
40	
41	Neph(5.6%)
42	Neph(46%)

Table D-7. Complete 0.95M Na Wash Endpoint MAR Assessment Results for Frit 209

Na Wash Endpoint	0.95M	0.95M
Frit	Frit 209	Frit 209
Case	Coupled	SO
Number of EVs	2256	2077
%WL, 24		highv(45%)
25		highv(39%)
26		highv(31%)
27		highv(19%)
28		highv(8.4%)
29		
30		
31		
32		
33		
34		
35		
36		
37		
38		
39		
40	lowv(15%) Neph(4.5%)	Neph(5.6%)
41	lowv(34%) lowv Neph(2.6%) Neph(13%)	Neph(47%)
42	lowv(3.0%) lowv Neph(42%) Neph(44%)	Neph(90%)

Table D-8. 0.95M Normalized SB10 Tank 40 Blend Projection for Coupled Operation Without MST (wt.%)

Na Wash Endpoint	0.95M
Projection	Coupled without MST
Oxide	
Al_2O_3	27.73
B_2O_3	0.04
BaO	0.08
CaO	1.24
Ce_2O_3	0.21
Cr_2O_3	0.31
CuO	0.05
Fe_2O_3	19.47
K_2O	0.10
La_2O_3	0.05
Li_2O	0.05
MgO	0.47
MnO	6.06
Na_2O	33.79
NiO	0.74
PbO	0.06
SO_4^{2-}	1.46
SiO_2	1.64
ThO_2	2.20
TiO_2	0.03
U_3O_8	3.93
ZnO	0.03
ZrO_2	0.26

Table D-9. SRAT Oxide Intervals for the 0.95M Na Wash Endpoint for Coupled Operation Without MST (wt.%)

Na Wash Endpoint	0.95M		
Al_2O_3	25.65	-	29.81
CaO	0.74	-	1.74
Fe_2O_3	18.01	-	20.93
MnO	5.56	-	6.56
Na_2O	31.25	-	36.32
NiO	0.24	-	1.24
SiO_2	1.14	-	2.14
ThO_2	1.70	-	2.70
TiO_2	0.00	-	0.53
U_3O_8	3.43	-	4.43
Others	2.67	-	3.67

Table D-10. Complete 0.95M Na Wash Endpoint MAR Assessment Results for Frit 473 and Frit 209 for Coupled Operation Without MST

Na Wash Endpoint	0.95M	0.95M
Frit	Frit 473	Frit 209
Case	Coupled without MST	
Number of EVs	2037	2037
%WL, 24	highv(54%)	
25	highv(51%)	
26	highv(45%)	
27	highv(34%)	
28	highv(13%)	
29		
30		
31		
32		
33		
34		
35		
36		
37		
38		Neph(0.54%)
39	Neph(0.54%)	Neph(10%)
40	Neph(8.1%)	Neph(80%)
41	Neph(66%)	lowv Neph(9.2%) Neph(87%)
42	Neph(95%)	lowv Neph(32%) Neph(68%) Del Gp lowv Neph(0.05%)

Appendix E. Supplementary Information for Development of the Variability Study Test Matrix

Table E-1. Major Oxide Intervals for the Overall SB10 Glass Composition Region (wt.%)

Oxide	Interval (wt.%)		
Al_2O_3	7.15	-	12.92
B_2O_3	4.80	-	7.48
CaO	0.19	-	0.74
Fe_2O_3	5.02	-	9.09
Li_2O	4.80	-	5.44
MnO	1.01	-	2.83
Na_2O	11.36	-	18.17
NiO	0.05	-	0.52
SiO_2	45.92	-	54.63
ThO_2	0.45	-	1.16
TiO_2	0.00		3.30
U_3O_8	1.01		1.91

Table E-2. Previous Glasses Identified in the Anticipated SB10 Glass Composition Region

SB6VS18	SB7aVS-09	SB7b-21	VSL-SB7a-13	VSL-SB7aNM-07
SB6VS19	SB7aVS-10	SB7b-22	VSL-SB7a-14	VSL-SB7aNM-08
SB6VS20	SB7aVS-11	SB7b-24	VSL-SB7a-15	VSL-SB7aNM-09
SB6VS21	SB7aVS-12	SB7b-29	VSL-SB7a-16	VSL-SB7aNM-10
SB6VS22	SB7aVS-13	SB7b-32	VSL-SB7a-17	VSL-SB7aNM-11
SB7a-702-02	SB7aVS-14	VSL-SB7a-01	VSL-SB7a-18	VSL-SB7aNM-12
SB7a-702-03	SB7aVS-15	VSL-SB7a-02	VSL-SB7a-19	VSL-SB7aNM-13
SB7a-702-04	SB7aVS-16	VSL-SB7a-03	VSL-SB7a-20	VSL-SB7aNM-14
SB7a-702-05	SB7aVS-17	VSL-SB7a-04	VSL-SB7a-21	VSL-SB7aNM-15
SB7aVS-01	SB7aVS-18	VSL-SB7a-05	VSL-SB7a-22	VSL-SB7aNM-16
SB7aVS-02	SB7aVS-19	VSL-SB7a-06	VSL-SB7a-23	VSL-SB7aNM-17
SB7aVS-03	SB7aVS-20	VSL-SB7a-07	VSL-SB7aNM-01	VSL-SB7aNM-18
SB7aVS-04	SB7aVS-21	VSL-SB7a-08	VSL-SB7aNM-02	VSL-SB7aNM-19
SB7aVS-05	SB7aVS-22	VSL-SB7a-09	VSL-SB7aNM-03	VSL-SB7aNM-20
SB7aVS-06	SB7aVS-23	VSL-SB7a-10	VSL-SB7aNM-04	VSL-SB7aNM-21
SB7aVS-07	SB7b-15	VSL-SB7a-11	VSL-SB7aNM-05	VSL-SB7aNM-22
SB7aVS-08	SB7b-19	VSL-SB7a-12	VSL-SB7aNM-06	VSL-SB7aNM-23

Table E-3. Variability Study Glasses Falling Outside of the Lower 95% Confidence Bands of the DWPF Durability Models

Glass ID	Element	Compositional View	Heat Treatment
SB7aVS-01	B	measured	quenched, CCC
	Li	measured	quenched
	Na	measured	CCC
SB7aVS-02	B	measured	CCC
SB7aVS-03	B	measured	quenched, CCC
SB7aVS-06	B	measured	quenched, CCC
	Li	measured	quenched, CCC
	Na	measured	quenched, CCC
VSL-SB7a-01	B	measured	CCC
VSL-SB7a-02	B	measured	quenched
VSL-SB7a-03	B	measured	CCC
VSL-SB7a-04	B	measured	quenched, CCC
VSL-SB7a-06	B	measured	quenched, CCC
	Li	measured	quenched, CCC
	Na	measured	CCC
VSL-SB7a-11	B	measured	quenched, CCC
VSL-SB7aNM-04	B	measured	CCC
VSL-SB7aNM-11	B	measured	CCC
VSL-SB7aNM-23	B	measured	CCC