INEEL/EXT-99-00574

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Workshop for Conducting Phase 2 of the INTEC Glass Composition Variation Study

**B. A. Staples
C. A. Musick**

Published June 1999

**Idaho National Engineering and Environmental Laboratory
High-Level Waste Program
Lockheed Martin Idaho Technologies Company
Idaho Falls, Idaho 83415**

**Prepared for the
U.S. Department of Energy
Assistant Secretary for Environmental Management
Under DOE Idaho Operations Office
Contract DE-AC07-94ID13223**

10-30-1944

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ABSTRACT

During March 30-31, 1999, the Phase 2 Idaho Nuclear Technology and Engineering Center (INTEC) Glass Composition Variation Study Workshop was held at the Shilo Inn in Idaho Falls, Idaho. The workshop had the purpose of establishing a preparation and characterization protocol for the phase 2b glasses of the INTEC composition variation study. The workshop also had the purpose of reviewing the most recent estimates of INTEC high-level waste compositions for their impacts on the vitrification of these wastes. Waste composition estimates discussed included those of the various calcine types and of the high activity waste fractions from the calcine dissolution/separations process. Persons from the Idaho National Engineering and Environmental Laboratory (INEEL), Pacific Northwest National Laboratories (PNNL), and Savannah River Technology Center (SRTC) participated in this workshop. As a result of the workshop, details for the preparation and characterization of the phase 2b matrix of glasses were completed. The impacts on vitrification of updated waste composition estimates were discussed. Actions for the preparation and characterization of the glasses and development of the separations flowsheet were established.

SUMMARY

The Phase 2 INTEC CVS workshop was held March 30 and 31, 1999 at the Shilo Inn in Idaho Falls, Idaho. This workshop provided a forum for collaborators from the INEEL, PNNL and SRTC to define the path forward in preparing and characterizing CVS phase 2b glasses and to:

1. Review technical progress in TTP ID-77-WT31,
2. Present the background for the phase 2b glass matrix,
3. Present the phase 2b matrix, and
4. To address other items given in the Organization and Agenda section.

The workshop agenda is given on page xvii. A list of workshop attendees is given on page xix.

Subjects addressed in the workshop include:

1. Updated estimates of calcine compositions in calcine storage bin sets 1-6,
2. Presentation and discussion of phase 2a test results,
3. Models for linking phase 1b and phase 2b composition-property relationships,
4. Phase 2b test matrix discussion,
5. Review of laboratory procedures to be used at INEEL, PNNL, SRTC for preparing and characterizing the phase 2b glasses,
6. Review of full separations flowsheet and compositions,
7. Review and discussion of options for pretreatment/separations flowsheet and the resulting HAW fraction compositions, and
8. Separations process path forward and review.

As a result of addressing these subjects, several actions and conclusions came from this workshop.

The calcine composition estimates updated at the workshop (See Appendix A) will be known as "March 1999 estimates." These were used to derive phase 2a and 2b glasses. The phase 2a glasses (See Appendix B) were prepared to observe the effects on product characteristics of higher concentrations of calcium and fluorine as given in the March 1999 estimates of calcine compositions. These effects were used to determine limits for each component in phase 2b composition space and for deriving property models used to link phase 1b and phase 2b glasses (See Appendix C). Only the properties of homogeneous phase 1b glasses were used to define these models. The derivation

of the phase 2b matrix of glasses (See Appendix D), its nature and the selection of compositions from it for preparation and characterization were discussed at the workshop.

A major purpose of the workshop was to establish the preparation and characterization protocols for the phase 2b glasses. Preparation and characterization would be performed in INTEC laboratories with support from PNNL and SRTC personnel. Agreement was established on the conduct of procedures for preparation, composition analysis, electronic analysis, durability testing, canister centerline cooling (CCC) tests, liquidus temperature (T_L) determination, and viscosity determination. Details of these procedures are given in this document (See pages 2-3). The report that captures the results of preparing and characterizing glasses of the phase 2b CVS test matrix will be issued by LMITCO personnel assigned to TTP ID-77-WT31.

Current full separations flowsheets and their HAW compositions (See Appendices E and F) were discussed. The major changes in the current HAW composition estimates, when compared to earlier versions, is reduction of the phosphate amount used in the separations process. Because of phosphate reduction in HAWs, the effects of other elements on vitrification must be considered. These elements currently include aluminum, calcium, fluorine, molybdenum, potassium, sulfur and zirconium. With the characterization of undissolved solids (UDS), more elements may be identified as having impacts on the vitrification process. Alteration of the separations flowsheet for the purpose of controlling the amounts of these elements was discussed. Personnel from PNNL and SRTC will issue a document that summarizes the impact on the vitrification process and glass product properties by elements present at high concentrations in HAWs. The content of this document will provide guidance during separations process development in optimizing HAW compositions for vitrification.

ACKNOWLEDGMENTS

The authors acknowledge the guidance and resources provided for this multi-institutional task from the U.S. Department of Energy's (USDOE) Tanks Focus Area. The following persons made significant technical contributions toward the completion of this workshop.

INEEL

Charles Barnes
John Harbour
Scott Herbst
James Herzog
Jack Law
Arlin Olson
James Rindfleisch
Brad Scholes
Terry Todd
Don Wood

PNNL

Pavel Hrma
Greg Piepel
John Vienna

SRTC

Tommy Edwards
Bill Holtzscheiter
Carol Jantzen
David Peeler

The following persons made significant contributions toward issuing this report.

Sharla Mickelsen, INEEL
Ina Moore, INEEL

Funding to conduct this workshop, a milestone of Technical Task Plan(TTP) ID-77WT-31, Subtask B was provided by the USDOE Office of Science and Technology.

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ACRONYMS

CCC	Canister centerline cooling
CVS	Composition variation study
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EGCR	Experimental glass composition range
HAW	High activity waste fraction
INEEL	Idaho National Engineering and Environmental Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LMITCO	Lockheed Martin Idaho Technologies Company
NBS	National Bureau of Standards
PCT	Product consistency test
PNNL	Pacific Northwest National Laboratory
SBW	Sodium bearing waste
SEM	Scanning electron microscopy
SRTC	Savannah River Technology Center
T_L	Liquidus temperature
TTP	Technical task plan
UDS	Undissolved solids
XRD	X-ray diffraction analysis

INTRODUCTION

Two significant options exist for the vitrification of calcined high-level waste (HLW) being stored at the INEEL's Idaho Nuclear Technology and Engineering Center (INTEC).

Separations—The "Separations" option dissolves retrieved calcine, then separates the radionuclides into a fraction of reduced mass. This fraction is known as the high activity waste fraction (HAW). Because of its significantly reduced mass compared to calcine, the "Separations" option has the potential for resulting in a much smaller mass of vitrified product that will go to a federal repository for storage. The separations process isolates and separates the radionuclides but also retains a significant amount of aluminum and zirconium from the dissolved calcine. The separations process also adds phosphate and potassium to the HAW. The concentrations of these elements in the HAW place its composition outside those of expected wastes to be immobilized in the DOE complex.

Direct Vitrification—The "Direct Vitrification" option vitrifies calcine as it is retrieved from the storage bins. The direct vitrification process appears simpler than the separations process, however a significantly larger mass of vitrified product results from it. The calcines have unique and complex compositions. Zirconia calcine, which comprises about 80% of the HLW mass stored at INTEC, contains high concentrations of calcium, zirconium and fluorine. Alumina calcine, the other major calcined waste, consists of as much as 90% alumina by mass. The concentrations in calcines of the elements discussed above are outside those expected in wastes to be immobilized in the DOE complex.

Because of the uniqueness of calcined HLW and the separated HAW compositions, a cooperative composition variation study (CVS) is in progress at the INEEL, PNNL and SRTC. This study has the goal of defining the composition-product characteristics of glasses being developed to vitrify the INTEC wastes. Performing the CVS is a subtask of Technical Task Plan (TTP) ID-77-WT31. As currently defined, the multi-year scope of this CVS is designed to be performed in two or more phases. The first phase began in FY98. This phase has been completed and its results described.¹ The second phase of the CVS began in FY99. Other phases may follow, depending on the results of phase 2b and the quality of INTEC waste composition estimates. Glasses to be prepared and characterized during phase 2b have been composed using updated estimates of the HAW and calcined waste compositions.

Given the range of the HAW and calcined HLW composition estimates, mixture design techniques were applied at PNNL to derive a glass formulation matrix for the first phase of the CVS.² Formulations for preparation and characterization with respect to homogeneity, viscosity, liquidus temperature and leaching response to the PCT were derived from this matrix through systematic selection. This approach is being applied to the derivation of phase 2b glass formulations. Phase 2a was performed to provide information that would link the results of phase 1b glass characteristics and the new estimates of INTEC wastes to phase 2b. However, because of the interest in direct vitrification, the availability of updated estimates of calcine composition and the results of phase 1, a forum was required to establish final details in the approach to conducting phase 2b of the CVS.

BACKGROUND

During FY-98, technical progress was made in TTP ID-77-WT31. This progress is a necessary precursor for performing additional phases of the CVS. The most significant progress made in phase 1 of the CVS includes:

1. Establishment of the ability to determine the liquidus temperature (T_L) on molten glass at INTEC laboratories,
2. Computerization of viscosity determinations on molten glass to obtain more reproducible results,
3. Application of the composition variation study (CVS) approach to the definition of an experimental glass composition region for INTEC waste compositions,
4. Observation of the approximate limit of phosphate concentration in the borosilicate phase 1 CVS glasses,
5. Observation of T_L in CVS glasses containing phosphate and of the principal phase (Li_3PO_4) crystallizing at this temperature,
6. Observation of T_L in the absence of phosphate in the CVS glasses and of the principal phase (Li_2SiO_3) crystallizing at this temperature,
7. Completion of CVS glass viscosity profiles as a function of melt temperature, and
8. Observation of effect of cooling apparently homogeneous CVS glasses at the rate expected at the centerline of a full-scale DWPF canister.

In addition, updated estimates of high activity waste (HAW) fraction compositions were available because of progress in FY98 in developing the separations flowsheets. Likewise, resources were available in FY98 to obtain more detailed estimates of INTEC calcined waste compositions.

ORGANIZATION AND AGENDA

The Phase 2 INTEC Glass Composition Variation Study Workshop was held at the Shilo Inn in Idaho Falls, Idaho, March 30 and 31, 1999. The workshop brought together collaborators from INEEL, PNNL and SRTC to define the path forward in preparing and characterizing phase 2b glasses. The following subjects were addressed in the workshop.

March 30, 1999

1. Updated estimates of calcine compositions in bin sets 1-6 (C. M. Barnes)
2. Presentation and discussion of phase 2a test results (J. D. Vienna)
3. Models for linking phase 1b and phase 2b composition-property relationships (G. F. Piepel)
4. Discussion on selecting phase 2b test matrix (T. B. Edwards)
5. Review of laboratory procedures to be used at INEEL, PNNL, SRTC (D. K. Peeler)

March 31, 1999

1. Review of glass formulations discussions held on March 30, 1999 (C.A. Musick)
2. Review of full separations flowsheet and compositions (J. D. Law/C. M. Barnes)
3. Review and discussion of options for pretreatment/separations flowsheet and their resulting HAW fraction compositions (J. D. Law)
4. Separations path forward and review (T. A. Todd)

ATTENDEES

Pacific Northwest National Laboratory

Greg Piepel
John Vienna

Savannah River Technology Center

Tommy Edwards
John Harbour
David Peeler

Idaho National Engineering Environmental Laboratory

Charles Barnes	Arlin Olson
Dan Griffith	Jim Rindfleisch
Scott Herbst	Bruce Staples
Jack Law	Terry Todd
Chris Musick	Don Wood

Workshop for Conducting Phase 2 of the INTEC Glass Composition Variation Study

PURPOSE AND SCOPE

Conducting this workshop and the issue of this report satisfy Milestone A2-2 of the FY99 Technical Task Plan (TTP) ID-77-WT31. The development activities and goals of Section A of this TTP allow for the performance of phase 2b of the CVS.

This workshop provided a forum to:

1. Review the technical progress in the task,
2. Present the background for the phase 2b glass matrix,
3. Present the phase 2b matrix,
4. Build the mechanism by which the glasses in the matrix would be prepared and characterized, and
5. To address other items given in the Organization and Agenda section.

Results and Discussion

As a result of the discussions held on the subjects given in the workshop agenda, conclusions and recommendations were made. These follow with respect to each agenda item as given above.

Updated Estimates of Calcine Compositions in Bin Sets 1-6

Information presented is the same as that released earlier in 1999. The only change is that material presented in the workshop includes nitrate and carbonate content estimates. These were omitted from information released earlier this year. The information presented here will be known as the "March 1999 calcine composition estimates."

Presentation and Discussion of Phase 2a Test Results

Calcium and fluoride concentrations are major differences between the phase 2b and phase 1b matrices. Fluoride was not a component in phase 1b, and calcium concentrations were much less in phase 1b than in phase 2b. Phase 2a was performed to observe the effects of higher and varying concentrations of these two components on glass solubility/volatilization, durability and viscosity. These observations from phase 2a provided the upper and lower limits for each of these components in phase 2b: CaO; 0.0-12 mass %, and F: 0.0-6.0 mass %. These components would be varied independently of each other in the phase 2b test matrix, and property coefficients obtained from the phase 2a studies would be used to define the phase 2b compositional space.

Models for linking Phase 1 and Phase 2b Composition-Property Relationship

Only the eighteen homogeneous phase 1b glasses were used to provide PCT durability (B, Li, Na) and viscosity data for the composition-property models used to link phase 1b and phase 2b glasses. These models underpredict this relationship and suggest that the worst boron releases are within the range of

inhomogeneous glasses. The model used to link viscosity of phase 1b and phase 2b glasses also underpredicts relationship with composition. Both these first order models, however, appear to be suitable for use in defining the phase 2b matrix.

Discussion on Selecting Phase 2b Test Matrix

Mixture analysis techniques were applied for defining the phase 2b matrix, and the limits of the twelve major components were based on the March 1999 composition estimates of calcine in the fourth bin set. Each major component is a dimension in the phase 2b matrix. Minor components were combined in the dimension known as "Others." Limits of Al_2O_3 and ZrO_2 and alkali metal oxides were set to screen out amounts that could result in potentially poor performers. The final experimental glass composition region (EGCR) contained over 16000 compositions summed across inner and outer layers. Glasses selected from the EGCR for preparation and characterization are fourteen from each layer including extreme vertices from each layer as well as duplicate pseudo-center points. Also added to the matrix are two homogeneous compositions (IG1-07 and IG1-38) from the phase 1b matrix and a "boss point" which is a pseudo center without "Others." This subset chosen for preparation and characterization appears to adequately address the range of waste compositions and was therefore converted to target batching compositions.

Review and Discussion of Laboratory Procedures to be Used at INEEL, PNNL, SRTC

Formal presentations were not made in the discussion of laboratory procedures to be used for the preparation and characterization of phase 2b glasses. This aspect of the workshop was conducted in a "round table" manner without prepared visual aids. Glass would be prepared and characterized in the manner presented below. Preparation would be performed at INTEC laboratories. Characterization would also be performed in INTEC laboratories with support in specific areas, as discussed below, provided by personnel at PNNL and SRTC laboratories.

Glass Preparation. Batching of each glass of the phase 2b matrix will be in accordance with the matrix to be supplied to INTEC personnel by T. B. Edwards before the end of April, 1999. Batches of mixed reactants for each formulation will be ground to pass a 100 mesh sieve then vitrified in 250-ml 90% Pt/10% Rh high form crucibles. A mass of mixed reactants that will fill each crucible to its limit will constitute a batch. Each batch will be brought up to the vitrification temperature of 1150°C and held there for an hour. On completion of this time period, the glass formed will be poured onto a quench plate, cooled to ambient temperature, ground to pass a 100 mesh sieve, and remelted for an hour at the same temperature. Any glass, such as that remaining in crucibles after pouring, containing visual residues after this treatment will be ground and remelted. Higher temperatures will be applied, if necessary, to achieve a visually homogeneous product. On achieving this condition, characterization testing will begin.

Characterization Testing

Glass Composition Analysis—Centroid glass, IG2-33 will be prepared first. This will be performed at INTEC and characterization with respect to composition will be completed at SRTC and INTEC before other phase 2b glasses are prepared. This action will be performed to ensure that a target product composition can be achieved. Of particular interest in the composition analysis will be the retention of fluoride in the glass. This analysis is necessary to determine whether or not more fluoride must be added in order to attain the target amount in the IG2-33 formulation product. Fluoride determination will be performed at the INTEC and SRTC laboratories. SRTC personnel also will send a sample of IG2-33 glass to the Corning analytical laboratories for independent fluoride analysis.

Electronic Analysis—X-ray diffraction analysis (XRD) will be performed on all phase 2b glasses. This analysis will be performed at INTEC's analytical laboratories. Scanning electron microscopy (SEM) will be performed on all glasses in which phase separation can be observed through optical microscopy, but not through XRD. SEM analyses will be performed at INTEC analytical laboratories.. On request from INTEC personnel, transmission electron microscopy (TEM) will be applied at SRTC to glasses in which glass in glass separation cannot be detected by visual or optical means.

Durability—The durability of phase 2b glasses will be observed by subjecting them to ASTM-C-1285-94, the Product Consistency Test (PCT). This action will include standardization and cleaning as described in ASTM C-1285-94. Reagent blanks and standards (ARM and EA) will be processed with the leach tests and the resulting leachates analyzed. Glasses will be processed in duplicate in the ratio of 1.5 grams of sample to 15 ml of deionized, distilled water. Portions of IG2-33 prepared for PCT testing will also be submitted to SRTC for PCT testing to compare with results obtained in INTEC laboratories. Personnel from SRTC recommend that customized analytical standards should be prepared after the composition of IG2-33 is determined. The analysis is needed in order to base the composition of this standard. Aliquots of this standard should be processed with the glasses and analyzed with their leachates. High Purity Chemists, Inc. has experience in making up these types of standards.

Glass composition analyses must be completed in order to normalize elemental leachabilities. These analyses can be performed according to SRTC mobile laboratory procedures. If INTEC analytical laboratories have no fluoride procedure that can be performed on dissolved glass, then the mobile laboratory can perform this analysis. If INTEC analytical laboratories cannot provide timely services, the SRTC mobile analytical laboratory can perform all PCT leachate analyses. In this case, it would be best to submit all leachates to the laboratory at the same time.

Canister Centerline Cooling Tests—Canister centerline cooling (CCC) tests will be performed in 90% Pt/10% Rh high form crucibles. A portion of the quenched glasses prepared as described above will be used for testing. The cooling rate applied from the vitrification temperature of 1150°C will be the same as used for the phase 1b glasses.³ Samples of the glasses formed under these cooling conditions will be subjected to electronic analysis as described above. An amount will also be archived for being subjected to the PCT in the future.

Liquidus Temperature—Liquidus temperature (T_L) will be performed at INTEC in the same manner as on phase 1b glasses at PNNL. In this case, the gradient furnace was used to form glasses at temperature increments beginning at 1150°C and going down to where crystallization is first observed. For the purposes of this study, obtaining an estimate within 10°C of the true T_L will be suitable. Before any phase 2b samples are analyzed, NBS standard 773 glass should be run in the gradient furnace to observe how closely its T_L can be approached. If necessary, samples can be prepared in the uniform temperature furnace to approach the standard's T_L more closely. A sample of IG2-33, prepared as described above, will be sent to PNNL for confirmatory T_L determination before T_L is measured on other glasses.

Viscosity—Viscosity profiles with respect to temperature will be performed at INTEC laboratories on phase 2b glasses. These will be completed over the temperature range of 950°C to 1250°C on each glass in the same manner as performed on phase 1b glasses. Calibrating the viscometer's sample thermocouple is crucial before determining the viscosity of samples. National Bureau of Standards (NBS) glass 711 is preferred for calibration actions, but this glass is currently unavailable. It is recommended that NBS glass 710B should be used in its place for calibration. Viscosity measurements at lower temperatures of the profile can be helpful in estimating where to expect crystallinity to begin forming during T_L measurements. During these measurements the effect of glass fluoride content on viscosity will be of particular interest.

Review of Responsibilities for Issuing Final Report on Phase 2b Test Matrix

The report that captures the results of preparing and characterizing glasses of the phase 2b CVS test matrix will be issued by LMITCO personnel assigned to TTP ID-77-WT31. Preparation and characterization activities on these glasses may be performed at all three participating laboratories. All technical data and information intended to be included in this report must be completed and sent to LMITCO personnel before August 31, 1999.

Review of Full Separations Flowsheets and Compositions

Current HAW compositions were presented and discussed. The amount of phosphate coming from the separations process into the HAW from all calcine types must be reduced to result in compositions that will vitrify into homogeneous products. This necessity is based on the results of characterizing the phase 1b glasses and is the basis for investigating options that reduce phosphate content. Other major components present in HAWs that may be cause for concern in vitrification after the reduction of phosphate include aluminum, calcium, fluorine as fluoride, potassium, molybdenum and zirconium. In the case of sodium bearing waste (SBW) HAW, relatively high amounts of sulfate must also be of concern in the vitrification process. Better estimates of undissolved solids (UDS) compositions are required not only for completing the composition of HAW and calcined HLW for vitrification, but also for completing the dissolution and separations processes.

Review and Discussion of Options for Pretreatment/Separations Flowsheet and Their Resulting HAW Fraction Compositions

Alterations in the separations flowsheet to effect phosphate reduction have been investigated through calculations. The impact of these calculations on the separations flowsheets for SBW, alumina calcine and zirconia calcine HAWs were presented and discussed. These calculations indicate that phosphate coming from strip solutions can be reduced in the processing of all three types of HAW. Large uncertainties remain in the composition and amount of UDS in calcines and SBW. The addition of UDS may have a significant impact on the amount of phosphate in HAWs, but in making the calculations to achieve phosphate reduction, only estimates are available of the UDS amounts and compositions. With reduction of phosphate in alumina calcine HAW, molybdenum and aluminum become the largest components present when UDS is included. With reduction of phosphate in zirconia calcine HAW, calcium and fluoride become the largest components present when UDS is included. In the case of SBW HAW, however, the addition of undissolved solids (UDS) increases the amount of phosphate in the waste. Potassium, sodium and sulfate remain the major components in SBW HAW in which UDS are included.

Path Forward for Vitrification-Separations Interface

In a "round table" discussion, separations personnel requested a guidance document that would relate the effects of major components of the various HAWs and calcined HLWs on the vitrification process and on CVS glass characteristics. This request was required because of the experience with P_2O_5 in phase 1b glasses and because P_2O_5 has been a major species in the separations flowsheet. With the reduction of P_2O_5 to concentrations that would have negligible effects on the properties of CVS glasses, other components could come into concentration levels that would be detrimental to those properties. Personnel from PNNL and SRTC therefore will issue a document that summarizes the impact of high concentrations of HAW and calcined HLW components on glass properties.

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3. S. L. Marra and C. M. Jantzen, "Characterization of Projected DWPF Glasses Heat Treated to Simulate Canister Centerline Cooling (U)," WSRC-TR-92-142, Rev. 1, June, 1993

Appendix A
Current Estimates of Calcine Compositions
in Bin Sets 1-6

Calcine Bin Set Average Composition

	Bin Set 1	Bin Set 2	Bin Set 3	Bin Set 4	Bin Set 5	Bin Set 6	Total
	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %
Al	83.05	33.44	13.65	11.92	13.26	41.26	21.78
B	0.43	0.76	1.00	1.10	1.07	0.73	0.94
Ca	0.00	23.25	30.79	34.45	29.65	12.65	26.80
Cd	0.00	0.00	0.00	0.00	3.54	1.31	1.11
CO3	0.00	3.32	3.79	1.59	2.67	4.40	3.08
Cr	0.00	0.19	0.25	0.30	0.15	0.22	0.21
F	0.00	20.23	25.15	24.30	19.62	5.93	19.90
Fe	1.47	0.16	0.28	0.65	0.63	1.05	0.51
Hg	3.28	0.02	0.00	0.00	0.00	0.01	0.09
K	0.00	0.17	0.24	0.53	0.80	2.00	0.60
Mg	0.00	0.67	0.78	0.32	0.55	0.89	0.63
Na	2.30	0.81	1.19	2.16	3.99	7.61	2.73
NO3	4.09	1.64	2.38	4.42	7.97	15.70	5.50
PO4	1.87	0.41	1.18	0.09	0.22	0.43	0.57
Sr	0.04	0.25	0.32	0.36	0.32	0.11	0.28
SO4	2.81	0.64	0.61	0.14	2.43	1.75	1.23
Zr	0.00	13.64	17.83	17.02	12.32	3.28	13.41
Total	99.34	99.61	99.44	99.36	99.19	99.32	99.38

Calcine Bin Set Average Composition

	Bin Set 1	Bin Set 2	Bin Set 3	Bin Set 4	Bin Set 5	Bin Set 6	Total
	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Ba	65	10	11	14	13	9	13
Ce	71	11	13	16	15	10	15
Cl	0	0	47	122	165	225	98
Cs	71	22	15	18	19	13	19
La	36	5	6	7	7	5	7
Mn	0	0	32	0	25	76	24
Mo	96	14	8	6	13	7	12
Nb	0	0	8	13	241	6	71
Nd	120	18	21	25	25	17	24
Ni	0	53	72	100	33	90	62
Pd	8	1	2	2	2	1	2
Pr	33	5	6	7	7	5	7
Rh	13	2	2	2	2	2	2
Ru	47	7	4	3	6	7	6
Sm	24	4	3	3	3	3	3
Sn	1	220	285	271	191	52	213
Tc	24	4	4	5	5	3	5
U	16	2	10	11	15	131	23
Total	625	378	548	624	787	662	605

Calcine Solids Storage Facilities

Total:
4166 m³
Calcine Waste
(as of 2/27/99)

Calcine: 1,000 m³
Capacity: 1,000 m³

Calcine: 1,000 m³
Capacity: 1,000 m³

Calcine: 1,000 m³
Capacity: 1,000 m³

Calcine: 1,000 m³
Capacity: 1,000 m³

Calcine Solids Storage Facilities

Note: Activities for the Calcine are given in parenthesis. Units are 10^5 Ci.

ICPPA-5257
(12-87)

Calcine Stratification in Bin Set #2 (ICPP-A-5257)

*NOTE: This Startup Material Also Contains 1.5m³ (53 ft³) of Al-Fluorapatite.

ICPP-A-6679
(12-87)

Calcine stratification in CSSF #3 (ICPP-A-6679)

Calcine stratification in Bin Set #4 (ICPP-A-10450)

Bin Set 1

A-8

Bin 7 of Bin Set 2

A-9

Bin 3 of Bin Set 3

Bin 5 of Bin Set 5

No Batches 81					87				
Bin Set 1					Bin Set 2A				
	Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%	Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%	
Al	47.64	0.83	46.76	49.71	47.16	2.13	42.67	49.42	
B	0.25	0.02	0.18	0.26	0.19	0.04	0.14	0.25	
Ca	0.00	0.00	0.00	0.00	0.78	1.01	0.00	2.86	
Fe	0.88	0.41	0.27	1.36	0.09	0.07	0.06	0.24	
Cs	0.03	0.00	0.02	0.04	0.02	0.00	0.02	0.03	
Hg	1.89	0.21	0.99	2.06	0.03	0.00	0.02	0.03	
K	0.00	0.00	0.00	0.00	0.08	0.16	0.00	0.48	
Mg	0.00	0.00	0.00	0.00	0.47	0.61	0.00	1.73	
Na	1.34	0.25	0.99	1.60	1.57	0.51	1.20	2.88	
Sr	0.02	0.00	0.01	0.02	0.02	0.00	0.01	0.02	
CO3	0.00	0.00	0.00	0.00	2.33	3.04	0.00	8.56	
NO3	2.21	0.62	0.99	2.85	2.89	1.08	2.14	5.65	
PO4	0.95	0.36	0.00	1.15	0.85	0.39	0.17	1.28	
SO4	1.63	0.18	0.78	1.75	1.33	0.58	9.27	1.80	
O	43.14	0.66	42.52	44.70	42.17	1.82	38.20	44.07	

No Batches 294					564				
	Bin Set 2					Bin Set 3			
	Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%		Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%
Al	15.34	9.74	7.17	41.27		11.94	4.11	8.23	39.47
B	0.72	0.18	0.23	0.89		0.82	0.07	0.46	1.00
Ca	24.02	7.49	4.99	31.14		24.83	4.18	5.45	29.01
Cr	0.20	0.07	0.03	0.29		0.21	0.03	0.08	0.26
Fe	0.13	0.04	0.07	0.21		0.23	0.08	0.11	0.48
Hg	0.00	0.01	0.00	0.03		0.00	0.00	0.00	0.01
K	0.11	0.23	0.00	0.96		0.16	0.25	0.00	0.81
Mg	0.27	0.32	0.00	0.97		0.65	0.44	0.00	1.81
Mn	0.00	0.00	0.00	0.00		0.02	0.03	0.00	0.11
Na	0.19	0.35	0.00	1.21		0.84	1.11	0.00	3.23
Ni	0.06	0.02	0.01	0.08		0.06	0.01	0.03	0.07
Sr	0.26	0.08	0.05	0.34		0.26	0.06	0.03	0.31
Sn	0.23	0.08	0.03	0.33		0.23	0.04	0.03	0.30
Zr	14.23	4.79	1.99	20.75		14.48	2.43	2.08	18.53
Cl	0.00	0.00	0.00	0.00		0.03	0.05	0.00	0.16
F	21.10	6.92	3.01	27.32		20.50	3.05	3.32	24.71
CO3	1.34	1.57	0.00	4.77		3.17	2.17	0.00	8.94
NO3	0.46	0.83	0.00	2.79		1.66	2.19	0.00	6.63
PO4	0.12	0.08	0.06	0.49		0.91	2.62	0.05	14.33
SO4	0.19	0.13	0.10	0.73		0.51	0.52	0.09	2.94
O	21.01	6.51	15.42	38.23		18.50	2.70	14.45	36.35

No Batches	249	Bin Set 4				Bin Set 5			
		Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%	Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%
Al		9.74	0.98	7.99	12.73	11.19	4.17	4.94	19.21
B		0.90	0.05	0.73	1.06	0.87	0.13	0.55	1.22
Ca		27.99	1.19	24.04	29.77	23.83	3.34	14.34	27.85
Cd		0.00	0.00	0.00	0.00	2.77	1.93	0.00	5.64
Cr		0.24	0.02	0.18	0.28	0.12	0.05	0.05	0.23
Fe		0.48	0.34	0.21	2.03	0.48	0.39	0.14	1.62
K		0.41	0.14	0.16	0.67	0.64	0.11	0.26	0.83
Mg		0.29	0.40	0.00	2.03	0.48	0.59	0.00	3.53
Mn		0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.08
Na		1.69	0.56	0.65	2.71	3.23	0.85	1.68	5.33
Nb		0.00	0.00	0.00	0.00	0.22	0.43	0.00	1.67
Ni		0.08	0.01	0.06	0.10	0.03	0.02	0.01	0.08
Sr		0.29	0.02	0.23	0.32	0.25	0.04	0.11	0.30
Sn		0.22	0.03	0.05	0.26	0.16	0.04	0.07	0.26
Zr		13.88	1.08	10.70	16.23	10.01	2.58	4.40	16.52
Cl		0.09	0.06	0.01	0.24	0.13	0.06	0.04	0.32
F		19.91	1.31	15.21	23.94	15.91	3.28	5.08	25.33
CO3		1.41	1.97	0.00	10.01	2.31	2.89	0.00	17.42
NO3		3.45	1.14	1.33	5.55	6.44	1.57	3.28	10.25
PO4		0.07	0.01	0.05	0.10	0.18	0.04	0.09	0.23
SO4		0.11	0.01	0.09	0.16	1.92	1.20	0.17	3.63
O		18.75	0.43	17.37	19.29	18.79	2.94	14.24	23.72

No. Batches	183			
	Bin Set 6			
	Average Wt%	Std Dev Wt%	Minimum Wt%	Maximum Wt%
Al	27.80	5.62	18.96	34.09
B	0.53	0.09	0.43	0.74
Ca	9.77	4.29	4.44	16.23
Cd	1.04	0.63	0.29	2.02
Cr	0.15	0.06	0.05	0.23
Fe	0.76	0.22	0.33	1.06
K	1.33	0.57	0.53	1.99
Mg	0.69	0.65	0.00	2.27
Mn	0.04	0.03	0.00	0.08
Na	5.17	0.90	3.08	6.60
Ni	0.06	0.04	0.01	0.11
Sr	0.03	0.04	0.00	0.12
Sn	0.04	0.03	0.01	0.11
U	0.03	0.01	0.01	0.04
Zr	2.75	2.04	0.62	6.76
Cl	0.15	0.04	0.09	0.21
F	4.73	2.58	1.62	8.86
CO3	3.42	3.19	0.00	11.19
NO3	10.62	2.13	6.13	13.78
PO4	0.26	0.93	0.01	7.19
SO4	1.31	0.27	1.03	1.96
O	29.31	4.07	23.08	33.98

Appendix B
Review of CVS Phase 2a Test Results

PHASE 2A SCOPING STUDIES

J.D. Vienna, D.K. Peeler,
H. Li, and I.A. Reamer

Tanks Focus Area
March 30, 1999

OBJECTIVES

- Evaluate effects of CaO and F on primary processing and product performance properties
 - solubility/volatilization, durability, viscosity
- Provide CaO and F bounds on which Phase 2b “direct vitrification” test matrix would be established
 - to minimize fabrication of unacceptable glasses

EXPERIMENTAL

- Three Phase 2a baseline glasses fabricated
 - CaO contents of 0.0, 3.0, and 10.0 mass %
 - target F contents of 0.0, 1.0, 2.0, 3.0, 4.0, and 5.0 mass% "spiked" at each CaO concentration
 - $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ ratio "fixed" at 2.24
- Melted at 1150°C for 4 hours (unless otherwise noted)
- Homogeneity evaluated via optical microscopy and/or XRD
 - quenched and heat treated glasses
- Viscosity (rotating spindle technique)
- Durability (PCT-A, in duplicate)

PHASE 2a DATA

Glass ID	CaO	F target	F meas	size (g)	melt T (C)	melt t (h)	Q cryst.	HT cryst	visc (Pa.s)	PCT-B (g/L)	PCT-Si (g/L)	PCT-Na (g/L)	PCT-Li (g/L)	pH
P2-0Ca-0F	0.00	0.00	--	400	1150	4	none	--	14.90	--	--	--	--	--
P2-0Ca-1F	0.00	0.91	0.95	400	1150	4	none	--	11.30	0.53	0.25	0.62	0.44	10.09
P2-0Ca-3F	0.00	3.20	--	300	1150	2 s	none	--	--	--	--	--	--	--
P2-0Ca-5F	0.00	5.22	--	300	1150	2 s	LiF	--	--	--	--	--	--	--
P2-3Ca-0F	3.00	0.00	--	400	1150	4	none	--	11.10	--	--	--	--	--
P2-3Ca-1F	2.69	0.91	0.89	400	1150	4	none	--	9.70	0.52	0.25	0.56	0.43	10.29
P2-9Ca-0F	9.27	0.00	--	400	1150	4	none	--	5.99	--	--	--	--	--
P2-9Ca-1F	9.18	0.91	0.90	400	1150	4	none	--	5.10	0.45	0.20	0.64	0.54	10.80
P2-9Ca-5F	8.83	4.76	--	300	1150	2 s	none	--	--	--	--	--	--	--
P2-9Ca-6F	8.70	6.10	--	300	1100	2 s	?CaF2?	--	--	--	--	--	--	--
P2-9Ca-8F	8.58	7.41	--	300	1100/1150	1/1 s	CaF2	--	--	--	--	--	--	--
P2-0Ca-0F	0.00	0.00	--	20	1150	4	none	--	--	0.30	0.27	0.04	0.69	9.17
P2-0Ca-1F	0.00	0.91	0.72	20	1150	4	none	none	--	0.44	0.26	0.54	0.41	10.12
P2-0Ca-2F	0.00	1.81	0.77	20	1150	4	none	none	--	0.49	0.25	0.56	0.41	10.08
P2-0Ca-3F	0.00	2.72	1.24	20	1150	4	none	none	--	0.51	0.24	0.56	0.40	10.04
P2-0Ca-4F	0.00	3.64	1.71	20	1150	4	none	s. xtl	--	0.57	0.23	0.60	0.43	9.95
P2-0Ca-5F	0.00	4.55	1.64	20	1150	4	none	--	--	0.58	0.23	0.61	0.44	9.83
P2-3Ca-0F	3.00	0.00	--	20	1150	4	none	--	--	0.22	0.16	0.06	0.55	9.42
P2-3Ca-1F	2.69	0.91	0.59	20	1150	4	none	none	--	0.44	0.22	0.58	0.44	10.40
P2-3Ca-2F	2.67	1.82	0.84	20	1150	4	none	none	--	0.46	0.23	0.57	0.40	10.30
P2-3Ca-3F	2.65	2.73	1.57	20	1150	4	none	none	--	0.45	0.22	0.54	0.39	10.08
P2-3Ca-4F	2.62	3.65	1.52	20	1150	4	none	s. xtl	--	0.48	0.22	0.54	0.39	10.10
P2-3Ca-5F	2.60	4.56	2.59	20	1150	4	none	--	--	0.54	0.22	0.56	0.40	10.07
P2-9Ca-0F	10.00	0.00	--	20	1150	4	none	--	--	0.21	0.10	0.24	0.42	10.01
P2-9Ca-1F	9.18	0.91	0.61	20	1150	4	none	none	--	0.45	0.21	0.76	0.65	10.90
P2-9Ca-2F	9.10	1.83	1.08	20	1150	4	none	none	--	0.52	0.21	0.72	0.58	10.81
P2-9Ca-3F	9.01	2.75	1.70	20	1150	4	none	none	--	0.57	0.24	0.81	0.65	10.83
P2-9Ca-4F	8.93	3.67	2.34	20	1150	4	none	s. xtl	--	0.60	0.23	0.78	0.64	10.80
P2-9Ca-5F	8.84	4.59	2.67	20	1150	4	none	--	--	0.56	0.20	0.74	0.58	10.71

DEFINITIONS

- CaO -- mass% in glass on an oxide (target, not measured)
- F target and F meas -- mass % in glass (as measured by ISE)
- Size -- melt size (20g, 300g, or 400g)
- s -- melt stirred
- Q -- melt quenched (air quenched)
- HT -- heat treated at 650°C for 24 hours
- Viscosity -- 1150°C (Pa-sec)
- PCT -- 7-day PCT at 90°C (in duplicate)
 - release normalize to "target" composition
 - average pH of duplicates

SUMMARY

- Bounds for Phase 2b test matrix defined as:
 - CaO: 0.0 - 12.0 mass%
 - F: 0.0 - 6.0 mass %
- CaO and F to be varied independently in the Phase 2b test matrix
- Property coefficients obtained from Phase 2a scoping studies were used to define/limit Phase 2b compositional space

Appendix C

Review of CVS Phase 1 Data and Preliminary CVS Phase 2 Models

INEEL CVS Phase 1 Data and Preliminary Models

- ★ **18 homogeneous compositions**
- ★ **PCT anomalies**
- ★ **Preliminary first-order mixture
models for In PCT boron (g/L)
and In η_{1150} (Pa-s)**

**Greg Piepel
Statistics Group
Pacific Northwest National Laboratory**

March 30, 1999

Data Used for First-Order Mixture Models Out of 18 Homogeneous Glasses

Glass	Homogeneous?	16 Values, Visc.	17 Values PCT (q/L)		
		at 1150 (Pa-s)	B	Li	Na
IG1-01	n	*	*		
IG1-02	n	*	*		
IG1-03	n	*	*		
IG1-04	n	*	*		
IG1-05	n	*	*		
IG1-06	y	7.14	19.24	19.07	17.88
IG1-07	y	9.44	0.56	0.72	0.12
IG1-08	n	*	*		
IG1-09	n	*	*		
IG1-10	y	2.91	29.35	21.31	19.02
IG1-11	y	11.84	0.58	0.76	1.87
IG1-12	y	6.51	9.21	----	8.01
IG1-13	y	not meas.	59.39	46.48	58.70
IG1-14	y	7.66	0.99	0.57	1.30
IG1-15	n	*	*		
IG1-16	y	7.83	0.70	0.43	1.19
IG1-17	n	*	*		
IG1-18	n	*	*		
IG1-19	n	*	*		
IG1-20	n	*	*		
IG1-21	n	*	*		
IG1-22	n	*	*		
IG1-23	n	*	*		
IG1-24	n	*	*		
IG1-25	n	*	*		
IG1-26	n	*	*		
IG1-27	n	*	*		
IG1-28	n	*	*		
IG1-29	y	15.53	0.45	0.71	0.35
IG1-30	y	2.12	24.28	16.31	17.95
IG1-31	y	1.97	3.03	2.54	1.57
IG1-32	n	*	*		
IG1-33	y	not meas.?	11.66	19.35	21.26
IG1-34	n	*	*		
IG1-35	y	9.17	0.88	36.80 *	0.71
IG1-36	y	3.35	17.72	17.97	17.87
IG1-37	y	5.88	(15.60) ^(a)	0.10	12.74
IG1-38	y	7.33	2.45	2.22	1.48
IG1-39	y	2.84	3.39	2.79	2.16
IG1-40	n	*	*		
IG1-41	n	*	*		
IG1-42	n	*	*		
IG1-43	y	7.60	1.45	0.71	1.10
IG1-44	n	*	*		

(a) Outlier in regression diagnostics, not used in model fit

18 Homogeneous INEEL Phase 1 Glasses (normalized w/o Others)

Pearson Pairwise Correlations Between INEEL Phase 1 Glass Components Based on the Compositions of the 18 Homogeneous Glasses (normalized w/o Others)

	Al2O3-nh	B2O3-nh	K2O-nh	Li2O-nh	Na2O-nh	P2O5-nh	SiO2-nh
B2O3-nh	0.090 0.723						
K2O-nh	-0.474 0.047	-0.090 0.722					
Li2O-nh	0.304 0.220	-0.235 0.348	-0.257 0.303				
Na2O-nh	-0.142 0.574	-0.539 0.021	-0.139 0.583	-0.428 0.076			
P2O5-nh	0.051 0.841	0.173 0.493	-0.279 0.261	-0.460 0.055	0.299 0.227		
SiO2-nh	0.063 0.804	-0.319 0.197	-0.123 0.626	0.403 0.097	-0.229 0.360	-0.311 0.209	
ZrO2-nh	-0.739 0.000	0.074 0.771	0.184 0.466	-0.258 0.301	0.072 0.777	-0.026 0.918	-0.493 0.038

Cell Contents: Correlation
p-Value

C-7

Appendix D
Review of Phase 2b CVS Test Matrix

Presentation and Discussion of Phase 2b CVS Test Matrix

SRTC

Tommy Edwards
David Peeler

PNNL

Greg Piepel
John Vienna

March 1999 Glass Formulation and Vitrification Development Workshop

March 30-31, 1999

Components and Their Ranges

Oxide		Inner Layer Bounds	Outer Layer Bounds
Al ₂ O ₃	min	0.08	0.035
	max	0.12	0.20
B ₂ O ₃	min	0.06	0.05
	max	0.12	0.18
CaO	min	0.04	0
	max	0.08	0.12
F	min	0.01	0
	max	0.025	0.06
Fe ₂ O ₃	min	0.005	0
	max	0.03	0.08
K ₂ O	min	0.03	0
	max	0.06	0.10
Li ₂ O	min	0.03	0
	max	0.06	0.09
Na ₂ O	min	0.10	0.05
	max	0.15	0.20
NiO	min	0.005	0
	max	0.01	0.015
P ₂ O ₅	min	0.01	0
	max	0.02	0.03
SiO ₂	min	0.40	0.35
	max	0.50	0.60
ZrO ₂	min	0.04	0
	max	0.08	0.14

Estimated Effects for Property Models And Property Bounds

Property Effects

Oxide	Electrical Conductivity Hanford CVS ln(S/m)	Nepheline (a)	Spinel TL (c) ° C	ln(Visc@1150,Pa's) from INEEL Phase 1	7-Day PCT NL[B] ln(g/L) from INEEL Phase 1
Al ₂ O ₃	increases	decreases	increases	increases	decreases
B ₂ O ₃	increases		increases	decreases	increases
CaO	increases		increases	decreases (d)	decreases (e)
F	---(b)		---(b)	decreases (d)	---(b)
Fe ₂ O ₃	increases		increases	decreases (e)	decreases (e)
K ₂ O	increases (a)	decreases	decreases	decreases	increases
Li ₂ O	increases		decreases	decreases	increases
Na ₂ O	increases	decreases	decreases	decreases	increases
NiO	---(b)		increases	---(b)	---(b)
P ₂ O ₅	---(b)		---(b)	increases	decreases
SiO ₂	increases	increases	increases	increases	decreases

a — See Phase 1 document
 b — No assumption was made for this effect
 c — From SP/SG Studies
 d — From Phase 2 data
 e — From Hanford CVS

Property Bounds

		Inner Layer Bounds	Outer Layer Bounds
Electrical Conductivity ln(S/m)	min	2.3	2.3
	max	4.61	4.61
EC S/m	min	10	10
	max	100	100
ln[PCT-B (g/L)]	min	na	na
	max	2.48	2.48
PCT -B (g/L)	min	na	na
	max	12	12
ln[Visc @ 1150 °C(Pa's)]	min	1.1	0
	max	2.08	3
Visc @ 1150 °C (Pa's)	min	3	1
	max	8	20
Nepheline	min	0	0
	max	na	na
Spinel T _L (° C)	min	na	na
	max	1050	1050

A Couple of Additional Constraints

		Inner Layer Bounds	Outer Layer Bounds
$\text{Al}_2\text{O}_3 + \text{ZrO}_2$	min		
	max	0.22	0.22
Sum of alkalis	min		
	max	0.25	0.25

Final EGCR

Inner and Outer Layers

			Inner Layer Bounds	Inner Layer EV's 5663	Inner Layer Centroid 1	Outer Layer EV's 10781	Outer Layer Centroid 1	Outer Layer Bounds
Number of Points	Al ₂ O ₃	min	0.08	0.0800	0.1007	0.0350	0.0967	0.035
		max	0.12	0.1200	0.1007	0.2000	0.0967	0.20
	B ₂ O ₃	min	0.06	0.0600	0.0790	0.0500	0.1040	0.05
		max	0.12	0.1200	0.0790	0.1800	0.1040	0.18
	CaO	min	0.04	0.0400	0.0558	0.0000	0.0420	0
		max	0.08	0.0800	0.0558	0.1200	0.0420	0.12
	F	min	0.01	0.0100	0.0163	0.0000	0.0254	0
		max	0.025	0.0250	0.0163	0.0600	0.0254	0.06
	Fe ₂ O ₃	min	0.005	0.0050	0.0163	0.0000	0.0348	0
		max	0.03	0.0300	0.0163	0.0800	0.0348	0.08
	K ₂ O	min	0.03	0.0300	0.0439	0.0000	0.0441	0
		max	0.06	0.0600	0.0439	0.1000	0.0441	0.10
	Li ₂ O	min	0.03	0.0300	0.0398	0.0000	0.0385	0
		max	0.06	0.0600	0.0398	0.0900	0.0385	0.09
	Na ₂ O	min	0.10	0.1000	0.1199	0.0500	0.1109	0.05
		max	0.15	0.1500	0.1199	0.2000	0.1109	0.20
	NiO	min	0.005	0.0050	0.0074	0.0000	0.0073	0
		max	0.01	0.0100	0.0074	0.0150	0.0073	0.015
	P ₂ O ₅	min	0.01	0.0100	0.0149	0.0000	0.0138	0
		max	0.02	0.0200	0.0149	0.0300	0.0138	0.03
	SiO ₂	min	0.40	0.4000	0.4468	0.3500	0.4260	0.35
		max	0.50	0.5000	0.4468	0.6000	0.4260	0.60
	ZrO ₂	min	0.04	0.0400	0.0592	0.0000	0.0565	0
		max	0.08	0.0800	0.0592	0.1400	0.0565	0.14
Sum of Oxides		min	1	1.0000	1.0000	1.0000	1.0000	1
		max	1	1.0000	1.0000	1.0000	1.0000	1
	Al ₂ O ₃ +ZrO ₂	min		0.1200	0.1599	0.0350	0.1532	
		max	0.22	0.2000	0.1599	0.2200	0.1532	0.22
Sum of alkalis		min		0.1600	0.2035	0.0500	0.1935	
		max	0.25	0.2500	0.2035	0.2500	0.1935	0.25
Electrical Conductivity ln[S/m]		min	2.3	2.74	3.25	1.43	3.17	2.3
		max	4.61	3.99	3.25	4.91	3.17	4.61
EC S/m		min	10	15.5	25.8	4.2	23.8	10
		max	100	54.1	25.8	135.6	23.8	100
ln[PCT-B (g/L)]		min		-3.43	-1.02	-8.54	-0.50	
		max	2.48	1.03	-1.02	2.48	-0.50	2.48
PCT-B (g/L)		min		0.03	0.36	0.0002	0.95	
		max	12	2.8	0.36	12	0.95	12
ln[Visc @ 1150 °C (Pa's)]		min	1.1	1.10	1.44	0.00	1.05	0
		max	2.08	2.08	1.44	3.00	1.05	3
Visc @ 1150 °C (Pa's)		min	3	3	4.2	1	2.9	1
		max	8	8	4.2	20	2.9	20
Nepheline		min	0	-0.12	0.03	-0.37	0.03	0
		max		0.17	0.03	0.47	0.03	
Spinel T _L (°C)		min		628.3	886.4	247.2	895.9	
		max	1050	1158.2	886.4	1659.0	895.9	1050

Phase 2b Test Matrix: Compositions as Mass Fractions

Design Point	Glass ID	Al ₂ O ₃	B ₂ O ₃	CaO	F	Fe ₂ O ₃	K ₂ O	Li ₂ O	Na ₂ O	NiO	P ₂ O ₅	SiO ₂	ZrO ₂
OL-EV	IG2-01	0.2000	0.0500	0.0000	0.0600	0.0000	0.0000	0.0000	0.2000	0.0150	0.0000	0.4750	0.0000
OL-EV	IG2-02	0.2000	0.1800	0.1200	0.0000	0.0000	0.0000	0.0000	0.0500	0.0000	0.0300	0.4200	0.0000
OL-EV	IG2-03	0.0350	0.1800	0.0000	0.0400	0.0800	0.0000	0.0000	0.0500	0.0150	0.0000	0.6000	0.0000
OL-EV	IG2-04	0.2000	0.1800	0.0000	0.0000	0.0000	0.1000	0.0900	0.0500	0.0150	0.0000	0.3500	0.0150
OL-EV	IG2-05	0.0350	0.0500	0.1200	0.0000	0.0800	0.0100	0.0000	0.2000	0.0150	0.0000	0.3500	0.1400
OL-EV	IG2-06	0.0650	0.1800	0.0000	0.0000	0.0800	0.0000	0.0900	0.0500	0.0150	0.0300	0.3500	0.1400
OL-EV	IG2-07	0.0800	0.0500	0.1200	0.0600	0.0000	0.1000	0.0000	0.0500	0.0150	0.0300	0.3550	0.1400
OL-EV	IG2-08	0.0350	0.1800	0.1200	0.0000	0.0000	0.1000	0.0000	0.1277	0.0000	0.0000	0.4373	0.0000
OL-EV	IG2-09	0.2000	0.0500	0.1200	0.0600	0.0800	0.0000	0.0741	0.0500	0.0000	0.0000	0.3659	0.0000
OL-EV	IG2-10	0.0350	0.0500	0.0000	0.0600	0.0800	0.1000	0.0840	0.0500	0.0000	0.0300	0.5110	0.0000
OL-EV	IG2-11	0.0350	0.0500	0.0751	0.0000	0.0000	0.0000	0.0900	0.1600	0.0150	0.0300	0.5449	0.0000
OL-EV	IG2-12	0.0350	0.1800	0.0000	0.0600	0.0000	0.0000	0.0052	0.2000	0.0000	0.0000	0.4074	0.1124
OL-EV	IG2-13	0.0489	0.0711	0.0000	0.0000	0.0000	0.0000	0.0900	0.0500	0.0000	0.0000	0.6000	0.1400
OL-EV	IG2-14	0.2000	0.0617	0.0000	0.0000	0.0800	0.1000	0.0000	0.1500	0.0000	0.0300	0.3583	0.0200
IL-EV	IG2-15	0.0800	0.0600	0.0400	0.0100	0.0050	0.0300	0.0600	0.1500	0.0050	0.0200	0.5000	0.0400
IL-EV	IG2-16	0.1100	0.1200	0.0400	0.0100	0.0050	0.0300	0.0300	0.1500	0.0050	0.0200	0.4000	0.0800
IL-EV	IG2-17	0.0800	0.0600	0.0800	0.0250	0.0050	0.0300	0.0300	0.1000	0.0050	0.0200	0.4850	0.0800
IL-EV	IG2-18	0.1200	0.0600	0.0400	0.0100	0.0300	0.0600	0.0300	0.1500	0.0050	0.0100	0.4050	0.0800
IL-EV	IG2-19	0.0800	0.0600	0.0400	0.0100	0.0050	0.0300	0.0600	0.1500	0.0100	0.0200	0.4950	0.0400
IL-EV	IG2-20	0.0800	0.0600	0.0400	0.0100	0.0050	0.0600	0.0300	0.1500	0.0100	0.0200	0.4950	0.0400
IL-EV	IG2-21	0.0800	0.0600	0.0800	0.0100	0.0200	0.0600	0.0300	0.1000	0.0100	0.0100	0.5000	0.0400
IL-EV	IG2-22	0.1200	0.0600	0.0400	0.0109	0.0050	0.0300	0.0600	0.1500	0.0050	0.0200	0.4191	0.0800
IL-EV	IG2-23	0.1058	0.1200	0.0400	0.0142	0.0050	0.0300	0.0300	0.1500	0.0050	0.0200	0.4000	0.0800
IL-EV	IG2-24	0.1200	0.0600	0.0800	0.0100	0.0050	0.0600	0.0568	0.1000	0.0100	0.0100	0.4082	0.0800
IL-EV	IG2-25	0.1200	0.0600	0.0800	0.0100	0.0050	0.0600	0.0580	0.1000	0.0050	0.0100	0.4120	0.0800
IL-EV	IG2-26	0.0803	0.0600	0.0400	0.0100	0.0050	0.0600	0.0497	0.1000	0.0050	0.0100	0.5000	0.0800
IL-EV	IG2-27	0.0988	0.0600	0.0800	0.0250	0.0050	0.0300	0.0312	0.1000	0.0100	0.0200	0.5000	0.0400
IL-EV	IG2-28	0.0800	0.0600	0.0740	0.0100	0.0300	0.0600	0.0300	0.1000	0.0100	0.0100	0.4960	0.0400
Pseudo-Center	IG2-1-29	0.0987	0.0915	0.0489	0.0209	0.0256	0.0440	0.0392	0.1154	0.0074	0.0144	0.4364	0.0579
IG1-07	IG2-1-30	0.1508	0.1508	0.0000	0.0000	0.0000	0.0000	0.0849	0.0502	0.0000	0.0000	0.5332	0.0302
IG1-38	IG2-1-31	0.0377	0.1256	0.0000	0.0000	0.0000	0.0251	0.0634	0.0879	0.0000	0.0126	0.5422	0.1055
Pseudo-Center	IG2-1-32	0.0987	0.0915	0.0489	0.0209	0.0256	0.0440	0.0392	0.1154	0.0074	0.0144	0.4364	0.0579

Pseudo-center determined by averaging the Inner-Layer Centroid and Outer-Layer Centroid compositions.

Phase 2b Test Matrix: Property Predictions

Design Point	Glass ID	Sum of Oxides	Al ₂ O ₃ +ZrO ₂	Sum of alkali's	Electrical Conductivity		PCT-Boron		Visc. @1150 °C		Nepheline	Spinel T _L (°C)
					ln[S/m]	S/m	ln[g/L]	g/L	ln[Pa's]	Pa's		
OL-EV	IG2-01	1.000	0.200	0.200	2.99	19.9	-3.53	0.03	2.81	16.6	-0.17	870.8
OL-EV	IG2-02	1.000	0.200	0.050	1.74	5.7	-6.10	0.00	2.74	15.5	-0.01	1196.4
OL-EV	IG2-03	1.000	0.035	0.050	1.72	5.6	-0.74	0.48	2.94	18.9	0.47	1044.3
OL-EV	IG2-04	1.000	0.215	0.240	3.90	49.4	1.27	3.56	0.07	1.1	-0.22	891.9
OL-EV	IG2-05	1.000	0.175	0.210	3.22	25.0	-0.94	0.39	1.00	2.7	-0.01	1176.6
OL-EV	IG2-06	1.000	0.205	0.140	3.82	45.6	1.01	2.75	0.01	1.0	0.16	1247.8
OL-EV	IG2-07	1.000	0.220	0.150	1.65	5.2	-4.37	0.01	1.45	4.3	0.00	1271.0
OL-EV	IG2-08	1.000	0.035	0.228	2.65	14.2	2.48	11.94	0.04	1.0	0.05	505.7
OL-EV	IG2-09	1.000	0.200	0.124	3.36	28.8	-4.26	0.01	0.00	1.0	-0.06	1205.1
OL-EV	IG2-10	1.000	0.035	0.234	3.58	35.9	1.94	6.96	0.00	1.0	0.23	549.4
OL-EV	IG2-11	1.000	0.035	0.250	4.61	100.5	2.16	8.67	0.00	1.0	0.25	542.5
OL-EV	IG2-12	1.000	0.147	0.205	3.25	25.8	2.48	11.94	0.00	1.0	0.06	617.4
OL-EV	IG2-13	1.000	0.189	0.140	3.56	35.2	-0.56	0.57	3.00	20.1	0.44	1047.3
OL-EV	IG2-14	1.000	0.220	0.250	2.84	17.1	-3.39	0.03	3.00	20.1	-0.36	891.0
IL-EV	IG2-15	1.000	0.120	0.240	3.92	50.4	0.45	1.57	1.18	3.3	0.10	656.0
IL-EV	IG2-16	1.000	0.190	0.210	3.35	28.5	-0.60	0.55	1.22	3.4	-0.06	847.6
IL-EV	IG2-17	1.000	0.160	0.160	2.75	15.6	-2.52	0.08	2.05	7.8	0.16	979.7
IL-EV	IG2-18	1.000	0.200	0.240	3.37	29.1	-1.18	0.31	1.74	5.7	-0.11	896.6
IL-EV	IG2-19	1.000	0.120	0.240	3.92	50.4	0.48	1.62	1.14	3.1	0.09	699.3
IL-EV	IG2-20	1.000	0.120	0.240	3.29	26.8	-0.26	0.77	1.91	6.8	0.05	711.7
IL-EV	IG2-21	1.000	0.120	0.190	2.83	16.9	-1.43	0.24	2.06	7.8	0.13	915.0
IL-EV	IG2-22	1.000	0.200	0.240	3.95	51.9	-0.71	0.49	1.10	3.0	-0.05	830.9
IL-EV	IG2-23	1.000	0.186	0.210	3.34	28.2	-0.49	0.61	1.10	3.0	-0.05	835.5
IL-EV	IG2-24	1.000	0.200	0.217	3.44	31.2	-1.40	0.25	1.10	3.0	-0.04	1002.0
IL-EV	IG2-25	1.000	0.200	0.218	3.48	32.5	-1.37	0.25	1.10	3.0	-0.03	956.0
IL-EV	IG2-26	1.000	0.160	0.210	3.25	25.8	-0.69	0.50	2.08	8.0	0.13	868.6
IL-EV	IG2-27	1.000	0.139	0.161	2.77	16.0	-2.62	0.07	2.08	8.0	0.14	956.0
IL-EV	IG2-28	1.000	0.120	0.190	2.85	17.3	-1.39	0.25	2.08	8.0	0.12	927.2
Pseudo-Center	IG2-29	1.000	0.157	0.199	3.21	24.8	-0.76	0.47	1.24	3.5	0.03	891.3
IG1-07	IG2-30	1.000	0.181	0.135	3.58	35.9	-0.78	0.46	2.16	8.7	0.19	930.6
IG1-38	IG2-31	1.000	0.143	0.176	3.44	31.2	1.08	2.94	2.02	7.5	0.31	804.9

Scatter Plot Matrix for Phase 2 Design Points

Phase 2b Test Matrix: Target Compositions for Batching

Design Point	Glass ID	Al ₂ O ₃	B ₂ O ₃	CaO	F	Fe ₂ O ₃	K ₂ O	Li ₂ O	Na ₂ O	NiO	P ₂ O ₅	SiO ₂	ZrO ₂	Others	Sum of Oxides
OL-EV	IG2-01	0.19858	0.04964	0.00000	0.05957	0.00000	0.00000	0.00000	0.19858	0.01489	0.00000	0.47162	0.00000	0.00717	1.000
OL-EV	IG2-02	0.19858	0.17872	0.11915	0.00000	0.00000	0.00000	0.00000	0.04964	0.00000	0.02979	0.41701	0.00000	0.00717	1.000
OL-EV	IG2-03	0.03475	0.17872	0.00000	0.03972	0.07943	0.00000	0.00000	0.04964	0.01489	0.00000	0.59573	0.00000	0.00717	1.000
OL-EV	IG2-04	0.19858	0.17872	0.00000	0.00000	0.00000	0.09929	0.08936	0.04964	0.01489	0.00000	0.34751	0.01489	0.00717	1.000
OL-EV	IG2-05	0.03475	0.04964	0.11915	0.00000	0.07943	0.00993	0.00000	0.19858	0.01489	0.00000	0.34751	0.13900	0.00717	1.000
OL-EV	IG2-06	0.06454	0.17872	0.00000	0.00000	0.07943	0.00000	0.08936	0.04964	0.01489	0.02979	0.34751	0.13900	0.00717	1.000
OL-EV	IG2-07	0.07943	0.04964	0.11915	0.05957	0.00000	0.09929	0.00000	0.04964	0.01489	0.02979	0.35247	0.13900	0.00717	1.000
OL-EV	IG2-08	0.03475	0.17872	0.11915	0.00000	0.00000	0.09929	0.00000	0.12679	0.00000	0.00000	0.43419	0.00000	0.00717	1.000
OL-EV	IG2-09	0.19858	0.04964	0.11915	0.05957	0.07943	0.00000	0.07357	0.04964	0.00000	0.00000	0.36330	0.00000	0.00717	1.000
OL-EV	IG2-10	0.03475	0.04964	0.00000	0.05957	0.07943	0.09929	0.08340	0.04964	0.00000	0.02979	0.50736	0.00000	0.00717	1.000
OL-EV	IG2-11	0.03475	0.04964	0.07457	0.00000	0.00000	0.00000	0.08936	0.15886	0.01489	0.02979	0.54102	0.00000	0.00717	1.000
OL-EV	IG2-12	0.03475	0.17872	0.00000	0.05957	0.00000	0.00000	0.00516	0.19858	0.00000	0.00000	0.40450	0.11160	0.00717	1.000
OL-EV	IG2-13	0.04855	0.07059	0.00000	0.00000	0.00000	0.00000	0.08936	0.04964	0.00000	0.00000	0.59573	0.13900	0.00717	1.000
OL-EV	IG2-14	0.19858	0.06126	0.00000	0.00000	0.07943	0.09929	0.00000	0.14893	0.00000	0.02979	0.35575	0.01986	0.00717	1.000
IL-EV	IG2-15	0.07943	0.05957	0.03972	0.00993	0.00496	0.02979	0.05957	0.14893	0.00496	0.01986	0.49644	0.03972	0.00717	1.000
IL-EV	IG2-16	0.10922	0.11915	0.03972	0.00993	0.00496	0.02979	0.02979	0.14893	0.00496	0.01986	0.39715	0.07943	0.00717	1.000
IL-EV	IG2-17	0.07943	0.05957	0.07943	0.02482	0.00496	0.02979	0.02979	0.09929	0.00496	0.01986	0.48155	0.07943	0.00717	1.000
IL-EV	IG2-18	0.11915	0.05957	0.03972	0.00993	0.02979	0.05957	0.02979	0.14893	0.00496	0.00993	0.40212	0.07943	0.00717	1.000
IL-EV	IG2-19	0.07943	0.05957	0.03972	0.00993	0.00496	0.02979	0.05957	0.14893	0.00993	0.01986	0.49148	0.03972	0.00717	1.000
IL-EV	IG2-20	0.07943	0.05957	0.03972	0.00993	0.00496	0.05957	0.02979	0.14893	0.00993	0.01986	0.49148	0.03972	0.00717	1.000
IL-EV	IG2-21	0.07943	0.05957	0.07943	0.00993	0.01986	0.05957	0.02979	0.09929	0.00993	0.00993	0.49644	0.03972	0.00717	1.000
IL-EV	IG2-22	0.11915	0.05957	0.03972	0.01082	0.00496	0.02979	0.05957	0.14893	0.00496	0.01986	0.41612	0.07943	0.00717	1.000
IL-EV	IG2-23	0.10505	0.11915	0.03972	0.01410	0.00496	0.02979	0.02979	0.14893	0.00496	0.01986	0.39715	0.07943	0.00717	1.000
IL-EV	IG2-24	0.11915	0.05957	0.07943	0.00993	0.00496	0.05957	0.05640	0.09929	0.00993	0.00993	0.40529	0.07943	0.00717	1.000
IL-EV	IG2-25	0.11915	0.05957	0.07943	0.00993	0.00496	0.05957	0.05759	0.09929	0.00496	0.00993	0.40907	0.07943	0.00717	1.000
IL-EV	IG2-26	0.07973	0.05957	0.03972	0.00993	0.00496	0.05957	0.04935	0.09929	0.00496	0.00993	0.49644	0.07943	0.00717	1.000
IL-EV	IG2-27	0.09810	0.05957	0.07943	0.02482	0.00496	0.02979	0.03098	0.09929	0.00993	0.01986	0.49644	0.03972	0.00717	1.000
IL-EV	IG2-28	0.07943	0.05957	0.07347	0.00993	0.02979	0.05957	0.02979	0.09929	0.00993	0.00993	0.49247	0.03972	0.00717	1.000
Pseudo-Ctr	IG2-29	0.09800	0.09085	0.04855	0.02070	0.02537	0.04369	0.03887	0.11458	0.00730	0.01425	0.43329	0.05744	0.00717	1.000
IG1-07*	IG2-30	0.15012	0.15012	0.00000	0.00000	0.00000	0.00000	0.08452	0.04998	0.00000	0.00000	0.53081	0.03006	0.00450	1.000
IG1-38*	IG2-31	0.03752	0.12500	0.00000	0.00000	0.00000	0.02498	0.06310	0.08748	0.00000	0.01254	0.53961	0.10500	0.00480	1.000
Pseudo-Ctr	IG2-32	0.09800	0.09085	0.04855	0.02070	0.02537	0.04369	0.03887	0.11458	0.00730	0.01425	0.43329	0.05744	0.00717	1.000

* The IG1-07 and IG1-38 glasses should be batched with "Others" as defined in the Phase 1 study.

Definition of Others for Phase 2

Oxide	Weight %
BaO	0.61
CeO ₂	0.75
Cl	4.05
Cr ₂ O ₃	9.12
Cs ₂ O	0.52
I	0.31
La ₂ O ₃	0.35
MgO	30.09
MnO	1.64
MoO ₃	0.94
NbO	2.40
Nd ₂ O ₃	1.17
PdO	0.21
PrO ₂	0.34
Rb ₂ O	0.32
Rh ₂ O ₃	0.34
RuO ₂	0.57
Sm ₂ O ₃	0.39
SnO	6.53
SO ₃	30.80
SrO	7.71
TcO	0.33
TcO ₃	0.31
Y ₂ O ₃	0.22
Total	100.02

Appendix E
**Review of Full Separations Flowsheet
and Compositions**

SBW Material Balance

	Barnes Flowsheet		0.001 M VDPA Strip		No P in Strip	
	w/o UDS	w/ UDS	w/o UDS	w/ UDS	w/o UDS	w/ UDS
	wt % normalized	wt % norm	wt % normalized	wt % norm	wt % normalized	wt % norm
Al	0.01	1.17	0.02	1.37	0.02	1.39
B	1.14E-04	1.94	1.58E-04	2.26	1.65E-04	2.30
Ba	0.10	0.05	0.14	0.06	0.15	0.06
Ca	1.29E-03	0.59	1.79E-03	0.69	1.87E-03	0.70
Cd + Ni	3.24E-04	1.05	4.48E-04	1.23	4.68E-04	1.25
Ce + TRU	0.18	0.09	0.26	0.11	0.27	0.11
Cl	0.08	1.81	0.11	2.11	0.11	2.15
Cr	1.38E-04	0.15	1.91E-04	0.17	1.99E-04	0.18
Cs	0.13	0.07	0.18	0.08	0.19	0.08
Cu	0	0.10	0	0.12	0	0.12
F	7.95E-04	1.73	1.10E-03	2.02	1.15E-03	2.05
Fe	0.10	1.67	0.14	1.95	0.14	1.98
K	22.04	12.36	30.51	14.42	31.88	14.69
Li	0	0.10	0	0.12	0	0.12
Mg	0	1.05	0	1.22	0	1.25
Mn	4.86E-04	0.25	6.73E-04	0.29	7.03E-04	0.30
Mo	5.43	3.84	7.52	4.48	7.85	4.56
Na	16.09	11.09	22.27	12.94	23.27	13.18
Nb	4.52E-09	0.10	6.25E-09	0.12	6.53E-09	0.12
Nd	0.21	0.11	0.30	0.13	0.31	0.13
Pb	0.60	0.41	0.83	0.48	0.86	0.49
Pd	3.44E-05	0.06	4.76E-05	0.07	4.97E-05	0.07
Pr	0.06	0.03	0.08	0.03	0.08	0.04
PO4	31.08	24.70	4.57	12.17	0.31	10.51
Rh	3.44E-05	0.10	4.76E-05	0.12	4.97E-05	0.12
Ru	1.58E-04	1.05	2.18E-04	1.22	2.28E-04	1.25
Si	0	2.65	0	3.10	0	3.15
Sm	0.04	0.02	0.05	0.02	0.05	0.02
Sn	0	0.52	0	0.61	0	0.62
Sr	0.06	0.03	0.09	0.04	0.09	0.04
SO4	3.44E-03	9.59	4.77E-03	11.18	4.98E-03	11.39
Tc	0.01	0.01	0.01	0.01	0.02	0.01
Ti	0	0.10	0	0.12	0	0.12
Zn	0	0.10	0	0.12	0	0.12
Zr	23.77	21.27	32.92	24.81	34.39	25.28
	100.00	100.00	100.00	100.00	100.00	100.00
Total Kg	10,287	20,023	7,316	16,905	6,989	16,558

Zirconium Calcine

			0.001 M VDPA strip		No P in strip		0.001 M VDPA strip, Remove 90% of F from strip product		0.001 M VDPA strip, Remove 99% of F from strip product		No P in strip, Remove 90% of F from strip product		No P in strip, Remove 99% of F from strip product	
	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS
Al	4.16E-03	3.83	0.01	5.96	0.01	6.36	0.01	7.59	0.02	7.81	0.02	8.24	0.02	8.50
B	3.84E-04	0.35	7.89E-04	0.55	0.00	0.59	1.32E-03	0.70	1.42E-03	0.72	1.65E-03	0.76	1.80E-03	0.78
Ba	0.23	0.17	0.48	0.26	0.54	0.28	0.81	0.33	0.86	0.34	1.00	0.36	1.09	0.37
Ca	0.01	11.06	0.02	17.24	0.03	18.38	0.04	21.95	0.04	22.56	0.05	23.83	0.06	24.56
Ce+TRU	0.36	0.26	0.74	0.40	0.84	0.43	1.24	0.51	1.33	0.52	1.54	0.55	1.69	0.57
Cl	3.68E-04	0.04	7.56E-04	0.06	8.56E-04	0.07	1.27E-03	0.08	1.36E-03	0.08	1.58E-03	0.08	1.73E-03	0.09
Cr	1.04E-04	0.10	2.13E-04	0.15	2.42E-04	0.16	3.58E-04	0.19	3.85E-04	0.20	4.46E-04	0.21	4.87E-04	0.21
Cs	0.45	0.32	0.93	0.50	1.05	0.53	1.56	0.64	1.67	0.66	1.94	0.69	2.11	0.71
F	21.89	23.09	44.96	36.00	50.93	38.38	7.58	18.52	0.84	16.23	9.44	20.11	1.07	17.66
Fe	0.15	0.31	0.31	0.49	0.35	0.52	0.52	0.62	0.56	0.64	0.64	0.67	0.70	0.69
Gd	0.01	0.01	0.02	0.01	0.02	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01
K	0.76	0.70	1.56	1.09	1.77	1.17	2.63	1.39	2.82	1.43	3.27	1.51	3.57	1.56
Mg	1.12E-04	0.10	2.30E-04	0.16	2.61E-04	0.17	3.87E-04	0.20	4.15E-04	0.21	4.82E-04	0.22	5.26E-04	0.23
Mo	7.21	5.04	14.82	7.86	16.78	8.38	24.88	10.01	26.69	10.29	30.97	10.87	33.83	11.20
Na	2.29	2.29	4.70	3.58	5.33	3.81	7.90	4.55	8.47	4.68	9.83	4.94	10.74	5.09
Nd	0.57	0.40	1.16	0.63	1.32	0.67	1.95	0.80	2.09	0.82	2.43	0.87	2.65	0.90
Ni	5.53E-05	0.03	1.14E-04	0.05	1.29E-04	0.05	1.91E-04	0.06	2.05E-04	0.07	2.38E-04	0.07	2.59E-04	0.07
Pb	0.02	0.02	0.05	0.03	0.05	0.03	0.08	0.03	0.08	0.03	0.10	0.03	0.11	0.04
PO4	57.61	40.28	12.91	6.89	1.36	0.72	21.68	8.77	23.26	9.02	2.50	0.94	2.73	0.97
Pr	0.15	0.11	0.31	0.17	0.35	0.18	0.52	0.21	0.56	0.22	0.65	0.23	0.71	0.24
Sm	0.07	0.05	0.14	0.08	0.16	0.08	0.23	0.10	0.25	0.10	0.29	0.10	0.32	0.11
Sn	9.45E-05	0.09	1.94E-04	0.14	2.20E-04	0.14	3.26E-04	0.17	3.50E-04	0.18	4.06E-04	0.19	4.43E-04	0.19
Sr	8.16	5.82	16.77	9.07	18.99	9.67	28.15	11.55	30.21	11.88	35.05	12.54	38.29	12.93
SO4	4.96E-05	0.05	1.02E-04	0.07	1.16E-04	0.08	1.71E-04	0.09	1.84E-04	0.09	2.13E-04	0.10	2.33E-04	0.10
Tc	0.03	0.02	0.05	0.03	0.06	0.03	0.09	0.04	0.09	0.04	0.11	0.04	0.12	0.04
Zr	0.03	5.48	0.06	8.54	0.07	9.11	0.10	10.88	0.11	11.18	0.13	11.81	0.14	12.17
Total kg	25,374	35,413	11,662	21,701	10,139	20,178	7,079	17,118	6,621	16,660	5,556	15,595	5,097	15,136

Alumina Calcine

			0.001 M VDPA strip		no P in Strip	
	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS	Weight % W/o UDS	Weight % With UDS
Al		23.43		44.32		49.20
B		0.12		0.23		0.26
Ba		0.02		0.03		0.04
Ce + TRU	1.32	1.00	3.65	1.89	4.54	2.10
Cl	0.42	0.31	1.16	0.59	1.44	0.65
Cs	1.35	1.02	3.72	1.92	4.62	2.13
Eu	0.03	0.02	0.09	0.05	0.11	0.05
Fe	0.02	0.43	0.04	0.82	0.05	0.91
Mo	14.25	10.53	39.36	19.92	48.93	22.11
Na	4.02	3.63	11.10	6.86	13.80	7.62
Nd	2.25	1.70	6.21	3.21	7.72	3.56
Pr	0.62	0.47	1.72	0.89	2.14	0.99
PO4	71.90	53.66	22.40	12.35	3.51	2.71
Ru		0.01		0.03		0.03
Sm	0.44	0.33	1.21	0.62	1.50	0.69
SO4		0.80		1.52		1.69
Sr	0.77	0.58	2.14	1.10	2.66	1.22
Tc	0.08	0.06	0.23	0.12	0.29	0.13
Zr	2.53	1.87	6.98	3.53	8.68	3.92
Total kg	6,101	8,087	2,133	4,118	1,692	3,677

Appendix F

Review of Options for Pretreatment/Separations Flowsheet and Their Resulting HAW Fraction Compositions

Dissolution & Filtration

- Large uncertainty in both quantity and composition of UDS
- For calcine dissolution
 - UDS assumed to be 2% of the feed calcine
 - UDS composition assumed equal to calcine
- Dissolver effluent filtered, filter normally backwashed to disover, periodically backwashed to HAW

Cs Sorbant: $(\text{NH}_4)_3\text{PO}_4 \cdot 12\text{MoO}_3 \cdot \text{H}_2\text{O}$
dissolved in NaOH

Spent sorbant, wt % as oxide

MoO ₃	73	P ₂ O ₅	3
Na ₂ O	21	Cs ₂ O	3

TRUEX

*For Al calcine and SBW, scrub is 0.1 M HNO_3

SREX

Total Calcine Feed Case (Bin Sets 1-6)

	Percent From UDS	Percent from dissolved calcine	Percent from Cs IX sorbant dissolution	Percent from TRUEX scrub feed	Percent from TRUEX strip feed	Percent from SREX scrub feed
Ag+	99.92	0.08				
Al+3	99.92	0.08				
As+3	100.00	1.58E-06				
B+3	99.92	0.08				
Ba+2	2.63	97.37				
Ca+2	99.92	0.08				
Cd+2	99.92	0.08				
Cl-	74.57	25.43				
Cr+3	99.92	0.08				
Cs+	2.00	0.08	98.00			
F-	28.49	0.00		71.51		
Fe+3	66.41	33.59				
Gd+3	2.00	98.00				
Hg+3	47.53	52.47				
K+	24.13	75.87				
Mg+2	99.92	0.08				
Mn+2	100.00	0.00				
Mo+6	0.08	3.87	96.05			
Na+	12.30	0.00	25.43			62.27
Nb+5	100.00	0.00				
Ni+2	99.88	0.12				
Pb+2	2.00	98.00				
PO4-3	0.43	0.00	1.07		98.50	
Sn+4	99.92	0.08				
Sr+2	2.00	98.00				
SO4-2	99.92	0.08				
Zr+4	99.61	0.39				
Total	28.77	4.05	7.46	15.23	40.30	4.20

Zirconia Calcine Feed Case (Bin Set 4)

	Percent From UDS	Percent from dissolved calcine	Percent from Cs IX sorbant dissolution	Percent from TRUEX scrub feed	Percent from TRUEX strip feed	Percent from SREX scrub feed
Ag+	100.00	0.00				
Al+3	99.92	0.08				
As+3	100.00	0.00				
B+3	99.92	0.08				
Ba+2	2.63	97.37				
Ca+2	99.92	0.08				
Cd+2	99.92	0.08				
Cl-	99.35	0.65				
Cr+3	99.92	0.08				
Cs+	2.00		98.00			
F-	33.76	0.00		66.24		
Fe+3	66.41	33.59				
Gd+3	2.00	98.00				
Hg+3	47.53	52.47				
K+	24.13	75.87				
Mg+2	99.92	0.08				
Mo+6	0.04	2.01	97.95			
Na+	10.65	0.00	24.55			64.80
Nb+5	100.00	0.00				
Ni+2	99.88	0.12				
PO4-3	0.07	0.00	1.00		98.93	
Sn+4	99.92	0.08				
Sr+2	2.00	98.00				
SO4-2	99.92	0.08				
Zr+4	99.61	0.39				
Total	29.61	5.84	6.71	14.79	38.96	4.08

Alumina Calcine Feed Case (Bin Set 1)

	Percent from UDS	Percent from dissolved calcine	Percent from Cs IX sorbant dissolution	Percent from TRUEX strip feed
Al	100.00			
B	100.00			
Cs	2.00		98.00	
Fe	97.40	2.60		
Hg	51.20	48.80		
Mo	0.26	12.68	87.06	
Na	18.12		81.88	
PO4	1.00		1.40	97.61
SO4	79.03	20.97		
Sr	2.00	98.00		
Zr	2.00	98.00		
Total	27.46	5.16	14.12	53.27

Sodium Bearing Waste

	Percent From UDS	Percent from dissolved calcine	Percent from dissolved IX sorbant	Percent from TRUEX strip feed	Percent from SREX scrub feed
Al	99.48	0.52			
B	100.00	0.00			
Ca	99.89	0.11			
Cd	99.90	0.10			
Cl	97.79	2.21			
Cr	99.95	0.05			
Cs	0.00	0.00	100.00		
Cu	100.00	0.00			
F	99.98	0.02			
Fe	96.94	3.06			
Hg	76.70	23.30			
K	8.42	91.58			
Li	100.00	0.00			
Mg	100.00	0.00			
Mn	99.90	0.10			
Mo	27.33	38.61	34.06		
Na	25.49	0.00	3.82		70.69
Nb	100.00	0.00			
Ni	99.99	0.01			
Pb	25.46	74.54			
PO4	35.36	0.17	0.27	64.20	
Se	0.00	100.00			
Si	100.00	0.00			
Sn	100.00	0.00			
SO4	99.98	0.02			
Sr	0.00	100.00			
Ti	100.00	0.00			
Zn	100.00	0.00			
Zr	42.58	57.42			
Total	41.04	37.55	1.56	13.28	6.57

Total Cacline	Low Kg	Expected Kg	High Kg		Low Wt%	Expected Wt%	High Wt%
Al	19422.7	19427.7	19510.0		6.92	6.60	6.44
B	840.8	840.8	840.8		0.30	0.29	0.28
Ba	143.4	495.0	504.8		0.05	0.17	0.17
Ca	23904.6	23910.8	24012.1		8.52	8.12	7.92
Ce+TRU	717.3	717.3	717.3		0.26	0.24	0.24
Cl	117.3	117.3	117.3		0.04	0.04	0.04
Cr	185.1	185.1	185.1		0.07	0.06	0.06
Cs	825.5	825.5	825.5		0.29	0.28	0.27
F	62282.6	62282.6	62282.6		22.20	21.14	20.55
Fe	467.5	686.8	1140.2		0.17	0.23	0.38
K	1069.6	2216.0	3208.8		0.38	0.75	1.06
Mg	562.0	562.0	562.0		0.20	0.19	0.19
Mo	16108.0	16160.1	16160.1		5.74	5.49	5.33
Na	7453.7	19753.4	8668.7		2.66	6.71	2.86
Nb	63.2	63.2	63.2		0.02	0.02	0.02
Nd	1066.1	1066.1	1066.1		0.38	0.36	0.35
Ni+Cd	1047.9	1047.9	1047.9		0.37	0.36	0.35
Pb	32.5	35.3	36.0		0.01	0.01	0.01
PO4	117868.5	117868.5	117868.5		42.02	40.01	38.90
Pr	290.7	290.7	290.7		0.10	0.10	0.10
Sm	143.0	143.0	143.0		0.05	0.05	0.05
Sn	190.1	190.1	190.1		0.07	0.06	0.06
Sr	12542.2	12542.2	12542.2		4.47	4.26	4.14
SO4	1099.5	1099.5	1099.5		0.39	0.37	0.36
Tc	41.8	41.8	41.8		0.01	0.01	0.01
Zr	12004.3	12004.3	29895.1		4.28	4.08	9.87
Total Kg	280,490	294,573	303,019		100.00	100.00	100.00

Zirconia Cacline	Low Kg	Expected Kg	High Kg		Low Wt%	Expected Wt%	High Wt%
Al	1351.0	1351.3	1357.0		3.85	3.67	3.52
B	124.7	124.7	124.7		0.36	0.34	0.32
Ba	17.1	59.2	60.4		0.05	0.16	0.16
Ca	3905.1	3906.1	3922.7		11.12	10.61	10.18
Ce+TRU	90.5	90.5	90.5		0.26	0.25	0.23
Cl	13.9	13.9	13.9		0.04	0.04	0.04
Cr	33.8	33.8	33.8		0.10	0.09	0.09
Cs	113.6	113.6	113.6		0.32	0.31	0.29
F	8156.1	8156.1	8156.1		23.23	22.15	21.16
Fe	75.1	110.4	183.3		0.21	0.30	0.48
Gd	1.7	1.9	1.9		0.00	0.01	0.00
K	119.6	247.7	358.7		0.34	0.67	0.93
Mg	36.4	36.4	36.4		0.10	0.10	0.09
Mo	1778.2	1781.1	1781.1		5.06	4.84	4.62
Na	810.2	2301.8	932.8		2.31	6.25	2.42
Nd	142.5	142.5	142.5		0.41	0.39	0.37
Ni	11.4	11.4	11.4		0.03	0.03	0.03
Pb	5.2	5.7	5.8		0.01	0.02	0.02
PO4	14231.0	14231.0	14231.0		40.52	38.65	36.92
Pr	38.2	38.2	38.2		0.11	0.10	0.10
Sm	17.1	17.1	17.1		0.05	0.05	0.04
Sn	30.7	30.7	30.7		0.09	0.08	0.08
Sr	2055.8	2055.8	2055.8		5.85	5.58	5.33
SO4	16.1	16.1	16.1		0.05	0.04	0.04
Tc	6.3	6.3	6.3		0.02	0.02	0.02
Zr	1936.1	1936.1	4821.6		5.51	5.26	12.51
Total Kg	35,118	36,819	38,543		100.00	100.00	100.00

Alumina Cacline	Low Kg	Expected Kg	High Kg		Low Wt%	Expected Wt%	High Wt%
Al	1895.4	1895.4	1905.0		23.51	23.43	23.30
B	10.0	10.0	10.0		0.12	0.12	0.12
Ba	1.5	1.5	1.5		0.02	0.02	0.02
Ce+TRU	80.7	80.7	80.7		1.00	1.00	0.99
Cl	25.1	25.1	25.1		0.31	0.31	0.31
Cs	82.2	82.2	82.2		1.02	1.02	1.01
Eu	2.0	2.0	2.0		0.02	0.02	0.02
Fe	34.8	34.9	84.9		0.43	0.43	1.04
Mo	840.9	851.9	851.9		10.43	10.53	10.42
Na	293.4	293.4	320.0		3.64	3.63	3.91
Nd	137.3	137.3	137.3		1.70	1.70	1.68
Pr	38.0	38.0	38.0		0.47	0.47	0.47
PO4	4341.0	4341.0	4341.0		53.84	53.66	53.10
Ru	1.1	1.1	1.1		0.01	0.01	0.01
Sm	26.7	26.7	26.7		0.33	0.33	0.33
SO4	64.9	64.9	64.9		0.81	0.80	0.79
Sr	47.2	47.2	47.2		0.59	0.58	0.58
Tc	5.0	5.0	5.0		0.06	0.06	0.06
Zr	136.0	151.1	151.1		1.69	1.87	1.85
Total	8,063	8,089	8,176		100.00	100.00	100.00

SBW HAW	Low Kg	Expected Kg	High Kg		Low Kg	Expected Kg	High Kg
Al	234.4	234.9	241.5	Nb	20.1	20.1	20.1
B	388.2	388.2	388.2	Nd	21.9	21.9	20.1
Ba	7.3	10.6	14.6	Pb	51.5	82.5	83.2
Ca	118.4	118.4	119.1	Pd	12.6	12.6	12.6
Cd + Ni	211.1	211.1	211.1	Pr	6.0	6.0	6.0
Ce+TRU	19.0	19.0	19.0	PO4	4946.6	4946.6	4946.6
Cl	361.8	361.8	361.8	Rh	21.0	21.0	21.0
Cr	29.9	29.9	29.9	Ru	210.0	210.0	210.0
Cs	13.5	13.5	13.5	Si	531.3	531.3	531.3
Cu	21.0	21.0	21.0	Sm	3.9	3.9	3.9
F	346.1	346.1	346.1	Sn	105.0	105.0	105.0
Fe	326.7	334.2	490.3	Sr	6.6	6.6	6.6
K	914.9	2475.1	3741.3	SO4	1919.6	1919.6	1919.6
Li	21.0	21.0	21.0	Tc	1.1	1.1	1.1
Mg	210.0	210.0	210.0	Ti	21.0	21.0	21.0
Mn	50.6	50.6	50.6	Zn	21.0	21.0	21.0
Mo	738.7	768.3	768.4	Zr	1087.8	4258.9	6930.8
Na	925.5	2220.8	3397.8	Total	13,925	20,023	25,307

SBW HAW	Low Wt%	Expected Wt%	High Wt%		Low Wt%	Expected Wt%	High Wt%
Al	1.68	1.17	0.95	Nb	0.14	0.10	0.08
B	2.79	1.94	1.53	Nd	0.16	0.11	0.09
Ba	0.05	0.05	0.06	Pb	0.37	0.41	0.33
Ca	0.85	0.59	0.47	Pd	0.09	0.06	0.05
Cd + Ni	1.52	1.05	0.83	Pr	0.04	0.03	0.02
Ce+TRU	0.14	0.09	0.08	PO4	35.52	24.70	19.55
Cl	2.60	1.81	1.43	Rh	0.15	0.10	0.08
Cr	0.21	0.15	0.12	Ru	1.51	1.05	0.83
Cs	0.10	0.07	0.05	Si	3.82	2.65	2.10
Cu	0.15	0.10	0.08	Sm	0.03	0.02	0.02
F	2.49	1.73	1.37	Sn	0.75	0.52	0.41
Fe	2.35	1.67	1.94	Sr	0.05	0.03	0.03
K	6.57	12.36	14.78	SO4	13.79	9.59	7.59
Li	0.15	0.10	0.08	Tc	0.01	0.01	0.00
Mg	1.51	1.05	0.83	Ti	0.15	0.10	0.08
Mn	0.36	0.25	0.20	Zn	0.15	0.10	0.08
Mo	5.31	3.84	3.04	Zr	7.81	21.27	27.39
Na	6.65	11.09	13.43	Total	100.00	100.00	100.00

Estimated INEEL calcine binset compositions in Wt%

Element	Binset #1	Binset #2	Binset #3	Binset #4	Binset #5	Binset #6	SBW
Al	89.56	35.17	14.56	12.69	14.84	151.65	20.20
B	0.47	0.80	1.06	1.17	1.20	0.92	0.28
Ba	0.07	0.02	0.01	0.01	0.01	0.01	0.00
Ca	0.00	24.45	32.83	36.67	33.19	15.84	2.22
Ce	0.08	0.02	0.01	0.02	0.02	0.01	0.00
Cl	0.00	0.00	0.05	0.13	0.19	0.28	1.45
Cr	0.00	0.20	0.27	0.32	0.17	0.27	0.24
Cs	0.06	0.02	0.01	0.02	0.01	0.01	0.00
F	0.00	21.28	26.81	25.86	21.97	7.43	1.36
Fe	1.58	0.17	0.30	0.69	0.70	1.31	1.51
I	0.00	0.00	0.00	0.00	0.00	0.01	0.02
K	0.00	0.18	0.25	0.56	0.90	2.60	9.17
La	0.04	0.01	0.01	0.01	0.01	0.01	0.00
Mg	0.00	0.71	0.83	0.34	0.62	1.12	0.05
Mn	0.00	0.00	0.03	0.00	0.03	0.10	0.84
Mo	0.10	0.03	0.01	0.01	0.01	0.01	0.12
Na	2.48	0.86	1.27	2.30	4.47	9.53	51.84
Nb	0.00	0.00	0.01	0.01	0.28	0.01	0.00
Nd	0.13	0.04	0.02	0.03	0.03	0.02	0.00
Ni	0.00	0.06	0.08	0.11	4.00	1.75	0.60
Pb	0.00	0.00	0.00	0.00	0.00	0.00	0.40
Pd	0.01	0.00	0.00	0.00	0.00	0.00	0.00
PO4	2.02	0.43	1.25	0.09	0.24	0.54	2.23
Pr	0.04	0.01	0.01	0.01	0.01	0.01	0.00
Rb	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Rh	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ru	0.05	0.01	0.00	0.00	0.01	0.01	0.05
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.12
Sm	0.03	0.01	0.00	0.00	0.00	0.00	0.00
Sn	0.00	0.23	0.30	0.29	0.21	0.07	0.02
SO4	3.03	0.68	0.65	0.15	2.72	2.19	6.24
Sr	0.04	0.26	0.34	0.39	0.35	0.13	0.00
Tc	0.03	0.01	0.00	0.00	0.01	0.00	0.00
Te	0.01	0.00	0.00	0.00	0.00	0.00	0.00
U	0.02	0.01	0.01	0.01	0.02	0.16	0.00
Y	0.00	0.00	0.01	0.01	0.01	0.00	0.00
Zr	0.14	14.34	19.01	18.12	13.79	4.10	1.03
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00