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LAW Simulant Recipes for Evaluation of Real-Time, In-Line Monitoring Instruments

M.J. Siegfried

M. E. Stone

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REVIEWS AND APPROVALS

AUTHORS:

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M. E. Stone, Chemical Processing Date

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PREFACE OR ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Statistically designed recipes were generated for evaluation of in-line instrumentation for the Real-Time In-Line Monitoring (RTIM) program in support of the Hanford Direct-Feed Low Activity Waste (DFLAW) program. The composition matrices were prepared based on Low Activity Waste (LAW) feed vector, melter feed, and Effluent Management Facility (EMF) feed information provided by the flowsheet integration modelling for the DFLAW portion of the Waste Treatment Plant (WTP) mission. These composition matrices were converted to recipes for the LAW feed using the approaches for LAW simulant recipes developed by Savannah River National Laboratory (SRNL). Recipes for the glass forming chemicals (GFCs) were developed based on expected mineral forms to be used to for each element to be added to the recipe. The recipe matrices are shown in the Appendix.

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LIST OF ACRONYMS

CRV	Concentrate Receipt Vessel
DFLAW	Direct Feed Low Activity Waste
EDTA	Ethylenediaminetetraacetic acid
EMF	Effluent Management Facility
GFC	Glass Former Chemical
IDF	Integrated Disposal Facility
LAW	Low Activity Waste
MFPV	Melter Feed Preparation Vessel
RTIM	Real-Time In-Line Monitoring
SDS	Safety Data Sheet
SRNL	Savannah River National Laboratory
TOC	Total Organic Carbon
VSL	Vitreous State Laboratory
WRPS	Washington River Protection Solutions
WTP	Waste Treatment and Immobilization Plant

1.0 Introduction

The Hanford site generated millions of gallons of waste during reprocessing of spent nuclear fuel to recover plutonium, uranium, and other isotopes. The waste was placed into 177 large underground storage tanks awaiting a final disposition path. The DFLAW program will begin the process of treatment, immobilization, and disposal of the tank waste stored at the Hanford site. The DFLAW process filters the supernate portion of the tank waste to remove entrained solids and then uses a non-elutable ion exchange media to remove cesium. Once the cesium is removed, the treated supernate is considered low-level (or low-activity) waste. The treated supernate is sent to the LAW facility, blended with GFCs, and converted into a glass waste form and poured into containers for final disposal at the Integrated Disposal Facility (IDF). Liquid effluents from the immobilization process are treated at the EMF to concentrate the effluent by evaporation and returning the concentrated effluent to the LAW facility. Condensate from the EMF evaporation process is sent to the Effluent Treatment Facility.

A large number of samples are taken at various stages of the treatment and immobilization process. The RTIM program was established by the Department of Energy – Office of River Protection to evaluate methods to reduce the number of samples [1]. Evaluation of commercial in-line instrumentation to replace selected samples is in progress as part of this program [2]. Simulants are needed at various stages in the process that span the expected compositional ranges to allow the instruments to be evaluated.

2.0 Experimental Procedure

The compositions of the treated supernate feed to the LAW facility were provided via emails from L. Cree of Washington River Protection Solutions (WRPS). The compositions were calculated from the TOPSim® model of the overall DFLAW flowsheet and provide the average composition of the LAW feed for each month of operation during the DFLAW program for modeling case ID 9157. The compositions of individual batches of melter feed were provided in a separate DFLAW modeling case ID 6858. These cases represent a snapshot of the process plan and that some differences can occur as the plans for tank waste processing evolve. However, the compositions provide the overall range and variability expected to be processed within the limits of the modelling efforts.

2.1 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.

3.0 Results and Discussion

3.1 LAW Feed Matrices

From the monthly data, calculation of the average, minimum, and maximum for each species are shown in Table 1. Next, species were excluded from the LAW feed matrix if the average concentration was below 200 ppm and the non-zero ppm species are shown in Table 2. The statistical compositional matrix was designed using the average, minimum, and maximum values. Organic species, shown in Table 3, other than oxalate, were added at a fixed amount in the feed for TOC, as shown in Table 1, and not considered part of the statistical design. A number of compositional matrices were made for the LAW feed, with an increasing number of data points. A space-filling matrix with 10 data points was developed, along with matrices that included 25, 45, and 75 number of data points. The matrices include all previous matrices as well as the additional data points added. All compositional matrices are shown in Table A- 1.

Table 1. LAW Feed Data Input for Matrix Formation

Species	AVERAGE	Maximum	Minimum	MW	AVERAGE	Maximum	Minimum
	mg/L	mg/L	mg/L	g/mol	molar	molar	molar
Na^+	126,926	130,606	119,245	23	5.52	5.68	5.18
NO_3^-	122,982	158,928	80,897	62	1.98	2.56	1.30
NO_2^-	49,038	53,959	34,882	46	1.07	1.17	0.76
CO_3^{-2}	26,651	35,689	18,039	60	0.44	0.59	0.30
OH^-	22,539	30,919	14,666	17	1.33	1.82	0.86
$Al(OH)_4^-$	9,976	14,194	6,320	95	0.11	0.15	0.07
K^+	4,499	14,454	1,088	39.1	0.12	0.37	0.03
SO_4^{-2}	4,123	6,150	2,745	96.1	0.043	0.064	0.029
Cl^-	2,773	3,389	1,869	35.5	0.078	0.095	0.053
PO_4^{-3}	1,601	2,234	1,186	95	0.017	0.024	0.012
TOC	1,471	2,291	640	12	0.123	0.191	0.053
CrO_4^{-2}	806	1,123	511	116	0.007	0.010	0.004
$C_2O_4^{-2}$	337	530	218	88	0.004	0.006	0.002
F^-	278	734	151	19	0.015	0.039	0.008

Table 2. Species not Included in Simulant Matrices

Species	PPM			Species	PPM		
	AVERAGE	Maximum	Minimum		AVERAGE	Maximum	Minimum
Si^{+4}	120	225	38	Cd^{+2}	2	6	0
Ca^{+2}	33	70	10	W^{+6}	2	6	0
Pb^{+2}	14	46	3	Ag^{+}	1	5	0
Mo^{+6}	14	33	0	V^{+5}	1	6	0
Ni^{+2}	12	22	3	Li^{+2}	1	5	0
Fe^{+3}	10	22	3	Cu^{+2}	1	2	0
Bi^{+3}	8	12	3	Co^{+3}	1	2	0
B^{+3}	8	20	0	Ba^{+2}	1	2	0
Se^{+6}	6	14	0	Ti^{+4}	1	2	0
Zr^{+4}	6	42	0	La^{+3}	0	1	0
As^{+5}	4	11	0	Hg^{+2}	0	2	0
Zn^{+2}	4	13	0	Sr^{+2}	0	1	0
Nd^{+3}	3	14	0	Y^{+3}	0	1	0
Sb^{+5}	3	9	0	Ru^{+3}	0	2	0
Ce^{+3}	3	8	0	Be^{+2}	0	1	0
Tl^{+3}	2	8	0	Rb^{+}	0	2	0
Mg^{+2}	2	11	0	CN^{-}	0	1	0
Mn^{+4}	2	5	1				

Table 3. TOC Species Added

TOC - Molar Basis	
30%	Trisodium citrate
30%	Sodium formate
30%	Sodium acetate
10%	Tetrasodium Ethylenediaminetetraacetic Acid (EDTA)

Next, matrix points with the maximum molar concentrations for each ion were evaluated using OLI® software to ensure that the composition would result in a supernate free of solids. No issues were noted in the matrix points evaluated.

Finally, the LAW feed compositional matrices shown in Appendix A, Section A-1 were converted into recipes that can be prepared using general instructions. One-liter receipts for each of these matrices are provided in Appendix A, Section A-1.1.

3.2 GFC Matrices

The evaluation of the GFC data provided followed a similar strategy as the LAW feed composition matrices. However, the GFC data was split into two regions based on the glass models used to calculate the GFC composition during the WRPS flowsheet model run. In addition, issues were noted with the flowsheet calculations that were performed with the 2016 glass models; this issue results in wider scatter than would be expected. As a result, a statistically designed matrix using the data should bound the expected actual range of composition data.

As with the LAW feed vector, the monthly data was used to calculate the average, minimum and maximum values. The average, minimum, maximum, and standard deviation were used to develop a statistically designed composition matrix for each set of GFC data, shown Table 4 and Table 5 with the resulting matrix shown in Table 6. The GFC values in Table 4 and Table 5 are the weight percent of the oxides from the glass former chemicals, excluding the sugar. The sugar addition is not impacted by waste loading and added based on the ILAW algorithm specification of 0.75 moles of sugar for each mole of nitrate and nitrite in the feed.

Table 4. GFC Simulant Composition Input – 2009 Glass Models

Species	Average	Max	Min	Std. Dev	Abs. Std. Dev.
Al_2O_3	6.9	7.0	6.8	0.1	0.9
B_2O_3	12.4	12.8	12.1	0.2	1.3
CaO	4.4	5.9	3.2	0.7	16.3
Fe_2O_3	6.8	7.0	6.7	0.1	1.3
Li_2O	0.7	2.2	0.0	0.8	114.0
MgO	1.8	1.9	1.8	0.0	1.3
Na_2O	0.5	1.7	0.0	0.5	113.9
SiO_2	56.7	58.1	54.9	1.0	1.7
SnO_2	0.0	0.0	0.0	0.0	0.0
TiO_2	1.7	1.8	1.7	0.0	1.3
V_2O_5	0.0	0.0	0.0	0.0	0.0
ZnO	4.3	4.5	4.2	0.1	1.3
ZrO_2	3.7	3.8	3.6	0.0	1.3
Sugar	7.3	8.5	5.5	0.9	12.2

Table 5. GFC Simulant Composition Input – 2016 Glass Models

Species	Average	Max	Min	Std. Dev	Abs. Std. Dev.
Al_2O_3	10.3	17.9	5.9	4.1	39.9
B_2O_3	11.2	18.7	8.1	4.1	36.8
CaO	6.1	14.5	0.0	4.5	74.3
Fe_2O_3	0.0	0.0	0.0	0.0	0.0
Li_2O	0.2	3.3	0.0	0.7	280.3
MgO	2.3	4.8	0.0	2.3	100.2
Na_2O	0.0	0.0	0.0	0.0	0.0
SiO_2	54.3	65.2	46.4	4.0	7.3
SnO_2	3.0	6.8	0.0	3.2	107.8
TiO_2	0.0	0.0	0.0	0.0	0.0
V_2O_5	4.1	5.5	0.0	2.1	50.3
ZnO	1.3	7.4	0.0	2.6	200.2
ZrO_2	7.1	9.2	0.0	2.9	40.0
Sugar	11.5	15.3	9.1	1.7	14.8

Table 6. GFC Composition Matrix (Oxides as mass fraction, Sugar is g/L)

Point	Al_2O_3	B_2O_3	CaO	Fe_2O_3	Li_2O	MgO	SiO_2	SnO_2	TiO_2	V_2O_5	ZnO	ZrO_2	Sugar
GFC-1	0.179	0.081	0.145	0	0	0	0.464	0.068	0	0.055	0.008	0	9.1
GFC-2	0.059	0.081	0.046	0	0.033	0	0.652	0	0	0.055	0.074	0	9.1
GFC-3	0.179	0.081	0	0	0	0	0.648	0	0	0	0	0.092	9.1
GFC-4	0.059	0.187	0	0	0	0.048	0.638	0.068	0	0	0	0	9.1
GFC-5	0.179	0.187	0	0	0	0.048	0.464	0	0	0.055	0.067	0	9.1
GFC-6	0.179	0.187	0.137	0	0.033	0	0.464	0	0	0	0	0	9.1
GFC-7	0.059	0.081	0.145	0	0.033	0.048	0.487	0	0	0.055	0	0.092	9.1
GFC-8	0.179	0.081	0	0	0.033	0.048	0.464	0.068	0	0	0.074	0.053	9.1
GFC-9	0.059	0.166	0.145	0	0	0	0.464	0	0	0	0.074	0.092	9.1
GFC-10	0.101	0.187	0	0	0.033	0	0.464	0.068	0	0.055	0	0.092	9.1
GFC-11	0.1232	0.1319	0.0618	0	0.0165	0.0192	0.5209	0.0272	0	0.0275	0.0297	0.0421	12.2
GFC-12	0.179	0.081	0.145	0	0	0	0.464	0.068	0	0.055	0.008	0	15.3
GFC-13	0.059	0.081	0.046	0	0.033	0	0.652	0	0	0.055	0.074	0	15.3
GFC-14	0.179	0.081	0	0	0	0	0.648	0	0	0	0	0.092	15.3
GFC-15	0.059	0.187	0	0	0	0.048	0.638	0.068	0	0	0	0	15.3
GFC-16	0.179	0.187	0	0	0	0.048	0.464	0	0	0.055	0.067	0	15.3
GFC-17	0.179	0.187	0.137	0	0.033	0	0.464	0	0	0	0	0	15.3
GFC-18	0.059	0.081	0.145	0	0.033	0.048	0.487	0	0	0.055	0	0.092	15.3
GFC-19	0.179	0.081	0	0	0.033	0.048	0.464	0.068	0	0	0.074	0.053	15.3
GFC-20	0.059	0.166	0.145	0	0	0	0.464	0	0	0	0.074	0.092	15.3
GFC-21	0.101	0.187	0	0	0.033	0	0.464	0.068	0	0.055	0	0.092	15.3
GFC-2009	0.069	0.125	0.049	0.069	0	0.019	0.572	0	0.018	0	0.044	0.037	7

The low standard deviation for the GFC recipe using the 2009 models led to a single matrix point to represent that composition. Thus, the two data sets were merged into one set of data when the compositional matrix was developed, as shown in Table 6. Point GFC-11 represents the average of the GFC points from the 2016 matrix.

The expected mineral forms are based on work performed by Vitreous State Laboratory (VSL) and SRNL are shown in Table 7[3,4], but some of the exact mineral form and particle sizes specified are no longer available. Thus, substitution of those will be made with materials as similar as possible. It should be noted that LAW contractor is developing specifications for the GFCs and may not use the same mineral forms recommended by VSL. Tin and vanadium are new GFCs added for the 2016 models and do not have a specified source. The oxide form of each should be used, with a particle size target of 325 mesh or less.

Table 7. Mineral Forms Specified by VSL

Glass Former Mineral	Compound	Source
Kyanite (325 Mesh)	Al_2SiO_5	Kyanite Mining Corp
Boric Acid (Technical - Granular)	H_3BO_3	U.S. Borax
Wollastonite (NYAD 325 Mesh)	$CaSiO_3$	NYCO
Lithium Carbonate (Technical grade)	Li_2CO_3	Chemettal-Foote
Ferric Oxide (Prince 5001, -325 Mesh)	Fe_2O_3	Prince Manufacturing Co.
Olivine (325 Mesh, #LE170)	Mg_2SiO_4	Unimin Corp
Silica (Sil-Co-Sil 75)	SiO_2	U.S. Silica
Titanium Dioxide (Rutile 94)	TiO_2	Chemalloy Co.
Zinc Oxide (Kadox-920)	ZnO	Zinc Corp of America
Zircon (Flour, 325 Mesh)	$ZrSiO_4$	Prince Minerals Inc.

Recipes for the GFC blends are shown in Appendix A, Section A-2. The recipes are based on 100 grams of oxides, hence the mass of GFCs are in excess of 100 grams.

3.3 EMF Feed Matrix

The compositions provided by WRPS for the EMF feed were from model run Case ID 9157. As with the LAW feed and the GFC data, the average, minimum, maximum, and standard deviation were calculated for each species, as shown in Table 8. Next, species were eliminated from the LAW feed matrix if the maximum concentration of the component was below 0.5 ppm. In addition, thallium was eliminated. The species with non-zero data from the composition provided but not included in the simulants are shown in Table 9. The recipes may be simplified by eliminating Se, Hg, As, Sb, and Pb if desired. A statistical matrix, from Table 8, was developed based on species with concentrations greater than 100 mg/L, species less than this were fixed at the average values. Nine different points were generated, point EMF-10 is the average.

The WRPS data for the EMF feed does not include solids entrainment of the melter feed into the melter overheads. The data in Table 8 and Table 9 only represents the expected volatile species from the melter. VSL testing has shown up to 1 wt% of the melter feed solids are entrained into the offgas, but the typical range is 0.1 to 0.3 wt%. Therefore, GFCs were added to the EMF recipes using the GFC-2009 and GFC-

11 compositions from Table 6 in the amounts determined for EMF evaporator testing[5]. Sugar is excluded because it will be destroyed during vitrification.

If the goal is to make a simulant of the EMF evaporator feed, then the EMF simulant can be filtered to remove solids and adjusted to pH 12 with 50% NaOH. When preparing EMF evaporator feed, the GFCs other than boric acid and lithium carbonate may be omitted.

The recipes for the EMF feed simulants are shown in Appendix A, Section A-3.1.

3.4 EMF Concentrate

The average values from the EMF feed simulant input values, shown in Table 8, along with the entrained GFCs using the GFC-2009 recipe and an estimated amount for the NaOH addition prior to evaporation were used to calculate a recipe for the EMF concentrate vessel. These recipes do not include the Se, Hg, As, Sb, and Pb that were included in Table 8.

Three EMF concentrate simulants were generated based on assuming a 10x, 15x, and 20x turndown in the EMF evaporator. The simulants assumed that solids filtered from the evaporator feed are added back to the concentrate. These recipes are shown in Appendix A, Section A-4.

Table 8. EMF Feed Composition Data

Species		AVERAGE	Maximum	Minimum	Standard Deviation	Relative Standard Deviation
H_2O	mg/L	996,761	998,892	993,169	781	0
NO_3^-	mg/L	3,417	4,423	2,476	480	14
Cl^-	mg/L	1,596	2,104	996	218	14
Na^+	mg/L	1,207	1,418	1,061	68	6
NH_4^+	mg/L	1,005	1,177	837	88	9
SO_4^{-2}	mg/L	534	2,191	24	578	108
F^-	mg/L	188	469	98	76	41
K^+	mg/L	168	543	43	92	55
CrO_4^{-2}	mg/L	44	62	29	9	20
$Al(OH)_4^-$	mg/L	14	21	9	3	19
PO_4^{-3}	mg/L	13	22	9	2	18
H^+	mg/L	13	17	5	2	12
Se^{+6}	mg/L	1.5	3.5	0.0	0.9	57.7
Hg^{+2}	mg/L	1.0	3.2	0.0	0.7	68.8
As^{+5}	mg/L	1.0	2.3	0.0	0.5	56.7
Sb^{+5}	mg/L	0.7	2.1	0.0	0.4	60.4
Pb^{+2}	mg/L	0.2	0.6	0.0	0.1	62.5

Table 9. EMF Feed Composition – Excluded Species

Species		AVERAGE	Maximum	Minimum	Standard Deviation	Relative Standard Deviation
Tl^{+3}	mg/L	0.4	1.6	0.0	0.4	84.3
Mo^{+6}	mg/L	0.2	0.4	0.0	0.1	53.7
NH_3	mg/L	0.1	0.1	0.1	0.0	11.1
Bi^{+3}	mg/L	0.1	0.2	0.0	0.0	29.7
Si^{+4}	mg/L	0.1	0.2	0.0	0.0	35.8
Ni^{+2}	mg/L	0.1	0.2	0.0	0.0	45.1
Cu^{+2}	mg/L	0.1	0.1	0.0	0.0	59.2
B^{+3}	mg/L	0.0	0.1	0.0	0.0	55.4
Ca^{+2}	mg/L	0.0	0.1	0.0	0.0	52.1
Te^{+6}	mg/L	0.0	0.1	0.0	0.0	106.2
Nd^{+3}	mg/L	0.0	0.1	0.0	0.0	93.6
Ce^{+3}	mg/L	0.0	0.1	0.0	0.0	70.3
Ag^+	mg/L	0.0	0.1	0.0	0.0	79.3
V^{+5}	mg/L	0.0	0.1	0.0	0.0	111.5

3.5 LAW Concentrate Receipt Vessel (CRV)

The CRV receives the LAW feed and as well as concentrated recycle from the EMF. The EMF concentrate recipe with a 15x turn down as the EMF concentrate composition and the estimated maximum and nominal LAW Feed to recycle ratios were used to determine the EMF concentrate amounts; this concentrate composition was blended with the 10-point LAW Feed Matrix.

The maximum expected recycle addition was estimated for a "sprint" scenario where the goal is to either catch up or get ahead of the EMF evaporation process. The maximum amount of recycle allowable was set by determining the ratio of LAW feed to recycle that would result in a sodium concentration of 4.5M in the resulting blend. This "maximum recycle" blend adds 2814 gallons of recycle to a 9,000-gallon CRV batch.

The typical recycle amount was calculated by assuming that 90% of the LAW feed is water, that volume of recycle returned is 150% of the water fed to the LAW system, and a 15x turn down in the evaporator. This calculation results in a nominal recycle addition of 810 gallons per 9,000-gallon CRV batch. This value matches well with the average amounts determined from TOPSim modeling of the LAW system (840 gallons per 9,000-gallon CRV batch).

The LAW recycle CRV recipes are batched using raw material, not blended with two different liquid streams. These recipes to make one liter of simulant are provided in Appendix A, Section A-5. If the 15x EMF concentrate and LAW feed simulants are available, they can be blended in the volume ratios of 810 gallons of EMF concentrate to 8190 gallons of LAW feed to prepare the nominal CRV feed simulant.

3.6 Melter Feed Prep Vessel (MFPV)

The MFPV blends the LAW waste with the GFCs to prepare melter feed for vitrification. The required GFC addition was determined by determining the amount of glass formers required to dilute the sodium in the feed to the targeted waste loading (wt% Soda of total oxides). The amount of feed oxides was calculated in each nominal recycle CRV simulant and subtracted from the required glass amount to obtain the required GFC addition on an oxide basis. The GFC oxides values were converted into the GFC addition amount based on the GFC-2009 recipe. Chlorine and fluorine were assumed have a negligible contribution to glass oxides. The waste loadings resulted in GFC additions as shown in Table 10, refer to Appendix A, Section A-2 for 100-gram oxide basis GFC recipes. If a GFC simulant other than GFC-2009 is used, it can be added to the CRV simulants in the amounts shown in Table 10 to generate a melter feed simulant, but the waste loadings will differ slightly since the different GFC blends have different amounts of boric acid and lithium carbonate. To adjust the values for the oxide content of each GFC recipe, multiply by the values shown in Table 11.

It should be noted that these recipes are not intended to represent actual melter feeds and may not make acceptable glass if vitrified. The sugar addition is not impacted by waste loading and was added based on the ILAW algorithm specification of 0.75 moles of sugar for each mole of nitrate and nitrite in the feed. The sugar values remain the same for each GFC blend and do not require any adjustments.

Table 10. GFC additions to One Liter of CRV Simulants for Melter Feed Preparation

MPFV Simulant ID	CRV Simulant	15% Soda Loading GFC Addition	20% Soda Loading GFC Addition	25% Soda Loading GFC Addition	Sugar
		grams	grams	grams	g/L
MFPV-1	CRV-11	1246.5	868.1	641.1	62.7
MFPV-2	CRV-12	1249.5	871.2	644.2	57.4
MFPV-3	CRV-13	1246.0	867.7	640.7	60.5
MFPV-4	CRV-14	1246.4	868.1	641.1	61.9
MFPV-5	CRV-15	1246.6	868.2	641.2	62.4
MFPV-6	CRV-16	1246.3	868.0	641.0	59.7
MFPV-7	CRV-17	1244.5	866.2	639.2	60.9
MFPV-8	CRV-18	1246.3	868.0	641.0	53.4
MFPV-9	CRV-19	1243.6	865.2	638.2	54.2
MFPV-10	CRV-20	1251.5	873.2	646.2	54.0

Table 11. Adjustment Factors for GFC Recipes

	Factor
GFC-1	0.875
GFC-2	1.092
GFC-3	0.935
GFC-4	1.040
GFC-5	0.997
GFC-6	0.992
GFC-7	0.996
GFC-8	0.983
GFC-9	0.892
GFC-10	1.081
GFC-11	0.988
GFC-12	0.875
GFC-13	1.092
GFC-14	0.935
GFC-15	1.040
GFC-16	0.997
GFC-17	0.992
GFC-18	0.996
GFC-19	0.983
GFC-20	0.892
GFC-21	1.081
GFC-2009	1.000

4.0 Conclusions

Recipes developed, as shown in Appendix A, are ready for use in the Real-Time, In-Line Monitoring program.

5.0 Recommendations

No recommendations were developed as part of this work scope.

6.0 References

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2. M.E. Stone, "Evaluation of a Material Balance Only and Material Balance with Real-Time In-line Monitoring Approaches for DFLAW Processing," Savannah River National Laboratory, Aiken, South Carolina, SRNL-STI-2019-00629, 2019.

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4. R.F. Schumacher, "Characterization of HLW and LAW Glass Formers - Final Report," Savannah River National Laboratory, Aiken, South Carolina, WSRC-TR-2002-00282, Rev 1, 2003.

5. D.J. Adamson, C.A. Nash, D.J. McCabe, C.L. Crawford, and W.R. Wilmarth, "Laboratory Evaporation Testing of Hanford Waste Treatment Plant Low Activity Waste Off-gas Condensate Simulant," Savannah River National Laboratory, Aiken, South Carolina, SRNL-STI-2013-00713, 2014.

6. D.J. Adamson, C.A. Nash, D.L. McClane, and D.J. McCabe, "Evaporation of Hanford Waste Treatment Plant Direct Feed Low Activity Waste Effluent Management Facility Core Simulant," Savannah River National Laboratory, Aiken, South Carolina, SRNL-STI-2016-00408, 2016.

Appendix A. Compositional Tables and Make-Up Instructions

A-1. LAW Feed Simulant

Table A- 1. LAW Feed Composition Matrices, values in Molar units

Source Table	Matrix Point ID	TOC	Na	NO_3	NO_2	CO_3	OH	$AlOH_4$	K	SO_4	Cl	PO_4	CrO_4	C_2O_4	F
10-point Matrix	LAW-1	0.123	5.432	2.187	0.962	0.471	1.161	0.117	0.195	0.043	0.076	0.018	0.006	0.004	0.021
10-point Matrix	LAW-2	0.123	5.442	1.925	0.950	0.474	1.342	0.122	0.128	0.049	0.080	0.018	0.007	0.004	0.029
10-point Matrix	LAW-3	0.123	5.282	2.097	0.936	0.494	1.114	0.101	0.217	0.045	0.072	0.018	0.007	0.004	0.025
10-point Matrix	LAW-4	0.123	5.313	2.183	0.921	0.381	1.260	0.113	0.197	0.045	0.077	0.019	0.006	0.004	0.027
10-point Matrix	LAW-5	0.123	5.389	2.160	0.972	0.430	1.229	0.108	0.203	0.044	0.074	0.017	0.008	0.005	0.023
10-point Matrix	LAW-6	0.123	5.320	1.938	1.055	0.394	1.331	0.124	0.179	0.051	0.069	0.018	0.007	0.003	0.020
10-point Matrix	LAW-7	0.123	5.405	2.116	0.938	0.398	1.425	0.100	0.236	0.050	0.068	0.017	0.007	0.003	0.024
10-point Matrix	LAW-8	0.123	5.282	1.719	0.952	0.438	1.546	0.113	0.195	0.046	0.074	0.020	0.007	0.004	0.025
10-point Matrix	LAW-9	0.123	5.350	1.716	0.996	0.484	1.545	0.104	0.249	0.049	0.077	0.017	0.008	0.004	0.021
10-point Matrix	LAW-10	0.123	5.340	1.690	1.009	0.489	1.417	0.106	0.121	0.046	0.075	0.016	0.007	0.005	0.022
25 point Matrix	LAW-11	0.123	5.321	2.186	0.930	0.451	1.132	0.113	0.210	0.050	0.068	0.019	0.007	0.004	0.021
25 point Matrix	LAW-12	0.123	5.352	2.018	0.990	0.442	1.221	0.107	0.122	0.044	0.082	0.016	0.006	0.003	0.017
25 point Matrix	LAW-13	0.123	5.261	2.006	0.996	0.488	1.143	0.116	0.259	0.053	0.082	0.016	0.007	0.004	0.026
25 point Matrix	LAW-14	0.123	5.420	2.128	0.931	0.475	1.197	0.105	0.165	0.051	0.077	0.017	0.006	0.005	0.025
25 point Matrix	LAW-15	0.123	5.359	1.909	1.031	0.517	1.159	0.106	0.148	0.045	0.074	0.019	0.008	0.004	0.023
25 point Matrix	LAW-16	0.123	5.346	2.248	1.013	0.395	1.116	0.116	0.195	0.042	0.073	0.017	0.007	0.004	0.026
25 point Matrix	LAW-17	0.123	5.433	2.137	0.950	0.403	1.431	0.101	0.246	0.043	0.073	0.016	0.007	0.004	0.023
25 point Matrix	LAW-18	0.123	5.280	1.781	1.040	0.396	1.508	0.111	0.226	0.052	0.073	0.020	0.007	0.004	0.018
25 point Matrix	LAW-19	0.123	5.464	1.782	1.072	0.487	1.501	0.122	0.254	0.046	0.079	0.019	0.006	0.004	0.021
25 point Matrix	LAW-20	0.123	5.290	1.676	1.027	0.454	1.501	0.112	0.189	0.043	0.068	0.017	0.006	0.004	0.028

Source Table	Matrix Point ID	TOC	Na	NO_3	NO_2	CO_3	OH	$AlOH_4$	K	SO_4	Cl	PO_4	CrO_4	C_2O_4	F
25 point Matrix	LAW-21	0.123	5.284	1.793	0.905	0.474	1.497	0.113	0.245	0.046	0.081	0.019	0.008	0.004	0.020
25 point Matrix	LAW-22	0.123	5.370	1.614	1.026	0.485	1.571	0.093	0.189	0.051	0.081	0.018	0.008	0.004	0.026
25 point Matrix	LAW-23	0.123	5.343	1.756	0.873	0.471	1.594	0.091	0.174	0.048	0.069	0.019	0.006	0.004	0.021
25 point Matrix	LAW-24	0.123	5.451	2.121	0.945	0.381	1.369	0.103	0.140	0.050	0.083	0.020	0.008	0.004	0.025
25 point Matrix	LAW-25	0.123	5.380	1.786	0.907	0.443	1.565	0.124	0.155	0.047	0.069	0.019	0.008	0.003	0.027
45 point Matrix	LAW-26	0.123	5.336	2.027	1.022	0.400	1.253	0.127	0.155	0.044	0.082	0.018	0.006	0.003	0.021
45 point Matrix	LAW-27	0.123	5.378	2.191	1.026	0.381	1.253	0.108	0.243	0.054	0.073	0.019	0.007	0.003	0.023
45 point Matrix	LAW-28	0.123	5.404	2.195	1.018	0.456	1.129	0.112	0.234	0.048	0.080	0.016	0.007	0.005	0.025
45 point Matrix	LAW-29	0.123	5.286	2.165	1.000	0.410	1.120	0.124	0.199	0.047	0.064	0.016	0.007	0.004	0.025
45 point Matrix	LAW-30	0.123	5.349	2.210	0.951	0.401	1.228	0.095	0.186	0.037	0.075	0.019	0.007	0.004	0.021
45 point Matrix	LAW-31	0.123	5.334	2.057	0.932	0.443	1.301	0.094	0.185	0.047	0.065	0.015	0.006	0.004	0.026
45 point Matrix	LAW-32	0.123	5.316	2.140	0.917	0.464	1.140	0.105	0.199	0.049	0.075	0.021	0.008	0.004	0.024
45 point Matrix	LAW-33	0.123	5.378	2.152	0.877	0.504	1.185	0.125	0.231	0.045	0.073	0.018	0.007	0.003	0.024
45 point Matrix	LAW-34	0.123	5.228	1.698	0.957	0.416	1.502	0.111	0.146	0.049	0.071	0.021	0.005	0.004	0.023
45 point Matrix	LAW-35	0.123	5.325	1.844	1.078	0.404	1.400	0.123	0.179	0.037	0.069	0.019	0.007	0.005	0.027
45 point Matrix	LAW-36	0.123	5.254	1.642	1.002	0.436	1.538	0.097	0.184	0.053	0.076	0.018	0.008	0.004	0.027
45 point Matrix	LAW-37	0.123	5.240	1.681	0.952	0.475	1.425	0.115	0.136	0.041	0.073	0.017	0.008	0.004	0.020
45 point Matrix	LAW-38	0.123	5.326	1.691	1.059	0.510	1.375	0.112	0.215	0.047	0.084	0.019	0.006	0.005	0.026
45 point Matrix	LAW-39	0.123	5.361	1.719	1.046	0.524	1.357	0.106	0.176	0.045	0.073	0.020	0.006	0.003	0.020
45 point Matrix	LAW-40	0.123	5.434	1.638	1.050	0.509	1.541	0.125	0.198	0.045	0.072	0.016	0.007	0.004	0.028
45 point Matrix	LAW-41	0.123	5.334	1.774	0.916	0.451	1.593	0.105	0.211	0.044	0.076	0.016	0.006	0.005	0.023
45 point Matrix	LAW-42	0.123	5.401	1.756	0.891	0.506	1.560	0.106	0.208	0.049	0.084	0.018	0.007	0.003	0.027
45 point Matrix	LAW-43	0.123	5.368	2.117	0.866	0.391	1.460	0.117	0.234	0.045	0.077	0.016	0.008	0.004	0.022
45 point Matrix	LAW-44	0.123	5.461	1.900	1.003	0.425	1.502	0.115	0.176	0.052	0.067	0.019	0.008	0.004	0.019
45 point Matrix	LAW-45	0.123	5.436	2.031	0.930	0.488	1.373	0.107	0.260	0.053	0.065	0.020	0.006	0.005	0.028

Source Table	Matrix Point ID	TOC	Na	NO_3	NO_2	CO_3	OH	$AlOH_4$	K	SO_4	Cl	PO_4	CrO_4	C_2O_4	F
75 point Matrix	LAW-46	0.123	5.298	1.714	0.872	0.454	1.557	0.117	0.148	0.054	0.073	0.019	0.008	0.003	0.019
75 point Matrix	LAW-47	0.123	5.253	1.738	0.908	0.407	1.530	0.108	0.112	0.040	0.078	0.021	0.008	0.004	0.025
75 point Matrix	LAW-48	0.123	5.236	2.064	0.942	0.398	1.183	0.091	0.132	0.051	0.075	0.020	0.009	0.005	0.029
75 point Matrix	LAW-49	0.123	5.211	1.751	0.868	0.463	1.532	0.119	0.268	0.048	0.077	0.019	0.008	0.005	0.029
75 point Matrix	LAW-50	0.123	5.398	2.085	0.891	0.398	1.477	0.109	0.245	0.053	0.078	0.017	0.008	0.005	0.025
75 point Matrix	LAW-51	0.123	5.208	1.674	0.984	0.426	1.557	0.105	0.233	0.051	0.071	0.017	0.006	0.004	0.025
75 point Matrix	LAW-52	0.123	5.217	1.764	1.052	0.395	1.473	0.109	0.211	0.037	0.074	0.015	0.008	0.005	0.021
75 point Matrix	LAW-53	0.123	5.391	2.045	0.999	0.389	1.454	0.098	0.243	0.049	0.065	0.016	0.008	0.003	0.026
75 point Matrix	LAW-54	0.123	5.418	2.158	1.057	0.369	1.379	0.097	0.281	0.047	0.065	0.021	0.007	0.004	0.026
75 point Matrix	LAW-55	0.123	5.479	2.183	0.919	0.407	1.468	0.108	0.258	0.049	0.063	0.016	0.006	0.004	0.017
75 point Matrix	LAW-56	0.123	5.419	1.704	0.987	0.520	1.529	0.130	0.207	0.039	0.073	0.017	0.007	0.004	0.016
75 point Matrix	LAW-57	0.123	5.424	1.726	0.997	0.476	1.551	0.113	0.172	0.042	0.068	0.019	0.007	0.005	0.026
75 point Matrix	LAW-58	0.123	5.336	1.747	1.034	0.437	1.485	0.121	0.204	0.050	0.084	0.020	0.006	0.004	0.015
75 point Matrix	LAW-59	0.123	5.464	1.734	1.037	0.402	1.626	0.127	0.144	0.053	0.075	0.018	0.007	0.003	0.026
75 point Matrix	LAW-60	0.123	5.477	2.129	0.909	0.369	1.461	0.110	0.136	0.045	0.082	0.016	0.006	0.004	0.024
75 point Matrix	LAW-61	0.123	5.285	1.655	1.058	0.498	1.471	0.109	0.280	0.049	0.076	0.018	0.008	0.003	0.025
75 point Matrix	LAW-62	0.123	5.327	1.923	0.955	0.515	1.322	0.092	0.254	0.043	0.070	0.019	0.006	0.003	0.027
75 point Matrix	LAW-63	0.123	5.387	1.775	1.057	0.499	1.307	0.105	0.123	0.049	0.071	0.016	0.008	0.003	0.027
75 point Matrix	LAW-64	0.123	5.293	1.702	0.921	0.507	1.441	0.100	0.142	0.040	0.082	0.017	0.006	0.004	0.022
75 point Matrix	LAW-65	0.123	5.406	2.246	0.889	0.440	1.274	0.119	0.266	0.039	0.081	0.018	0.007	0.003	0.031
75 point Matrix	LAW-66	0.123	5.348	2.144	0.948	0.416	1.341	0.099	0.290	0.045	0.082	0.017	0.006	0.005	0.029
75 point Matrix	LAW-67	0.123	5.314	2.244	0.920	0.409	1.188	0.128	0.262	0.048	0.075	0.021	0.006	0.004	0.024
75 point Matrix	LAW-68	0.123	5.270	2.072	0.971	0.501	1.112	0.100	0.251	0.053	0.065	0.018	0.007	0.004	0.017
75 point Matrix	LAW-69	0.123	5.265	1.854	0.981	0.511	1.178	0.104	0.154	0.055	0.082	0.016	0.006	0.004	0.019
75 point Matrix	LAW-70	0.123	5.434	2.254	0.885	0.473	1.130	0.120	0.162	0.048	0.070	0.019	0.007	0.003	0.021

Source Table	Matrix Point ID	TOC	Na	NO_3	NO_2	CO_3	OH	$AlOH_4$	K	SO_4	Cl	PO_4	CrO_4	C_2O_4	F
75 point Matrix	LAW-71	0.123	5.377	2.055	0.954	0.493	1.136	0.116	0.151	0.049	0.070	0.020	0.006	0.005	0.030
75 point Matrix	LAW-72	0.123	5.316	2.269	0.896	0.416	1.123	0.104	0.157	0.040	0.078	0.016	0.007	0.004	0.021
75 point Matrix	LAW-73	0.123	5.289	2.151	1.027	0.381	1.113	0.108	0.142	0.048	0.072	0.019	0.006	0.004	0.023
75 point Matrix	LAW-74	0.123	5.410	2.254	1.069	0.419	1.096	0.124	0.232	0.048	0.072	0.016	0.008	0.004	0.022
75 point Matrix	LAW-75	0.123	5.414	2.197	0.990	0.478	1.150	0.097	0.240	0.042	0.079	0.019	0.008	0.004	0.018

A-1.1. LAW Feed Simulant Preparation Instructions

The LAW feed simulant is prepared by using the following addition sequence. Values shown in the sequence and in Table A-2 are based on preparation of one liter of simulant. The solution may be heated during preparation to allow faster dissolution, but the temperature should not exceed 50° Celsius. Amounts of each chemical, other than water, are shown in Table A-2.

Step 1. Mix while stirring in a 1L volumetric flask

- ~500 ml Deionized Water
- Sodium Acetate
- Trisodium Citrate
- Tetrasodium EDTA
- Sodium Oxalate
- Aluminum Nitrate
- Sodium Chloride
- Trisodium Phosphate
- Sodium Sulfate
- Sodium Chromate
- Sodium Nitrate
- Potassium Nitrate
- Sodium Fluoride

Step 2. Mix until dissolved

Step 3. Add slowly in order while mixing

- Sodium Hydroxide (double the added mass if using 50 wt% Sodium Hydroxide)
- Sodium Formate
- Sodium Nitrite
- Sodium Carbonate
- Deionized Water (Fill to 1L)

Step 4. Agitate for 24 hours. Do not filter any undissolved solids.

Step 5. Remove stir bar and top off to 1L. Transfer contents to a poly bottle.

LAW Simulant Preparation Precautions

- Safety Data Sheets (SDSs) should be reviewed for all compounds in the simulant formulations.
- Appropriate personal protective equipment as specified on the SDS should be worn when working with chemicals.
- Addition of transition metal nitrates to the initial solutions will produce a very acidic solution.
- Addition of NaOH results in significant heat generation. Add the NaOH slowly to allow heat to dissipate, or cool the mixing container by using external or internal cooling (ice bath, cooling coils, etc.)
- During initial stages of NaOH addition, significant Al solids will form, possibly causing mixing difficulties. The Al solids will return to solution when pH 9 is exceeded.
- Carbonate salts are added after the NaOH to avoid carbonate decomposition.
- Addition of sodium nitrite must occur after addition of NaOH to avoid generation of NOx gas.

Table A- 2. LAW Feed Simulant Addition Amounts, shown in grams per liter of simulant

Matrix Point ID	Potassium Nitrate	Sodium Nitrate	Sodium Nitrite	Sodium Carbonate	Sodium Hydroxide	Aluminum Nitrate	Sodium Sulfate	Sodium Chloride	Trisodium Phosphate	Sodium Chromate	Sodium Oxalate	Sodium Fluoride	Trisodium Citrate	Sodium Formate	Sodium Acetate	Tetrasodium EDTA
LAW-1	19.751	139.376	66.404	49.903	65.233	25.004	6.149	4.426	2.987	1.014	0.471	0.863	9.522	2.510	3.027	4.726
LAW-2	12.930	121.635	65.537	50.263	73.223	26.008	7.030	4.664	2.895	1.169	0.473	1.208	9.522	2.510	3.027	4.726
LAW-3	21.897	134.170	64.596	52.325	60.625	21.413	6.451	4.203	2.989	1.189	0.515	1.036	9.522	2.510	3.027	4.726
LAW-4	19.916	139.875	63.565	40.333	68.541	24.146	6.447	4.492	3.045	0.983	0.582	1.121	9.522	2.510	3.027	4.726
LAW-5	20.555	138.845	67.095	45.621	66.399	22.948	6.265	4.348	2.772	1.258	0.672	0.979	9.522	2.510	3.027	4.726
LAW-6	18.105	117.826	72.821	41.742	73.093	26.456	7.207	4.037	2.896	1.080	0.460	0.825	9.522	2.510	3.027	4.726
LAW-7	23.900	134.306	64.727	42.222	72.993	21.295	7.123	3.984	2.824	1.140	0.459	1.008	9.522	2.510	3.027	4.726
LAW-8	19.714	100.672	65.682	46.374	79.936	24.082	6.466	4.317	3.250	1.142	0.566	1.033	9.522	2.510	3.027	4.726
LAW-9	25.197	98.272	68.727	51.254	78.361	22.077	6.963	4.479	2.868	1.215	0.487	0.901	9.522	2.510	3.027	4.726
LAW-10	12.229	106.265	69.635	51.802	73.662	22.624	6.532	4.363	2.687	1.121	0.619	0.938	9.522	2.510	3.027	4.726
LAW-11	21.212	139.047	64.190	47.812	63.427	24.142	7.034	3.956	3.176	1.121	0.506	0.874	9.522	2.510	3.027	4.726
LAW-12	12.356	133.766	68.284	46.870	66.015	22.855	6.281	4.775	2.658	0.960	0.406	0.696	9.522	2.510	3.027	4.726
LAW-13	26.191	118.931	68.712	51.770	64.282	24.704	7.502	4.820	2.564	1.137	0.481	1.091	9.522	2.510	3.027	4.726
LAW-14	16.638	140.195	64.217	50.332	64.621	22.315	7.255	4.481	2.715	0.933	0.632	1.046	9.522	2.510	3.027	4.726
LAW-15	14.964	122.548	71.150	54.774	63.403	22.681	6.429	4.342	3.065	1.291	0.546	0.953	9.522	2.510	3.027	4.726
LAW-16	19.730	145.028	69.861	41.861	63.154	24.637	5.919	4.257	2.867	1.174	0.570	1.099	9.522	2.510	3.027	4.726
LAW-17	24.864	134.886	65.561	42.679	73.429	21.583	6.172	4.247	2.677	1.173	0.552	0.961	9.522	2.510	3.027	4.726
LAW-18	22.825	103.960	71.757	41.927	78.012	23.580	7.356	4.286	3.241	1.089	0.544	0.752	9.522	2.510	3.027	4.726
LAW-19	25.679	98.717	73.962	51.581	79.575	26.018	6.464	4.619	3.158	0.915	0.504	0.883	9.522	2.510	3.027	4.726
LAW-20	19.099	97.802	70.834	48.106	77.985	23.878	6.125	3.982	2.855	1.037	0.573	1.157	9.522	2.510	3.027	4.726
LAW-21	24.728	102.927	62.466	50.255	77.883	23.970	6.538	4.708	3.046	1.254	0.573	0.841	9.522	2.510	3.027	4.726
LAW-22	19.145	97.380	70.760	51.361	77.719	19.791	7.248	4.737	2.896	1.248	0.563	1.103	9.522	2.510	3.027	4.726
LAW-23	17.573	111.145	60.200	49.955	78.367	19.474	6.754	4.048	3.054	0.974	0.518	0.869	9.522	2.510	3.027	4.726
LAW-24	14.181	141.984	65.191	40.398	71.272	21.998	7.065	4.835	3.329	1.330	0.481	1.038	9.522	2.510	3.027	4.726
LAW-25	15.716	106.973	62.555	46.931	82.398	26.390	6.615	4.033	3.062	1.306	0.464	1.150	9.522	2.510	3.027	4.726

Matrix Point ID	Potassium Nitrate	Sodium Nitrate	Sodium Nitrite	Sodium Carbonate	Sodium Hydroxide	Aluminum Nitrate	Sodium Sulfate	Sodium Chloride	Trisodium Phosphate	Sodium Chromate	Sodium Oxalate	Sodium Fluoride	Trisodium Citrate	Sodium Formate	Sodium Acetate	Tetrasodium EDTA
LAW-26	15.687	126.684	70.490	42.351	70.472	27.110	6.215	4.770	2.929	1.018	0.438	0.877	9.522	2.510	3.027	4.726
LAW-27	24.543	138.174	70.821	40.420	67.341	22.908	7.628	4.290	3.084	1.105	0.407	0.957	9.522	2.510	3.027	4.726
LAW-28	23.665	138.073	70.239	48.331	63.098	23.890	6.829	4.667	2.675	1.114	0.608	1.030	9.522	2.510	3.027	4.726
LAW-29	20.126	135.614	69.008	43.449	64.572	26.309	6.722	3.767	2.600	1.173	0.592	1.069	9.522	2.510	3.027	4.726
LAW-30	18.835	147.664	65.608	42.541	64.360	20.300	5.296	4.392	3.129	1.108	0.527	0.863	9.522	2.510	3.027	4.726
LAW-31	18.728	135.214	64.271	46.951	67.003	19.942	6.705	3.797	2.519	0.959	0.473	1.096	9.522	2.510	3.027	4.726
LAW-32	20.135	138.232	63.281	49.230	62.392	22.360	6.958	4.367	3.383	1.273	0.578	1.024	9.522	2.510	3.027	4.726
LAW-33	23.361	131.408	60.519	53.426	67.382	26.591	6.369	4.244	2.966	1.185	0.398	1.028	9.522	2.510	3.027	4.726
LAW-34	14.801	103.456	66.013	44.124	77.869	23.713	7.029	4.126	3.384	0.887	0.570	0.976	9.522	2.510	3.027	4.726
LAW-35	18.132	110.243	74.356	42.862	75.618	26.102	5.260	4.059	3.132	1.089	0.627	1.139	9.522	2.510	3.027	4.726
LAW-36	18.575	99.162	69.115	46.242	77.055	20.689	7.536	4.426	2.952	1.332	0.504	1.121	9.522	2.510	3.027	4.726
LAW-37	13.736	101.897	65.703	50.371	75.462	24.574	5.843	4.256	2.862	1.343	0.558	0.825	9.522	2.510	3.027	4.726
LAW-38	21.745	97.010	73.086	54.103	72.868	23.778	6.629	4.905	3.142	0.970	0.653	1.091	9.522	2.510	3.027	4.726
LAW-39	17.780	104.240	72.138	55.502	71.175	22.502	6.442	4.265	3.213	1.027	0.428	0.848	9.522	2.510	3.027	4.726
LAW-40	20.027	90.587	72.412	53.988	81.578	26.569	6.443	4.202	2.597	1.146	0.497	1.194	9.522	2.510	3.027	4.726
LAW-41	21.366	106.063	63.169	47.827	80.500	22.366	6.237	4.448	2.566	0.998	0.627	0.977	9.522	2.510	3.027	4.726
LAW-42	21.044	104.468	61.443	53.674	79.394	22.628	6.921	4.918	3.009	1.102	0.452	1.134	9.522	2.510	3.027	4.726
LAW-43	23.611	130.205	59.728	41.436	77.144	24.942	6.330	4.492	2.678	1.254	0.524	0.922	9.522	2.510	3.027	4.726
LAW-44	17.840	117.151	69.190	45.024	78.457	24.475	7.318	3.930	3.040	1.260	0.592	0.786	9.522	2.510	3.027	4.726
LAW-45	26.312	123.094	64.164	51.676	72.082	22.869	7.547	3.778	3.214	1.032	0.616	1.195	9.522	2.510	3.027	4.726
LAW-46	14.949	103.213	60.176	48.106	81.009	24.949	7.691	4.274	3.040	1.296	0.464	0.780	9.522	2.510	3.027	4.726
LAW-47	11.354	110.609	62.633	43.114	78.505	23.029	5.644	4.530	3.374	1.292	0.483	1.071	9.522	2.510	3.027	4.726
LAW-48	13.318	140.892	65.026	42.218	61.925	19.463	7.219	4.361	3.215	1.422	0.644	1.206	9.522	2.510	3.027	4.726
LAW-49	27.051	95.822	59.918	49.022	80.262	25.302	6.864	4.477	3.082	1.259	0.619	1.235	9.522	2.510	3.027	4.726
LAW-50	24.802	128.514	61.460	42.175	76.550	23.266	7.524	4.529	2.811	1.331	0.611	1.060	9.522	2.510	3.027	4.726
LAW-51	23.592	95.645	67.895	45.126	79.121	22.405	7.234	4.135	2.820	0.947	0.547	1.051	9.522	2.510	3.027	4.726

Matrix Point ID	Potassium Nitrate	Sodium Nitrate	Sodium Nitrite	Sodium Carbonate	Sodium Hydroxide	Aluminum Nitrate	Sodium Sulfate	Sodium Chloride	Trisodium Phosphate	Sodium Chromate	Sodium Oxalate	Sodium Fluoride	Trisodium Citrate	Sodium Formate	Sodium Acetate	Tetrasodium EDTA
LAW-52	21.363	104.122	72.597	41.826	76.387	23.276	5.253	4.318	2.527	1.262	0.623	0.895	9.522	2.510	3.027	4.726
LAW-53	24.563	128.111	68.943	41.258	73.891	20.947	7.009	3.776	2.581	1.315	0.436	1.072	9.522	2.510	3.027	4.726
LAW-54	28.417	134.814	72.949	39.082	70.638	20.620	6.667	3.777	3.446	1.155	0.598	1.096	9.522	2.510	3.027	4.726
LAW-55	26.129	135.983	63.421	43.154	76.061	23.083	6.919	3.661	2.565	0.942	0.539	0.724	9.522	2.510	3.027	4.726
LAW-56	20.971	94.143	68.117	55.073	81.862	27.591	5.472	4.270	2.764	1.151	0.518	0.656	9.522	2.510	3.027	4.726
LAW-57	17.381	103.182	68.822	50.409	80.137	24.119	5.897	3.956	3.160	1.055	0.627	1.108	9.522	2.510	3.027	4.726
LAW-58	20.645	100.212	71.308	46.304	78.796	25.813	7.056	4.924	3.268	1.024	0.537	0.649	9.522	2.510	3.027	4.726
LAW-59	14.602	102.666	71.519	42.643	85.386	27.077	7.525	4.362	2.943	1.095	0.413	1.086	9.522	2.510	3.027	4.726
LAW-60	13.709	141.335	62.736	39.118	76.042	23.453	6.420	4.766	2.633	1.009	0.558	1.025	9.522	2.510	3.027	4.726
LAW-61	28.335	89.136	72.986	52.734	76.214	23.151	7.020	4.420	3.008	1.310	0.448	1.058	9.522	2.510	3.027	4.726
LAW-62	25.715	118.313	65.896	54.613	67.644	19.673	6.146	4.104	3.057	0.971	0.408	1.153	9.522	2.510	3.027	4.726
LAW-63	12.451	113.530	72.924	52.932	69.155	22.461	6.904	4.151	2.700	1.260	0.444	1.123	9.522	2.510	3.027	4.726
LAW-64	14.306	107.085	63.538	53.707	73.699	21.375	5.665	4.820	2.842	1.015	0.502	0.923	9.522	2.510	3.027	4.726
LAW-65	26.844	137.910	61.347	46.600	70.073	25.424	5.496	4.724	2.881	1.183	0.404	1.308	9.522	2.510	3.027	4.726
LAW-66	29.323	132.320	65.418	44.091	69.517	21.123	6.395	4.802	2.761	0.907	0.636	1.228	9.522	2.510	3.027	4.726
LAW-67	26.458	135.853	63.474	43.315	67.982	27.251	6.850	4.409	3.398	1.029	0.535	0.987	9.522	2.510	3.027	4.726
LAW-68	25.353	129.294	66.983	53.054	60.499	21.307	7.515	3.788	2.936	1.205	0.542	0.712	9.522	2.510	3.027	4.726
LAW-69	15.530	117.930	67.710	54.131	63.784	22.203	7.852	4.771	2.607	0.966	0.577	0.807	9.522	2.510	3.027	4.726
LAW-70	16.352	147.164	61.052	50.085	64.400	25.592	6.836	4.072	3.049	1.094	0.441	0.863	9.522	2.510	3.027	4.726
LAW-71	15.298	132.206	65.845	52.249	64.016	24.726	6.962	4.088	3.312	1.043	0.639	1.249	9.522	2.510	3.027	4.726
LAW-72	15.909	152.994	61.826	44.134	61.531	22.098	5.694	4.578	2.562	1.103	0.583	0.872	9.522	2.510	3.027	4.726
LAW-73	14.350	143.141	70.892	40.364	61.883	23.094	6.860	4.199	3.109	1.014	0.494	0.972	9.522	2.510	3.027	4.726
LAW-74	23.491	140.166	73.773	44.445	63.686	26.431	6.837	4.212	2.557	1.232	0.571	0.923	9.522	2.510	3.027	4.726
LAW-75	24.238	141.589	68.339	50.660	61.565	20.708	6.011	4.641	3.081	1.310	0.557	0.738	9.522	2.510	3.027	4.726

A-2. GFC Simulant

GFC simulants are prepared by blending the GFCs in the amounts shown in Table A- 3 to make 100 grams of Oxides.

Table A- 3. GFC Simulant Addition Amounts

Target	Al_2O_3	B_2O_3	CaO	Fe_2O_3	Li_2O	MgO	SiO_2	SnO_2*	TiO_2	V_2O_5*	ZnO	ZrO_2	Sugar
Source	Kyanite	Boric Acid	Wollastonite	Hematite	Lithium Carbonate	Olivine	Silica	Tin Oxide	Rutile	Vanadium oxide	Zinc Oxide	Zircon	glucose
Compound	Al_2SiO_5	H_3BO_3	$CaSiO_3$	Fe_2O_3	Li_2CO_3	Mg_2SiO_4	SiO_2	SnO_2	TiO_2	V_2O_5	ZnO	$ZrSiO_4$	$C_{12}H_{22}O_{11}$
	grams	grams	grams	grams	grams	grams	grams	grams	grams	grams	grams	grams	grams
GFC-1	28.4	14.4	30.0	0.0	0.0	0.0	29.8	6.8	0.0	11.0	0.8	0.0	9.1
GFC-2	9.4	14.4	9.5	0.0	16.3	0.0	83.4	0.0	0.0	11.0	7.4	0.0	9.1
GFC-3	28.4	14.4	0.0	0.0	0.0	0.0	73.0	0.0	0.0	0.0	0.0	13.7	9.1
GFC-4	9.4	33.2	0.0	0.0	0.0	16.8	78.0	6.8	0.0	0.0	0.0	0.0	9.1
GFC-5	28.4	33.2	0.0	0.0	0.0	16.8	42.1	0.0	0.0	11.0	6.7	0.0	9.1
GFC-6	28.4	33.2	28.4	0.0	16.3	0.0	31.1	0.0	0.0	0.0	0.0	0.0	9.1
GFC-7	9.4	14.4	30.0	0.0	16.3	16.8	26.5	0.0	0.0	11.0	0.0	13.7	9.1
GFC-8	28.4	14.4	0.0	0.0	16.3	16.8	38.3	6.8	0.0	0.0	7.4	7.9	9.1
GFC-9	9.4	29.5	30.0	0.0	0.0	0.0	33.6	0.0	0.0	0.0	7.4	13.7	9.1
GFC-10	16.1	33.2	0.0	0.0	16.3	0.0	52.8	6.8	0.0	11.0	0.0	13.7	9.1
GFC-11	19.6	23.4	12.8	0.0	8.2	6.7	48.9	2.7	0.0	5.5	3.0	6.3	12.2
GFC-12	28.4	14.4	30.0	0.0	0.0	0.0	29.8	6.8	0.0	11.0	0.8	0.0	15.3
GFC-13	9.4	14.4	9.5	0.0	16.3	0.0	83.4	0.0	0.0	11.0	7.4	0.0	15.3
GFC-14	28.4	14.4	0.0	0.0	0.0	0.0	73.0	0.0	0.0	0.0	0.0	13.7	15.3
GFC-15	9.4	33.2	0.0	0.0	0.0	16.8	78.0	6.8	0.0	0.0	0.0	0.0	15.3
GFC-16	28.4	33.2	0.0	0.0	0.0	16.8	42.1	0.0	0.0	11.0	6.7	0.0	15.3
GFC-17	28.4	33.2	28.4	0.0	16.3	0.0	31.1	0.0	0.0	0.0	0.0	0.0	15.3
GFC-18	9.4	14.4	30.0	0.0	16.3	16.8	26.5	0.0	0.0	11.0	0.0	13.7	15.3
GFC-19	28.4	14.4	0.0	0.0	16.3	16.8	38.3	6.8	0.0	0.0	7.4	7.9	15.3
GFC-20	9.4	29.5	30.0	0.0	0.0	0.0	33.6	0.0	0.0	0.0	7.4	13.7	15.3
GFC-21	16.1	33.2	0.0	0.0	16.3	0.0	52.8	6.8	0.0	11.0	0.0	13.7	15.3
GFC-2009	11.0	22.1	10.2	13.7	0.0	6.5	63.5	0.0	1.8	0.0	4.4	5.5	7.0

*Sn and V are shown in red since they do not have a specified GFC compound.

A-3. EMF Feed Simulant Input Matrix

Table A- 4. Statistical Matrix for EMF Feed Simulant (Molar units)

	NO_3^-	**Cl^-**	**Na^+**	**$NH4^+$**	**SO_4^{-2}**	**F^-**	**K^+**	CrO_4^{-2}	$Al(OH)_4^-$	PO_4^{-3}	H^+	Se^{+6}	Hg^{+2}	As^{+5}	Sb^{+5}	Pb^{+2}
EMF-1	0.060	0.050	0.058	0.059	0.0082	0.0135	0.0071	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-2	0.060	0.049	0.055	0.063	0.0084	0.0153	0.0075	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-3	0.059	0.048	0.059	0.063	0.0136	0.0135	0.0096	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-4	0.067	0.049	0.059	0.062	0.0084	0.0143	0.0094	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-5	0.063	0.049	0.055	0.061	0.0091	0.0138	0.0118	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-6	0.059	0.053	0.059	0.059	0.0098	0.0137	0.0115	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-7	0.061	0.055	0.057	0.063	0.0086	0.0131	0.0107	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-8	0.059	0.051	0.059	0.063	0.0078	0.0198	0.0070	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-9	0.060	0.050	0.058	0.062	0.0085	0.0205	0.0115	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003
EMF-10 (center)	0.061	0.051	0.058	0.061	0.0090	0.0153	0.0098	0.0005	0.0002	0.0002	0.0169	0.000045	0.000016	0.000031	0.000017	0.000003

A-3.1. EMF Feed Simulant Preparation Instructions

Step 1. Add 800 grams of water to a 1L volumetric flask.

Step 2. Add reagents as shown in the Table A- 5. (Se, Hg, As, Sb, Tl, and Pb may be omitted if desired.)

Step 3. Mix for 1 hour.

Step 4. Remove stir bar and fill to 1L with water.

Step 5. Transfer contents to a polybottle.

Step 6. While mixing, add GFCs as shown in Table A- 6. Choose either the GFC-2009 or GFC-11 model values. (Note: If making evaporator feed simulant, only boric acid and lithium carbonate need to be added.)

Step 7. Mix for 1 hour.

Step 8. If making EMF evaporator feed simulant:

Step 7.1. Filter the slurry through a 10-micron filter and discard solids.

Step 7.2. While mixing, add 50 wt% NaOH solution to the simulant to adjust pH to 12.

Table A- 5. EMF Feed Simulant Supernate Addition Amounts, shown in grams

	$NaNO_3$	NaCl	NH_4NO_3	NH_4Cl	Na_2SO_4	NaF	KF	Na_2CrO_4	$NaAlO_2$	Na_2HPO_4-$2H_2O$	HCl	$Se(NO_3)_6$	$Hg(NO_3)_2$	$As(NO_3)_5$	$Sb(NO_3)^5$	$Pb(NO_3)_2$
EMF-1	0.0608	1.9159	4.6946	0.0000	1.1585	0.2664	0.4138	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-2	0.0000	1.6774	4.7929	0.1728	1.1919	0.3299	0.4339	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-3	0.0000	1.5529	4.6703	0.2629	1.9241	0.1647	0.5577	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-4	0.3662	1.8561	4.9899	0.0000	1.1884	0.2067	0.5456	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-5	0.1254	1.8534	4.8570	0.0000	1.2987	0.0844	0.6836	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-6	0.0006	2.0924	4.7032	0.0000	1.3969	0.0941	0.6657	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-7	0.0000	2.1036	4.8344	0.1190	1.2173	0.0998	0.6214	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-8	0.0000	1.7086	4.6653	0.2366	1.1135	0.5353	0.4074	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-9	0.0000	1.7789	4.7287	0.1392	1.2042	0.3758	0.6705	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010
EMF-10	0.0000	1.9048	4.8264	0.0563	1.2725	0.2305	0.5699	0.0810	0.0164	0.0314	0.6169	0.0203	0.0052	0.0119	0.0073	0.0010

Table A- 6. EMF Feed Simulant GFC Additions (Amounts in grams)

Material	Formula	Suggested Vendor	GFC-2009	GFC-11
Kyanite (325 Mesh)	Al_2SiO_5	Kyanite Mining Corp	0.608	1.097
Boric Acid (Technical - Granular)*	H_3BO_3	U.S. Borax	1.222	1.309
Wollastonite (NYAD 325 Mesh)	$CaSiO_3$	NYCO	0.564	0.716
Ferric Oxide (Prince 5001, -325 Mesh)**	Fe_2O_3	Prince Manufacturing Co.	0.758	0.000
Lithium Carbonate (Technical Grade)	Li_2CO_3	Chemettal-Foote	0.000	0.459
Olivine (325 Mesh, #LE170)	Mg_2SiO_4	Unimin Corp	0.359	0.375
Silica (Sil-Co-Sil 75)	SiO_2	U.S. Silica	3.512	2.736
Tin oxide (~325 mesh)***	SnO_2	NA	0.000	0.151
Titanium Dioxide (Rutile 94)	TiO_2	Chemalloy Co.	0.100	0.000
Vanadium Oxide (~325 mesh)***	V_2O_5	NA	0.000	0.308
Zinc Oxide (K-920)	ZnO	Zinc Corp of America	0.243	0.168
Zircon (Flour, 325 Mesh)	$ZrSiO_4$	Prince Minerals Inc.	0.304	0.352

Suggested vendors are based on GFC specifications recommended by VSL.
* Only boric acid and lithium carbonate must be added if filtering simulant to make evaporator feed simulant.
** The ferric oxide vendor no longer offers the Prince 5001 product. A different ferric oxide must be substituted
*** Recommendations for suggested vendors have not been made for the tin and vanadium oxides.

A-4. EMF Concentrate Simulant Preparation

Step 1. Add 700 grams of water to a 1L volumetric flask.

Step 2. Add reagents as shown in Table A- 7, except for NaOH.

Step 3. Mix for 1 hour.

Step 4. While mixing, add the NaOH solution (double the added mass if using 50 wt% Sodium Hydroxide).

Step 5. Mix for 30 minutes.

Steo 6. Remove stir bar and fill to 1L with water

Step 7. Transfer contents to a polybottle.

Step 8. While mixing, add GFCs as shown in Table A- 8. Choose either the GFC-2009 or GFC-11 model values.

Step 9. Mix for 1 hour.

Table A- 7. EMF Concentrate Supernate Chemical Additions

Evaporator Turn Down		10x	15x	20x
Material	Formula	Grams	Grams	Grams
Ammonium nitrate	NH_4NO_3	44.080	66.120	88.160
Sodium Chloride	NaCl	18.859	28.289	37.719
Sodium Sulfate	Na_2SO_4	7.894	11.841	15.788
Sodium Fluoride	NaF	2.354	3.531	4.708
Potassium Fluoride	KF	1.814	2.721	3.628
Sodium chromate	Na_2CrO_4	0.608	0.912	1.216
Sodium Aluminate	$NaAlO_2$	0.120	0.180	0.240
Dibasic Sodium Phosphate Dihydrate	$Na_2HPO_4.2H_2O$	0.211	0.317	0.422
Hydrochloric Acid	HCl	4.644	6.965	9.287
Sodium Hydroxide (50% solution)	NaOH	80.057	120.085	160.113

Table A- 8. EMF Concentrate Simulant GFC Additions (in grams) Per Liter of Simulant

			GFC-2019 Additions			GFC-11 Additions		
Evaporator Turn Down			10x	15x	20x	10x	15x	20x
Material	Formula	Suggested Vendor						
Kyanite (325 Mesh)	Al_2SiO_5	Kyanite Mining Corp	6.083	9.125	12.166	10.966	16.448	21.931
Boric Acid (Technical - Granular)	H_3BO_3	U.S. Borax	12.222	18.332	24.443	13.092	19.637	26.183
Wollastonite (NYAD 325 Mesh)	$CaSiO_3$	NYCO	5.641	8.461	11.281	7.161	10.742	14.322
Ferric Oxide (Prince 5001, -325 Mesh)	Fe_2O_3	Prince Manufacturing Co.	7.576	11.364	15.153	0.000	0.000	0.000
Lithium Carbonate (Technical grade_	Li_2CO_3	Chemettal-Foote	0.000	0.000	0.000	4.588	6.881	9.175
Olivine (325 Mesh, #LE170)	Mg_2SiO_4	Unimin Corp	3.595	5.392	7.189	3.748	5.623	7.497
Silica (Sil-Co-Sil 75)	SiO_2	U.S. Silica	35.116	52.675	70.233	27.358	41.037	54.716
Tin oxide (~325 mesh)	SnO_2	NA	0.000	0.000	0.000	1.511	2.266	3.021
Titanium Dioxide (Rutile 94)	TiO_2	Chemalloy Co.	0.995	1.493	1.991	0.000	0.000	0.000
Vanadium Oxide (~325 mesh)	V_2O_5	NA	0.000	0.000	0.000	3.077	4.616	6.154
Zinc Oxide (K-920)	ZnO	Zinc Corp of America	2.433	3.650	4.867	1.678	2.518	3.357
Zircon (Flour, 325 Mesh)	$ZrSiO_4$	Prince Minerals Inc.	3.042	4.562	6.083	3.525	5.287	7.049

A-5. CRV Simulant Preparation Instructions

The CRV simulant is prepared by using the following addition sequence. Values shown in the sequence and in the recipe tables are based on preparation of 1L of simulant. The solution may be warmed during preparation to allow faster dissolution, but temperature should not exceed 50° Celsius. Amounts of each chemical, other than water, are shown in Table A- 9 and Table A- 10.

Step 1. Mix while stirring in a 1L volumetric flask

- ~500 ml Deionized Water
- Sodium Acetate
- Trisodium Citrate
- Tetrasodium EDTA
- Sodium Oxalate
- Aluminum Nitrate
- Sodium Chloride
- Sodium Dihydrogen Phosphate
- Dibasic sodium phosphate
- Sodium Sulfate
- Sodium Nitrate
- Potassium Nitrate
- Sodium chromate
- Ammonium nitrate

Step 2. Mix until dissolved

Step 3. Add slowly in order while mixing

- Hydrochloric acid
- Sodium Hydroxide (double the added mass if using 50 wt% Sodium Hydroxide))
- Sodium Formate
- Sodium Nitrite
- Sodium Carbonate

- Potassium Carbonate
- Sodium Aluminate
- Potassium Fluoride
- GFC chemicals (Table A- 10).
- Deionized Water (Fill to 1L)

Step 4. Agitate for 24 hours. Do not filter any undissolved solids.

CRV Simulant Preparation Precautions

- SDSs should be reviewed for all compounds in the simulant formulations.
- Appropriate personal protective equipment as specified on the SDS should be worn when working with chemicals.
- Addition of transition metal nitrates to the initial solutions will produce a very acidic solution.
- Addition of NaOH results in significant heat generation. Add the NaOH slowly to allow heat to dissipate, or cool the mixing container by using external or internal cooling (ice bath, cooling coils, etc.)
- During initial stages of NaOH addition, significant Al solids will form, possibly causing mixing difficulties. The Al solids will return to solution when pH 9 is exceeded.
- Carbonate salts are added after the NaOH to avoid carbonate decomposition.
- Addition of sodium nitrite must occur after addition of NaOH to avoid generation of NOx gas.
- Ammonium nitrate will decompose and emit ammonia gas when sodium hydroxide is added to mixture.

Table A- 9. CRV Chemical Additions

Matrix ID	Potassium Nitrate	Sodium Nitrate	Sodium Nitrite	Sodium Carbonate	Sodium Hydroxide	Aluminum Nitrate	Sodium Sulfate	Sodium Chloride	Sodium Phosphate	Sodium Chromate	Sodium Oxalate	Sodium Fluoride	Trisodium Citrate	Sodium Formate	Sodium Acetate	Tetrasodium EDTA	Ammonium nitrate	Potassium Fluoride	Sodium Aluminate	Dibasic Sodium Phosphate Dihydrate	Hydrochloric Acid
	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L
CRV-1	13.58	95.79	45.64	34.30	79.60	17.19	7.65	11.23	2.05	0.96	0.32	1.62	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-2	8.89	83.60	45.04	34.55	85.10	17.88	8.26	11.40	1.99	1.07	0.32	1.85	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-3	15.05	92.22	44.40	35.96	76.44	14.72	7.86	11.08	2.05	1.08	0.35	1.73	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-4	13.69	96.14	43.69	27.72	81.88	16.60	7.86	11.28	2.09	0.94	0.40	1.79	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-5	14.13	95.43	46.12	31.36	80.40	15.77	7.73	11.18	1.90	1.13	0.46	1.70	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-6	12.44	80.98	50.05	28.69	85.01	18.18	8.38	10.97	1.99	1.01	0.32	1.59	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-7	16.43	92.31	44.49	29.02	84.94	14.64	8.32	10.93	1.94	1.05	0.32	1.72	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-8	13.55	69.19	45.14	31.87	89.71	16.55	7.87	11.16	2.23	1.05	0.39	1.73	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-9	17.32	67.54	47.24	35.23	88.63	15.17	8.21	11.27	1.97	1.10	0.33	1.64	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-10	8.40	73.04	47.86	35.60	85.40	15.55	7.92	11.19	1.85	1.03	0.43	1.67	6.54	1.72	2.08	3.25	19.14	0.79	0.05	0.09	2.02
CRV-11	17.97	126.83	60.43	45.41	69.37	22.75	6.58	6.38	2.72	1.00	0.43	1.08	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-12	11.77	110.69	59.64	45.74	76.64	23.67	7.38	6.60	2.63	1.14	0.43	1.39	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-13	19.93	122.09	58.78	47.62	65.18	19.49	6.86	6.18	2.72	1.16	0.47	1.24	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-14	18.12	127.29	57.84	36.70	72.38	21.97	6.85	6.45	2.77	0.97	0.53	1.31	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-15	18.71	126.35	61.06	41.52	70.43	20.88	6.69	6.31	2.52	1.22	0.61	1.19	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-16	16.48	107.22	66.27	37.99	76.52	24.08	7.55	6.03	2.63	1.06	0.42	1.04	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-17	21.75	122.22	58.90	38.42	76.43	19.38	7.47	5.98	2.57	1.11	0.42	1.21	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-18	17.94	91.61	59.77	42.20	82.75	21.91	6.87	6.29	2.96	1.12	0.52	1.23	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-19	22.93	89.43	62.54	46.64	81.32	20.09	7.32	6.43	2.61	1.18	0.44	1.11	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58
CRV-20	11.13	96.70	63.37	47.14	77.04	20.59	6.93	6.33	2.45	1.10	0.56	1.15	8.67	2.28	2.75	4.30	5.51	0.23	0.01	0.03	0.58

Shaded rows are maximum recycle matrix. Non-shaded rows are nominal recycle.

Table A- 10. CRV GFC Additions From Carryover

Maximum Recycle	Kyanite (325 Mesh)	Boric Acid (Technical - Granular)	Wollastonite (NYAD 325 Mesh)	Ferric Oxide (Prince 5001, -325 Mesh)	Lithium Carbonate	Olivine (325 Mesh, #LE170)	Silica (Sil-Co-Sil 75)	Tin oxide (~325 mesh)	Titanium Dioxide (Rutile 94)	Vanadium Oxide (~325 mesh)	Zinc Oxide (K-920)	Zircon (Flour, 325 Mesh)
Matrix ID	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L
CRV-1	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-2	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-3	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-4	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-5	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-6	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-7	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-8	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-9	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
CRV-10	2.64	5.31	2.45	3.29	0.00	1.56	15.25	0.00	0.43	0.00	1.06	1.32
Average Recycle	Kyanite (325 Mesh)	Boric Acid (Technical - Granular)	Wollastonite (NYAD 325 Mesh)	Ferric Oxide (Prince 5001, -325 Mesh)	Lithium Carbonate	Olivine (325 Mesh, #LE170)	Silica (Sil-Co-Sil 75)	Tin oxide (~325 mesh)	Titanium Dioxide (Rutile 94)	Vanadium Oxide (~325 mesh)	Zinc Oxide (K-920)	Zircon (Flour, 325 Mesh)
Matrix ID	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L	g/L
CRV-11	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-12	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-13	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-14	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-15	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-16	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-17	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-18	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-19	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38
CRV-20	0.76	1.53	0.71	0.95	0.00	0.45	4.39	0.00	0.12	0.00	0.30	0.38

Distribution:

alex.cozzi@srnl.doe.gov
david.crowley@srnl.doe.gov
c.diprete@srnl.doe.gov
a.fellinger@srnl.doe.gov
erich.hansen@srnl.doe.gov
connie.herman@srnl.doe.gov
patricia.lee@srnl.doe.gov
Joseph.Manna@srnl.doe.gov
john.mayer@srnl.doe.gov
daniel.mccabe@srnl.doe.gov
Gregg.Morgan@srnl.doe.gov
frank.pennebaker@srnl.doe.gov
William.Ramsey@SRNL.DOE.gov
michael.stone@srnl.doe.gov
Boyd.Wiedenman@srnl.doe.gov
Records Administration (EDWS)
Anthony.Howe@srnl.doe.gov
Matthew.Siegfried@srnl.doe.gov
mailto:Christine.langton@srnl.doe.gov
daniel.mccabe@srnl.doe.gov
Richard.wyrwas@srnl.doe.gov
Elaine_N_Porcaro@orp.doe.gov
Isabelle_wheeler@orp.doe.gov
Rlakis@lanl.gov
annjunghans@lanl.gov
skocevska@gatech.edu
martha.grover@chbe.gatech.edu
rwr@gatech.edu
dongsang.kim@pnnl.gov
sam.bryan@pnnl.gov
Michael.Minette@pnnl.gov
John.Vienna@pnnl.go
Amanda.Lines@pnnl.gov