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LEACHING SAVANNAH RIVER PLANT NUCLEAR WASTE GLASS IN A SATURATED TUFF ENVIRONMENT

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ABSTRACT

Samples of SRP glass containing either simulated or actual radioactive waste were leached at 90°C under conditions simulating a saturated tuff repository environment. The leach vessels were fabricated of tuff and actual tuff groundwater was used. Thus, the glass was leached only in the presence of those materials (including the Type 304L stainless steel canister material) that would be in the actual repository. Tests were performed for time periods up to 6 months at a SA/V ratio of 100 m^{-1}. Results with glass containing simulated waste indicated that stainless steel canister material around the glass did not significantly affect the leaching. Based on Li and B (elements not in significant concentrations in the tuff or tuff groundwater), glass containing simulated waste leached identically to glass containing actual radioactive waste. The tuff buffered the pH so that only a slight increase was observed as a result of leaching. Results with glass containing actual radioactive waste indicated that tuff reduced the concentrations of Cs-137, Sr-90, and Pu-238 in the free groundwater in the simulated repository by 10-100X. Also, radiolysis of the groundwater by the glass (approximately 1000 rad/hr) did not significantly affect the pH in the presence of tuff. Measured normalized mass losses in the presence of tuff for the glass based on Cs-137, Sr-90, and Pu-238 in the free groundwater were extremely low, nominally 0.02, 0.02, and 0.005 g/m^2, respectively, indicating that the glass-tuff system retained radionuclides well.

INTRODUCTION

Savannah River Laboratory (SRL) and Lawrence Livermore National Laboratory (LLNL), as participants in the Nevada Nuclear Waste Storage Investigations Project (NNWSI), have a joint program investigating the performance of waste packages containing Savannah River Plant (SRP) high-level nuclear waste borosilicate glass in a tuff repository environment. This paper presents a summary of the results of the first phase of this joint SRL/LLNL program. In this phase, the waste package (SRP glass and stainless steel) was leached in a saturated tuff environment, i.e., in the presence of excess groundwater. A saturated environment represents a possible worst case since the potential repository horizon being investigated by NNWSI is in the unsaturated zone and the amount of water will be limited. In these saturated tests, the glass and waste package components were leached in cups fabricated from tuff representative of the repository rock. Actual groundwater was used. The cup had a tuff lid; thus, the package was leached in presence of only those materials that would be in a repository. The entire assembly was sealed in a Teflon® vessel so that the loss of groundwater during the test was minimized.

In previous leach tests, SRP glasses, both radioactive [1] and simulated [2], have been leached in groundwaters of generic composition. Glass with simulated waste has also been leached in the presence of rock from candidate repository geologies [2]. The results of these tests suggested that the glass should perform well in a repository environment and that the groundwaters or the rocks did not accelerate leaching over that in deionized water. Previous tests in the LLNL program investigating tuff as a possible repository site have shown that the presence of tuff decreased the leaching of PNL 76-68 glass [3]. The concentration of leached species was much lower when tuff was present in the system.

In this paper, leach results in the presence and absence of tuff cups are presented for both glass containing actual radioactive SRP waste and glass containing nonradioactive simulated waste. Based on results for Li and B, both glasses leach similarly even though radiolysis effects were noted in some long-term tests. For the radioactive glass, results are presented for Cs-137, Sr-90, and Pu-238. In these tests, the presence of tuff significantly decreases the concentrations of leached species. Results indicate that the SRP Type 304L stainless steel canister does not affect the leaching. Finally, the results in the presence of tuff are extrapolated to the behavior of full-size canisters of SRP glass in a saturated tuff environment.

EXPERIMENTAL

The two glasses used in this study were prepared using slurry fed continuous melters. For the radioactive glass, the melter was in a shielded facility and was operated remotely. For both glasses, the respective waste slurries were mixed with SRL Frit 165 (28 wt% waste on a dry basis) and melted at 1150°C. The radioactive waste was obtained from SRP storage Tank 42. The glass melts were poured into thin-wall Type 304L stainless steel cylinders 1.8 cm OD. These cylinders were then sawed to produce 2 mm thick disks for leaching. Final compositions of the glasses (Table I) were determined by analyzing solutions of dissolved glass. SEM micrographs indicated the presence of less than 1% crystals (ferrite spinels) in either glass.

Table I

Principal Oxide Components (wt %) in Glasses for the Tuff Repository Testing Program[a]

	Radioactive Waste Glass[b]	Simulated Waste Glass		Radioactive Waste Glass[b]	Simulated Waste Glass
SiO_2	51.3	56.2	Al_2O_3	10.5	4.9
Na_2O	12.4	10.9	Fe_2O_3	7.1	12.3
Li_2O	6.4	4.7	MnO_2	2.1	2.8
B_2O_3	8.4	7.0	CaO	0.7	2.0
MgO	1.	0.78	NiO	0.9	0.96

a 28% Waste, 72% Frit 165

b Surface Dose Rate = 1300 rad/hr; specific activities (mCi/g) of principal radionuclides: Sr-90, 5.0; Cs-137, 0.09; Pu-238, 0.05.

Tuff cups were prepared from tuff from an outcrop at Fran Ridge on the Nevada test site. This tuff is representative of that at the proposed repository horizon except for the presence of caliche in the outcrop. Caliche is composed primarily of soluble $SO_4^=$, Cl^-, and NO_3^- salts of Na, Ca, and Mg. The cups were cylinders 5 cm OD by 7.3 cm long and contained a borehole 2.5 cm diameter by nominally 7 cm deep. The lids were tuff disks 5 cm OD by 0.6 cm thick.

Detailed leaching procedures are presented elsewhere [4]. Only the especially pertinent procedures will be summarized here. Each test in a tuff cup contained 3 or 4 glass disks (SA per disk = 4.7 cm^2) separated by Type 304L stainless steel spacers in a Type 304L stainless steel basket. For tests where steel was absent, Pt was used. The glass disks had 600 grit surfaces on both sides and were cleaned (along with the outer Teflon® vessels) following MCC-I test procedures. Caliche was not preleached from the tuff cups; however, they were saturated with actual tuff groundwater prior to each test. Sufficient groundwater from well J-13 at the Nevada test site was added to the borehole to achieve a SA/V (glass surface area to groundwater volume) of 100 m^{-1}. J-13 water is a tuffaceous groundwater which contains 0.04, 0.14, 27, and 42 ppm of Li, B, Si, and Na. Principal anions are HCO_3^- and SO_4^{2-}. To ensure that groundwater remained in the borehole during the test, approximately 40 mL of groundwater was placed in the annular space between the tuff cup and the Teflon® vessel. All tests were performed in Blue-M ovens at 90°C. This is close to the expected maximum temperature at which leaching could occur for SRP waste glass in a repository in tuff.

After each test, final volumes and pH values in the boreholes and in annular spaces were accurately measured. The solutions were then analyzed. Concentrations of nonradioactive cations were determined by inductively coupled plasma induced spectroscopy. Anion concentrations were determined by ion chromatography. Cs-137, Sr-90, and Pu-238 were determined by calibrated counting techniques.

RESULTS AND DISCUSSIONS

Detailed experimental data and discussions are in Reference 5. Only a summary will be presented here.

Leach results are presented as normalized mass losses based on the respective elements for each time period. This quantity is given by $NL_i = N_i/(SA \times X_i)$ where NL_i is the mass of glass dissolved per unit area based on species i. N_i is the total amount of species i measured in the solution, SA is the surface area of the glass, and X_i is the mass fraction of i in the glass.

pH Changes in the Presence and Absence of Tuff

During the leach tests, the pH of the tuff groundwater changed from its pretest value of 7.4 (Table II). When tuff rock was present, the changes were small, indicating that tuff rock buffered the pH. Also, the changes in presence of Type 304L stainless steel were not significantly different than those in its absence. Tuff rock could buffer the pH by two mechanisms - furnishing species such as silica that decrease the overall dissolution of the glass or by furnishing species that neutralize alkaline or acidic species produced by leaching or by radiolysis. In all the tests with rock present, the pH values of the solutions in the borehole and in the annular space were equal. When glass alone was leached, the pH increased or decreased depending on whether the glass was nonradioactive or radioactive. When the glass was nonradioactive, the pH increased because of ion exchange of alkali ions (Li^+ and Na^+) with H_3O^+ ions in the tuff groundwater. When the glass was radioactive, the pH decreased in those tests that were 56 days or longer. Anion analysis indicated significant amounts of F^- and NO_3^- had formed in these tests by radiolysis of Teflon® and of moist air, respectively. Formation of such anions would be accompanied by H^+ formation and cause a pH decrease. Apparently, the air and Teflon® had received sufficient dose at 56 days or greater to affect the leaching. Leach results for B and Li for these long tests were unrealistically high. Such effects are not expected in a saturated repository environment where Teflon® and air would be absent. When the tuff cups were present, much less F^- was formed because the Teflon® was effectively shielded by the tuff vessel. NO_3^- was still formed but not in amounts sufficient to overcome the buffering capacity of the rock.

Table II

Final pH Values for Leach Tests in Tuff Groundwater in Presence and Absence of Tuff Rock Cups. Initial pH = 7.4[a]

Leach Time, days	System				
	Nonradioactive Glass			Radioactive Glass	
	Glass Only	Tuff and 304L Steel[b]	Tuff and No Steel[b]	Glass Only	Tuff and 304L Steel[b]
28	9.2	8.5	7.8	7.9	7.9
56	c	c	c	6.0	c
70	c	c	c	6.0	7.6
90	9.6	8.3	8.3	5.3	8.0
127	c	c	c	6.1	7.6
180	9.9	8.4	7.7	c	c

a T=90°C, (SA) glass/solution = 100 m^{-1}. Except where noted, the results are averages of duplicate tests. Observed uncertainties $\leq 5\%$.

b Measured in the borehole of the tuff cup. Values in an annular space were within experimental error of those in the borehole.

c Tests were not performed for this system and this time period.

Comparison of Leach Results for Actual and Simulated Waste Glass

Based on the normalized mass losses for Li and B, the glass with actual high-level radioactive waste and that with simulated waste leach identically except for the long-term tests in the absence of tuff where radiolysis was a factor. Results for both glasses are shown in Figure 1. Li and B are the best components in the two glasses to compare. These elements have reasonable releases and have low concentrations in the groundwater and in any caliche that may leach from the tuff cups. Figure 1 shows data for leaching in the presence and absence of tuff cups and presence and absence of Type 304L stainless steel. Results for each test with tuff cups are presented rather than averages so that the reproducibility of the test method is illustrated. Results for groundwater alone are averages of duplicate tests and observed deviations are indicated by error bars. For the tests in groundwater alone, data for the radioactive glass for tests 56 days and longer are not included because of the radiolysis effects discussed earlier. The results for tests of 14, 28, and 32 days with radioactive glass are included. Final pH values for these tests were approximately 7, indicating that radiolysis effects were not yet significant. The normalized mass losses in groundwater alone are reasonable for this large SA/V ratio, and are in agreement with results of Bazan [6] at comparable values of SA/V X t.

Normalized mass losses for tests with tuff leach cups were calculated assuming that all the Li and B that was detected in the borehole and the annular space came from the glass. For the long tests, some Li and B were in the annular space suggesting that they had migrated through the tuff. The amount of Li in the caliche was small; thus, the Li results accurately indicate the performance of the glass. Higher levels of B were present in the caliche; thus, some B could have leached from the tuff cup even in tests where small amounts of caliche was present. Presence of B from the different amounts of caliche in the cups could explain the relatively large scatter in the normalized mass losses based on B in the presence of tuff. Accurate correction for the amount of B leached from the rock was impossible because of the nonhomogeneity of the rocks and the migration of species through the tuff cups.

The results in Figure 1 indicate that Type 304L stainless steel is not affecting the leaching. More important, however, the presence of tuff decreases the amount of Li or B in the final leach solutions.

Effect of Tuff on Leached Radionuclide Concentrations

Normalized mass losses for actual radioactive glass based on Cs-137, Sr-90, and Pu-238 in the presence and absence of tuff are shown in Figure 2. Radionuclide concentrations both in the borehole and in the annular space were used in calculating the normalized mass losses. In some longer tests, significant amounts of the radionuclides had diffused through the cups. This diffusion is discussed later. Results of all the tests with radioactive glass are presented in Figure 2. Single tests were performed for each time with the tuff cups. Duplicate and triplicate tests were performed in absence of tuff and the error bars indicate the reproducibility of the data.

For the tests longer than 32 days in groundwater alone where the pH decreased due to radiolysis (Table II), the amounts of Cs-137, Sr-90, and Pu-238 in solution were equal to or less than those at shorter times even though the releases of Li and B increased significantly [5]. This indicates that the concentrations of these three radionuclides are controlled by the solubility of some solid phase and not by dissolution of the glass. Constant values for NL(Cs-137) and decreasing values for NL(Sr-90) at long times have been observed in other leach tests at 90°C [7]. Nearly constant values for Pu have also been measured [7], suggesting that the large curvature in Figure 2 for NL(Pu-238) may be due to experimental error. This is reasonable considering the large uncertainity in the Pu-238 results. The values for normalized mass losses based on the radionuclides are reasonable when compared to results obtained at a lower SA/V [7].

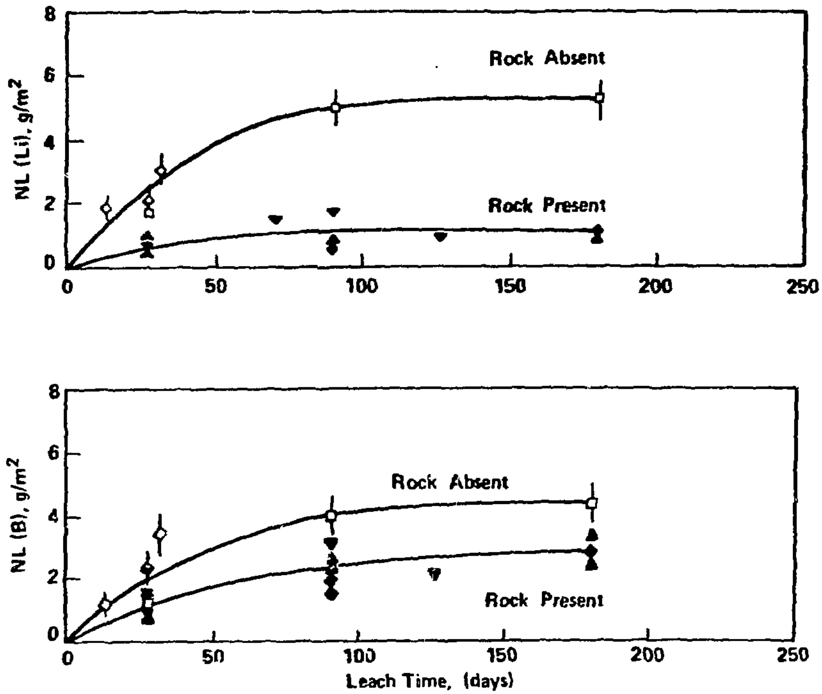

Figure 1. Normalized Mass Losses Based on Li and B for Actual and Simulated SRP Waste Glass in Presence (solid symbols) and Absence (open symbols) of Tuff Leach Vessels. ▼ Radioactive glass, entire system; ◇, Radioactive glass, tuff absent; ▲ Nonradioactive glass, entire system; ◆ Nonradioactive glass, Type 304L SS absent; □, Nonradioactive glass, tuff absent. T = 90°C, SA/V = 100 m^{-1}

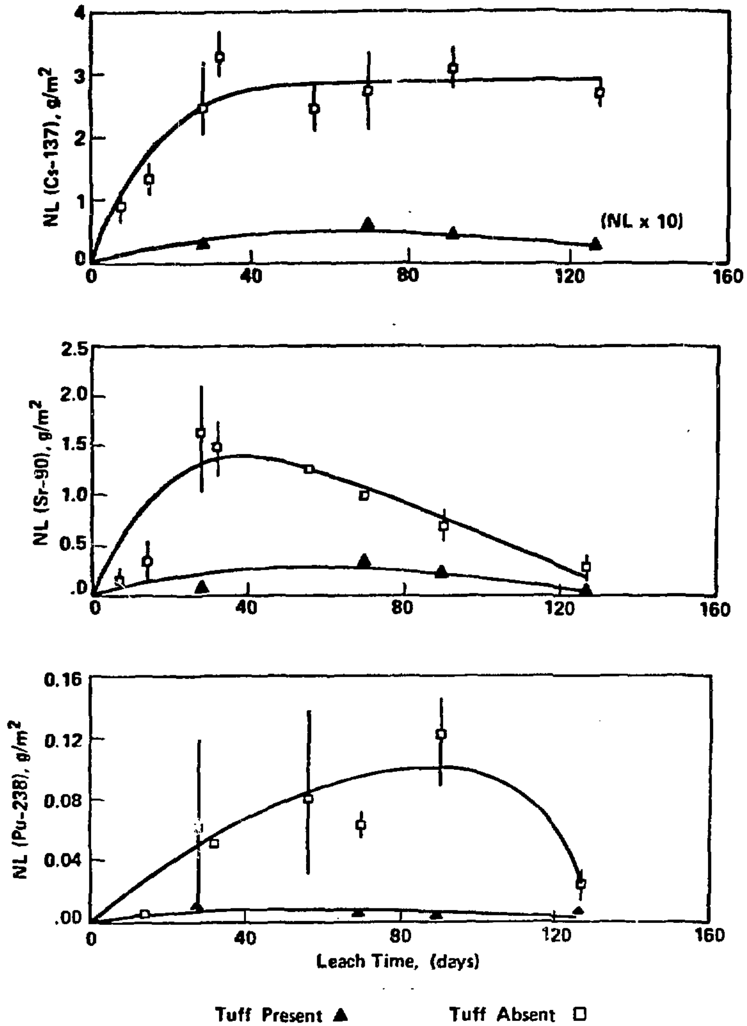

Figure 2. Decrease in Normalized Mass Losses for Cs-137, Sr-90, and Pu-238 to Tuff Rock. T = 90°C, SA/V = 100 m^{-1}

Tuff rock decreased the concentration of each radionuclide in the final solutions. In the 127-day test, the decrease was 120X for Cs-137, 14X for Sr-90, and 4X for Pu-238 compared to results in groundwater alone. After the tests, the cups were radioactive indicating the presence of Cs-137, and presumably Sr-90 and Pu-238, within the cups. Sorption could be one cause of the decrease. The larger decrease for Cs-137 than for Sr-90 is consistent with Cs-137 having a larger batch adsorption coefficient than Sr-90 for this type of tuff. The measured coefficient for Cs-137 is 6X larger than that for Sr-90 [8]. Ion exchange with cations in the feldspar in the tuff could also cause part of the decrease. Finally, the rock could be furnishing species (such as Si) to the solution that would slow the dissolution of the glass. This does not appear to be the most significant effect of the rock since the normalized mass loss based on B is decreased by only 2X by the presence of the tuff (Figure 1) while decreases for the radionuclides were much larger.

Radionuclide Migration Through the Tuff Leach Vessels

In tests longer than 28 days, significant fractions of the leached radionuclides had migrated through the 1.3 cm thick wall of the tuff leach vessel (Table III). No radioactivity migrated through in the 28-day tests. In the 70-day test, more radioactivity was in the annular space than in the borehole in that cup. Also in this test, the concentrations of caliche species (Na^+, Ca^{2+}, Cl^-, and SO_4^{2-} ions) were equal on both sides of the tuff wall suggesting free migration of these species through the cup. Close examination of this cup showed that a crack had developed as a result of dissolution of the caliche. The cup used for the 127-day test was preleached to remove the caliche. Removal was confirmed by the appearance of very little caliche material in the final leachate. For this test, only Sr-90 migrated through the tuff. Failure of Cs-137 to migrate to the annular space is consistent with its much larger adsorption coefficient than that for Sr-90. LLNL is now analyzing the migration data to obtain estimates of diffusion coefficients for the respective species.

Table III

Fraction of Radioactivity Migrating Through the Tuff Leach Cups in Long Term Tests[a]

Leach Time, days	Fraction of Radioactivity in Annular Space		
	Cs-137	Sr-90	Pu-238
70	0.51	0.72	0.13
90	0.29	0.35	0.00
127	0.00	0.15	0.00

[a] Radioactivity remaining in the rock was not included in this calculation.

Application to Repository Disposal

The results presented in Figure 2 indicate very low concentrations of Cs, Sr, and Pu from the waste glass in the groundwater in the presence of tuff. Based on the estimated isotopic ratios of these respective elements in the glass [9] and the half-lives of the measured radionuclides, the concentrations of the total amounts of Cs, Sr, and Pu in the borehole of the 127-day test in presence of tuff are 0.007 ppb, 0.2 ppb, and 0.006 ppb, respectively. To apply these results to repository disposal, it is necessary to extrapolate the groundwater volumes of these laboratory-scale tests to those for full size canisters of SRP waste glass. Extrapolation of the surface area of the glass in these small-scale tests to the surface area of completely exposed monolith of SRP glass (5 M^2) requires that 50 L of groundwater be in the repository borehole. If the annular space in the laboratory scale test is included, a total of 213 L would be in the full-scale case. Using these volumes and the concentrations measured in the small-scale tests, the fraction of each element in the groundwater can be calculated since the amount of each in the actual glass is known [9]. If one assumes that the concentrations measured in the 127-day test can be extrapolated to one year, the annual releases of Cs, Sr, and Pu are less than 10^{-7} of the inventory even if the amount of groundwater equivalent to water in the annular space is considered. Longer tests are planned to measure the concentrations of the radionuclides after a year.

Conditions used in these experiments correspond to the case where a glass waste form is in contact with 50 L of water that has accumulated in a borehole. This condition is substantially different from the expected condition in an unsaturated zone tuff horizon where water would not accumulate in the borehole, but would pass through and drain away. The water flux past each DHLW canister should be approximately 1 L per year. The dissolution rate of the glass waste form under this condition should be much less than that observed under the condition of complete immersion.

CONCLUSIONS

The data presented in this study support the following conclusions concerning the performance of SRP radioactive high-level waste glass in a saturated tuff repository environment.

1. Borosilicate glass containing actual radioactive waste from an SRP waste tank and glass containing simulated waste leach identically within the experimental uncertainities in this study.

2. Tuff rock buffers pH changes caused by leaching and by radiolysis.

3. The presence of tuff significantly decreases the concentrations of Cs-137, Sr-90, and Pu-238 in the leach solutions by sorption or ion exchange processes.

4. The presence of Type 304L stainless steel does not significantly affect the leaching process.

5. Extrapolation of these results to a geologic repository containing full-scale canisters of SRP glass in a saturated tuff environment suggests that annual fractional releases of the three radionuclides will be much less than 10^{-5}.

FUTURE STUDIES

These results are from the first part of an intensive program investigating the performance of SRP glass in a geologic repository in tuff. Further experiments are being performed not only at SRL but also at LLNL and Argonne National Laboratory (ANL). The future experiments concentrate on evaluating the performance of the glass and the waste package in an unsaturated repository environment.

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APPENDICES:

Data Tables for Experiments

APPENDIX 1: LEACHING TUFF VESSELS IN J-13 WATER

TEST COMPONENTS:
TUFF PRESENT.
STEEL ABSENT.
GLASS ABSENT.

INITIAL VOLUMES: (ml)
BOREHOLE 18.3
ANNULAR SPACE 35.0

T = 90°C

FINAL CONCENTRATIONS (PPM)

TEST NAME	LEACH TIME, DAYS	SOLUTION	INITIAL pH	FINAL pH	FINAL VOLUME	CATIONS Si	B	Na	Li	Al	Fe	Ca	Mn	Mg	Sr	U	ANIONS F-	Cl-	NO2-	NO3-	SO4-
T-1	100	BOREHOLE-H	7.4	7.3	5	82.7	5.52	154.0	.434	N.D.	N.D.	N.A.	1.29	28.8	8.81	2.08	70	3.0E+2	N.A.	8.4E+2	1.1E+3
		BOREHOLE-F				79.1	5.24	149.8	.419	N.D.	N.D.	N.A.	1.09	27.8	2.08	2.08	N.A.	5.0E+2	N.A.	8.1E+2	1.1E+3
		ANNULAR	7.4	7.9	38	55.4	3.99	87.5	.198	N.D.	N.D.	N.A.	N.D.	7.78	2.77	1.23	N.A.	1.8E+2	N.A.	3.8E+2	3.8E+2
T-2	100	BOREHOLE-H	7.4	8.5	7.3	75.8	.94	59.3	.02	N.D.	N.D.	N.A.	N.D.	.20	.10	N.D.	N.A.	1.5E+1	N.A.	4.[illegible]E+1	7.3E+1
		BOREHOLE-F				65.7	.09	60.8	.00	N.D.	N.D.	N.A.	N.D.	.02	.24	N.D.	1.8	1.8E+1	N.A.	4.2E+1	7.8E+1
		ANNULAR	7.4	8.8	33	52.5	.49	33.3	.02	N.D.	N.D.	N.A.	N.D.	.04	.09	N.D.	N.A.	9.4E+0	N.A.	2.1E+1	2.8E+1
NOMINAL J-13 WATER (PPM):						30.5	.14	40.7	.041	0.0	0	13.4	0	1.35	0.0	0.0	2	6.7	0	8.9	19.1
ANALYTICAL DETECTION LIMITS (PPM):						.25	.01	.10	.01	.30	.05	.10	.03	.01	.01	.50	.10	.20	1.00	1.50	.50

NOTES:
N.A. = DATA NOT AVAILABLE.
N.D. = SPECIES NOT DETECTED.
ICP DILUTION FACTOR = 1
IC DILUTION FACTOR = 1

BOREHOLE-H = SOLUTION SAMPLED WHILE HOT.
BOREHOLE-F = SOLUTION SAMPLED AFTER COOLING AND FILTERING.
TEST NAME DESIGNATION: RG=RADIOACTIVE GLASS, NG = NONRADIOACTIVE GLASS, S=304L SS, T=TUFF.

APPENDIX 2: LEACHING RADIOACTIVE SRP GLASS AND 304L SS IN TUFF VESSELS

TEST COMPONENTS:
TUFF PRESENT.
STEEL PRESENT
GLASS PRESENT.

INITIAL VOLUMES: (mL)
BOREHOLE 17.8
ANNULAR SPACE 45.0

GLASS SURFACE AREA = 14.2 CM2
T = 90°C

TEST NAME	LEACH TIME, DAYS	SOLUTION	INITIAL pH	FINAL pH	FINAL VOLUME	Cs-137 (DPM/ML)	Sr-90 (DPM/ML)	Pu 238 (DPM/ML)	Si	B	Na	Li	Al	Fe	Ca	Mn	Mg	F-	Cl-	NO2-	NO3-	SO4-
									FINAL CONCENTRATIONS (PPM): CATIONS									ANIONS (PPM)				
RGST-1	28	BOREHOLE-C	7.4	7.8	14.0	904	8.00E+4	40	51.0	2.09	40.9	1.38	N.D.	.14	15.3	N.D.	.28	11.2	9.9	8.9	17.4	30.0
		ANNULAR	7.4	7.5	45.3	BKG.	BKG.	8	40.8	.01	41.2	N.D.	N.D.	.11	14.7	N.D.	.09	21.1	8.8	14.1	14.4	28.3
RGST-2	28	BOREHOLE-C	7.4	8.0	12.9	508	1.29E+5	25	57.5	1.73	74.3	1.00	N.D.	.07	54.0	N.D.	.10	27.2	27.2	33.4	28	108
		ANNULAR	7.4	7.9	40.5	BKG.	BKG.	BKG.	49.1	.83	54.7	.13	N.D.	N.D.	41.7	N.D.	.22	25.1	19.9	11.7	37.1	105
RGST-3	28	BOREHOLE-C	7.7	7.9	19.1	531	9.25E+4	141	63.5	1.85	80.8	1.72	N.D.	.19	229	.005	3.00	30.2	105	N.D.	206	557
		ANNULAR	7.7	7.9	44.5	BKG.	4.44E+3	38	59.4	1.04	83.8	.35	N.D.	.10	244	N.D.	3.23	13.7	42.8	3.1	178	587
RGST-4	70	BOREHOLE-C	7.3	7.7	9.0	1200	2.79E+5	82	56.8	4.22	200.0	2.17	N.D.	N.D.	840	.001	1.14	7.9	155	59.1	904	337
		ANNULAR	7.3	7.5	37.6	300	1.00E+5	3	55.4	3.87	248.0	1.12	N.D.	N.D.	811	.008	2.37	13.8	738	59.1	1051	334
RGST-5	90	BOREHOLE-C	7.3	8.0	12.7	939	2.07E+5	25	75.9	2.05	120.5	3.10	N.D.	1.93	407	.047	3.02	9.0	747	98.8	201	588
		ANNULAR	7.3	8.0	41.9	119	4.77E+4	BKG.	58.1	1.60	90.0	.01	.43	.12	392	N.D.	2.58	20.7	238	44.8	343	448
RGST-6	127	BOREHOLE-C	7.7	7.8	14.3	822	3.24E+4	50	71.8	2.08	43.2	.29	N.D.	N.D.	37.8	N.D.	.007	8.9	28.8	8.9	150	16.8
		ANNULAR	7.7	7.1	42.6	BKG.	1.08E+3	5	87.4	1.03	38.1	.49	N.D.	N.D.	15.8	.036	.42	28.4	10.5	17.2	13.3	34.9
NOMINAL	J-13	WATER	(PPM):						30.5	.14	40.7	.04	0.0	0.0	13.4	0.0	1.35	2	6.7	8	6.9	19.1
ANALYTICAL DETECTION LIMITS:						100	50	8	.25	.01	.10	.01	.30	.05	.10	.03	.01	.10	.20	1.00	1.55	.50

NOTES:
N.A. = DATA NOT AVAILABLE.
N.D. = SPECIES NOT DETECTED.
BKG. = ONLY BACKGROUND RADIATION DETECTED.
DPM = DISINTEGRATIONS PER MINUTE.
ICP DILUTION FACTOR = 10.
IC DILUTION FACTOR = 1-20.

BOREHOLE-H = SOLUTION SAMPLED WHILE HOT.
BOREHOLE-F = SOLUTION SAMPLED AFTER COOLING AND FILTERING.
BOREHOLE-C = SOLUTION SAMPLED AFTER COOLING,AND NOT FILTERED.
TEST NAME DESIGNATION: RG=RADIOACTIVE GLASS, NG = NONRADIOACTIVE GLASS, S=304L SS, T=TUFF.

APPENDIX 3: LEACHING SIMULATED SRP GLASS AND 304L SS IN TUFF VESSELS

TEST COMPONENTS:
TUFF PRESENT
STEEL PRESENT
GLASS PRESENT

INITIAL VOLUMES: (mL)
BOREHOLE 10.3
ANNULAR SPACE 35.0

GLASS SURFACE AREA = 10.6 CM2.
T = 90°C

TEST NAME	LEACH TIME, DAYS	SOLUTION	INITIAL pH	FINAL pH	FINAL VOLUME	Si	B	Na	Li	Al	Fe	Ca	Mn	Mg	Sr	U	F-	Cl-	NO2-	NO3-	SO4-
						FINAL CATIONS						CONCENTRATIONS (PPM)						ANIONS			
NGST-1	28	BOREHOLE-H	7.4	8.5	13	71.4	1.01	70.5	.98	N.D.	N.D.	14.1	N.D.	.17	.09	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				64.4	1.06	70.0	1.04	N.D.	N.D.	14.4	N.D.	.34	.12	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	8.5	40	49.5	.45	36.4	.01	N.D.	N.D.	5.7	N.D.	.08	.03	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
NGST-2	28	BOREHOLE-H	7.4	8.5	10	78.7	4.43	89.4	2.09	N.D.	N.D.	10.1	N.D.	.03	.07	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				74.8	4.01	71.5	2.32	N.D.	N.D.	10.2	N.D.	.21	.09	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	8.5	42	50.7	.59	35.3	.04	N.D.	N.D.	5.7	N.D.	N.D.	.05	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
NGST-3	91	BOREHOLE-H	7.4	8.2	11	93.3	3.12	110.3	.95	N.D.	N.D.	32.1	N.D.	.16	.10	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				94.2	3.24	114.4	1.00	N.D.	N.D.	34.7	N.D.	.27	.19	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	8.5	38	64.7	1.95	100.6	.35	N.D.	N.D.	21.4	N.D.	10.59	.12	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
NGST-4	91	BOREHOLE-H	7.4	8.2	9	92.9	3.85	112.7	2.31	N.D.	N.D.	199.9	N.D.	.74	1.11	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				90.3	3.00	112.4	2.34	N.D.	N.D.	197.8	N.D.	.92	1.09	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	8.5	[illegible]	55.4	1.74	86.0	.53	N.D.	N.D.	58.7	.03	1.04	.57	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
NGST-5	180	BOREHOLE-H	7.4	8.4	7	84.2	4.71	122.0	2.35	N.D.	N.D.	N.A.	N.D.	.23	.92	N.D.	N.A.	63.0	N.A.	1.0E+2	1.9E+2
		BOREHOLE-F				77.3	4.33	119.0	2.19	N.D.	N.D.	N.A.	N.D.	.42	.07	N.D.	2.9	70.0	N.A.	1.7E+2	1.0E+2
		ANNULAR	7.4	8.7	38	49.4	1.09	55.4	.59	N.D.	N.D.	N.A.	N.D.	.15	.29	N.D.	0.4	30.2	N.A.	1.0E+2	8.0E+1
NGST-6	180	BOREHOLE-H	7.4	8.9	8	78.[illegible]	5.02	59.5	1.75	30.00	N.D.	N.A.	N.D.	N.D.	.50	N.D.	N.A.	13.0	N.A.	42.0	21.3
		BOREHOLE-F				68.2	5.20	59.2	1.68	N.D.	N.D.	N.A.	N.D.	.11	.11	N.D.	3.0	19.9	N.A.	60.9	30.0
		ANNULAR	7.4	8.0	35	43.1	2.58	20.3	.39	N.D.	N.D.	N.A.	N.D.	N.D.	.03	N.D.	3.1	0.5	N.A.	19.3	0.7
NOMINAL	J-13	WATER	(PPM)			30.5	.14	45.7	.04	0.9	0.0	13.4	0.0	1.35	0.0	0.0	2	6.7	0	8.9	19.1
ANALYTICAL DETECTION LIMITS						.25	.01	.10	.01	.30	.05	.10	.03	.01	.01	.50	.10	.20	1.00	1.50	.50

NOTES:
N.A. = DATA NOT AVAILABLE.
N.D. = NOT DETECTED.
ICP DILUTION FACTOR = 1.
IC DILUTION FACTOR = 1.

BOREHOLE-H = SOLUTION SAMPLED WHILE HOT.
BOREHOLE-F = SOLUTION SAMPLED AFTER COOLING AND FILTERING.
TEST NAME DESIGNATION: RG = RADIOACTIVE GLASS, NG = NONRADIOACTIVE GLASS, S = 304L SS, T = TUFF.

APPENDIX 4: LEACHING SIMULATED SRP GLASS IN TUFF VESSELS

TEST COMPONENTS:
TUFF PRESENT.
STEEL ABSENT.
GLASS PRESENT.

INITIAL VOLUMES: (mL)
BOREHOLE 17.0
ANNULAR SPACE 35.0

GLASS SURFACE AREA = 17.0 CM2
T = 90°C

FINAL CONCENTRATIONS (PPM)

TEST NAME	LEACH TIME, DAYS	SOLUTION	INITIAL pH	FINAL pH	FINAL VOLUME	CATIONS Si	B	Na	Li	Al	Fe	Ca	Mn	Mg	Sr	U	ANIONS F-	Cl-	NO2-	NO3-	SO4-
NGT-1	28	BOREHOLE-H	7.4	7.8	14	67.8	0.11	703.4	2.47	N.D.	N.D.	>1000	.30	91.31	10.20	2.03	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				69.2	0.36	719.2	2.05	N.D.	N.D.	>1000	.32	93.35	10.40	2.00	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	7.5	38	54.2	0.22	509.1	.98	N.D.	N.D.	>1000	.07	52.29	8.97	2.13	N.A.	N.A.	N.A.	N.A.	N.A.
NGT-2	28	BOREHOLE-H	7.4	8.1	17	62.5	4.34	214.0	2.47	N.D.	N.D.	305.5	.08	11.35	1.77	1.01	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				63.8	4.47	222.0	2.65	N.D.	N.D.	317.1	.10	11.84	1.83	1.00	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	8.0	32	49.5	2.01	158.2	.20	N.D.	N.D.	227.1	N.D.	6.51	1.33	.04	N.A.	N.A.	N.A.	N.A.	N.A.
NGT-3	91	BOREHOLE-H	7.4	8.3	8	72.4	2.90	88.9	1.75	N.D.	N.D.	39.7	N.D.	.42	N.D.	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				67.1	2.83	67.9	1.00	N.D.	.55	43.2	N.D.	.55	N.D.	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	6.7	38	59.3	.99	49.7	.22	N.D.	N.D.	30.0	N.D.	.20	N.D.	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
NGT-4	91	BOREHOLE-H	7.4	8.3	12	91.7	2.96	141.3	1.89	.2570	N.D.	104.0	N.D.	.67	.67	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		BOREHOLE-F				94.0	2.02	133.0	1.82	6.0	N.D.	100.9	N.D.	.71	.84	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
		ANNULAR	7.4	8.5	34	73.8	1.27	110.0	0.0	0	84.03	.0059	.35	.20	.52	N.D.	N.A.	N.A.	N.A.	N.A.	N.A.
NGT-5	100	BOREHOLE-H	7.4	7.7	7	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	1.2E+1	4.2E+2	N.A.	2.0E+3	1.2E+3
		BOREHOLE-F				70.2	5.39	349.0	2.65	.07	N.D.	N.A.	N.D.	19.40	8.5[illegible]	2.13	3.9E+0	5.0E+2	N.A.	2.0E+3	1.2E+3
		ANNULAR	7.4	8.1	38	48.0	3.00	230.0	.64	.0566	N.D.	N.A.	N.D.	4.09	4.32	1.08	N.A.	3.0E+2	N.A.	1.9E+3	8.4E+2
NOMINAL	J-13	WATER	(PPM)			38.5	.14	40.7	.04	0.0	0.0	13.4	0.0	1.35	0.0	0.0	2	6.7	0	8.9	19.1
ANALYTICAL DETECTION LIMITS						.25	.01	.10	.01	.30	.05	.10	.03	.01	.01	.50	.10	.30	1.00	1.50	.50

NOTES:
N.A. = DATA NOT AVAILABLE.
N.D. = SPECIES NOT DETECTED.
ICP DILUTION FACTOR = 1
IC DILUTION FACTOR = 1

BOREHOLE-H = SOLUTION SAMPLED WHILE HOT.
BOREHOLE-F = SOLUTION SAMPLED AFTER COOLING AND FILTERING.

TEST NAME DESIGNATION: NG=NONRADIOACTIVE GLASS, NG = NONRADIOACTIVE GLASS, S=304L SS, T=TUFF.

APPENDIX 5: LEACHING RADIOACTIVE SRP GLASS AND 304L SS IN J-13 WATER ONLY.

TEST COMPONENTS:
TUFF ABSENT. INITIAL VOLUME: 4.7 ML.
STEEL PRESENT. GLASS SURFACE AREA = 4.7 CM2
GLASS PRESENT. T = 90°C

FINAL CONCENTRATIONS

TEST NAME	LEACH TIME, DAYS	SOLUTION	INITIAL pH	FINAL pH	FINAL VOLUME	DPM/ML Cs-137	Sr-90	Pu-239	Sb-125	CATIONS (PPM) Si	B	Na	Li	Al	Fe	Ca	Mn	Mg	ANIONS (PPM) F-	Cl-	NO2-	NO3-	SO4-
RGS-1	7	J-13 WATER	7.4	≈7	4.00	2.14E+4	2.40E+5		BKG.	20.1	1.39	40.2	2.02	1.02	.06	9.14	.10	.24	17.2	5.7	N.D.	6.7	10.1
RGS-2	7	J-13 WATER	7.4	≈7	4.00	2.00E+4	3.00E+5		BKG.	20.5	2.32	40.1	1.40	.97	.04	8.48	.10	.09	17.3	5.4	N.D.	4.7	15.8
RGS-3	7	J-13 WATER	7.4	≈7	4.66	[illegible]	3.22E+5		BKG.	25.5	1.60	40.5	3.43	1.25	.00	7.44	.09	1.09	24.2	5.5	N.D.	7.5	19.1
RGS-4	14	J-13 WATER	7.4	≈7	4.75	4.01E+4	4.14E+5	80	BKG.	30.7	2.08	40.1	5.97	N.D.	N.D.	8.34	.09	.40	19.[illegible]	4.7	8.1	2.1	9.2
RGS-5	14	J-13 WATER	7.4	≈7	4.97	2.95E+4	5.37E+5	58	BKG.	31.8	2.07	47.9	4.09	.82	.10	6.04	N.D.	.72	10.4	5.2	7.2	2.2	9.1
RGS-6	14	J-13 WATER	7.4	≈7	4.41	4.33E+4	1.01E+6	25	BKG.	41.5	2.00	52.0	5.75	.77	.15	7.14	.14	.41	22.4	4.9	14.1	3.2	9.5
RGS-7	28	J-13 WATER	7.4	8.0	4.71	8.00E+4	4.33E+6	1071	BKG	[illegible]	4.24	40.6	7.24	7.00	.14	6.40	1.70	1.47	125	11.5	17.0	4.0	10.9
RGS-8	28	J-13 WATER	7.4	7.0	4.43	5.99E+4	3.47E+6	1511	BKG.	[illegible]	4.00	44.4	5.04	2.64	N.D.	6.30	.71	.58	61	24.4	24.5	1.0	17.0
RGS-9	28	J-13 WATER	7.4	7.2	4.71	8.04E+4	2.04E+6	105	BKG.	39.0	4.24	42.0	5.84	1.10	.07	5.52	.29	.30	80	15.9	63	2.0	10.0
RGS-10	32	J-13 WATER	7.7	6.9	4.40	1.00E+5	3.05E+6	600	BKG.	75.7	9.32	70.5	10.90	3.20	.15	4.32	3.99	2.03	201	30	50.1	19.1	35.4
RGS-11	32	J-13 WATER	7.7	7.0	4.94	7.61E+4	2.24E+6	3020	BKG.	86.8	5.50	57.5	7.45	7.02	.51	10.70	1.71	1.04	107	25	34.2	17.0	42.2
RGS-12	56	J-13 WATER	7.7	5.1	4.03	6.70E+4	5.00E+5	1950	BKG.	84.1	27.51	90.2	20.30	13.13	.52	1.42	7.40	1.15	230	5.4	54.3	5.7	23.1
RGS-13	56	J-13 WATER	7.7	6.0	4.11	6.00E+4	2.01E+6	302	BKG.	93.4	13.05	64.3	10.47	9.94	3.01	2.40	5.22	.03	132	4.5	10.9	5.1	17.1
RGS-14	71	J-13 WATER	7.7	5.9	4.00	9.01E+4	4.90E+6	891	1.00E+4	121.5	18.00	71.9	14.70	15.21	.20	5.00	5.74	1.50	102	N.A.	92	5.2	22.0
RGS-15	71	J-13 WATER	7.7	8.1	4.30	5.77E+4	2.00E+6	010	1.40E+4	156.6	23.03	106.2	23.30	20.50	.14	1.44	9.39	.76	210	N.A.	100	4.5	22.0
RGS-16	91	J-13 WATER	7.7	5.8	4.57	8.97E+4	1.17E+6	1795	9.01E+3	153.5	27.00	139.0	31.40	23.50	.20	1.36	15.90	.79	88	27.2	100	44.3	17.5
RGS-17	91	J-13 WATER	7.7	5.0	5.00	6.70E+4	1.40E+6	1000	1.01E+4	147.0	24.40	137.2	33.20	21.00	.30	.73	11.10	1.00	196	92.2	124	5.2	14.7
RGS-18	127	J-13 WATER	7.7	6.1	4.36	8.21E+4	7.10E+5	300	5.20E+3	151.0	47.20	219.0	55.00	24.40	.21	.67	11.50	.39	272	N.A.	N.A.	N.A.	20.0
RGS-19	127	J-13 WATER	7.7	6.1	3.39	1.01E+5	5.42E+5	300	4.40E+3	135.0	50.00	270.0	65.00	34.40	.21	.65	10.00	.30	300	N.A.	N.A.	N.A.	25.0
NOMINAL J-13 WATER (PPM)										30.5	.14	45.7	.04	0.0	0.0	13.4	0.0	1.35	2	6.7	0	8.9	19.1
ANALYTICAL DETECTION LIMITS						100	50	6		.25	.01	.10	.01	.30	.05	.10	.03	.01	.10	.20	1.00	1.50	.50

NOTES: N.A. = DATA NOT AVAILABLE.
N.D. = SPECIES NOT DETECTED.
BKG. = ONLY BACKGROUND RADIATION DETECTED

DPM = DISINTEGRATIONS PER MINUTE
ICP DILUTION FACTOR = 10.
IC DILUTION FACTOR = 1-20.

TEST NAME DESIGNATION:
RG=RADIOACTIVE GLASS. NG = NONRADIOACTIVE GLASS, S=304L SS, T=TUFF.

APPENDIX 6: LEACHING SIMULATED SRP GLASS IN J-13 WATER.

TEST COMPONENTS:
TUFF ABSENT.
STEEL ABSENT.
GLASS PRESENT.

INITIAL VOLUME: 10.3 mL.
T = 90°C

GLASS SURFACE AREA = 10.3 CM2
T = 90°C

FINAL CONCENTRATIONS (PPM)

TEST NAME	LEACH TIME, DAYS	SOLUTION	INITIAL pH	FINAL pH	FINAL VOLUME	CATIONS Si	B	Na	Li	Al	Fe	Ca	Mn	Mg	Sr	U	ANIONS F-	Cl-	NO3-	HCO3-	SO4=
NG-1	28	J-13 WATER-H	7.4	9.3	12	58.8	3.00	67.8	5.25	.49	N.D.	4.03	N.D.	0	.04	.60	N.A.	N.A.	N.A.	N.A.	N.A.
NG-2	28	J-13 WATER-F				58.2	4.21	70.6	5.78	N.D.	N.D.	5.04	N.D.	.07	.07	.57	N.A.	N.A.	N.A.	N.A.	N.A.
NG-3	28	J-13 WATER-H	7.4	9.15	12	54.5	4.32	80.5	5.31	.71	.10	2.30	N.D.	0	.03	.64	N.A.	N.A.	N.A.	N.A.	N.A.
NG-4	28	J-13 WATER-F				52.4	4.45	70.3	3.04	N.D.	N.D.	3.04	N.D.	.05	.04	.51	N.A.	N.A.	N.A.	N.A.	N.A.
NG-5	91	J-13 WATER-H	7.4	9.6	17	77.8	8.26	98.4	10.72	1.10	.06	.07	N.D.	0	N.D.	.99	N.A.	N.A.	N.A.	N.A.	N.A.
NG-6	91	J-13 WATER-F				75.2	7.93	94.1	10.25	1.02	.10	2.00	N.D.	.010	.02	1.01	N.A.	N.A.	N.A.	N.A.	N.A.
NG-7	91	J-13 WATER-H	7.4	9.7	16	87.2	10.67	104.5	13.16	1.80	.74	.28	1.00	.0504	N.D.	1.44	N.A.	N.A.	N.A.	N.A.	N.A.
NG-8	91	J-13 WATER-F				87.4	10.04	108.1	13.37	1.40	.42	.03	.09	.0247	N.D.	1.39	N.A.	N.A.	N.A.	N.A.	N.A.
NG-9	180	J-13 WATER-H	7.4	10.2	10	108.8	14.90	140.0	19.60	2.03	.41	N.A.	.09	.0335	N.D.	2.29	9.30	13.4	N.A.	40.1	31.9
NG-10	180	J-13 WATER-F				102.0	14.40	130.0	17.90	1.80	N.D.	N.A.	N.D.	.0520	.05	2.20	0.53	13.7	N.A.	42	30.0
NG-11	180	J-13 WATER-H	7.4	9.9	14	97.1	15.90	120.0	19.10	1.70	.17	N.A.	.05	.0072	N.D.	2.32	5.4	11.4	N.A.	40.1	18.4
NG-12	71	J-13 WATER-F				98.5	10.00	120.0	19.30	1.75	N.D.	N.A.	N.D.	.0399	N.D.	2.35	0.5	10.9	N.A.	53.1	23.5
NOMINAL	J-13	WATER	(PPM)			30.5	.14	45.7	.04	0.0	0.0	13.4	0.0	1.35	0	0	2	6.7	0	0.9	19.1
	ANALYTICAL DETECTION		LIMITS			.25	.01	.10	.01	.30	.05	.10	.03	.01	.01	.5	.10	.20	1.00	1.50	.50

NOTES:
N.A. = DATA NOT AVAILABLE.
N.D. = SPECIES NOT DETECTED.
J-13 WATER-H = SOLUTION SAMPLED WHILE HOT.
J-13 WATER-F = SOLUTION SAMPLED AFTER COOLING AND FILTERING

ICP DILUTION FACTOR = 1.
IC DILUTION FACTOR = 1.

TEST NAME DESIGNATION: RG = RADIOACTIVE GLASS, NG = NONRADIOACTIVE GLASS, S = 304L SS, T = TUFF.