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Determining the Dissolution Rates of Actinide Glasses: A Time and Temperature Product Consistency Test Study (U)

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Determining the Dissolution Rates of Actinide Glasses:
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Vitrification has been identified as one potential option for the disposition of actinide materials such as Americium (Am), Curium (Cm), Neptunium (Np), and Plutonium (Pu). A process is being developed at the Savannah River Site to safely vitrify all of the highly radioactive Am/Cm material and a portion of the fissile (Pu) actinide materials stored on site. Vitrification of the Am/Cm will allow the material to be transported and easily stored at the Oak Ridge National Laboratory. The Am/Cm glass has been specifically designed to be (1) highly durable in aqueous environments and (2) selectively attacked by nitric acid to allow recovery of the valuable Am and Cm isotopes. A similar glass composition will allow for safe storage of surplus plutonium. This paper will address the composition, relative durability, and dissolution rate characteristics of the actinide glass, Löffler Target, that will be used in the Americium/Curium Vitrification Project at Westinghouse Savannah River Company near Aiken, South Carolina. The first part discusses the tests performed on the Löffler Target Glass concerning instantaneous dissolution rates. The second part presents information concerning pseudo-activation energy for the one week glass dissolution process.

Part I: Product Consistency Test Dissolution Rate Study

Product Consistency Test Description

One, two, four, and eight week Product Consistency Tests (PCT Test Method B) were completed on an actinide glass known as Löffler Target, fused silica, and quartz. The PCT's were done according to the requirements in the American Society for Testing and Materials (ASTM) Test Method C1285-94 *Determining Chemical Durability of Nuclear Waste Glasses: The Product Consistency Test (PCT)*[1] The experiment was designed to determine the dissolution rate of the actinide glass. Quartz and fused silica were included in the test matrix in order to baseline the data.

Each glass was done in triplicate for a one, two, four, and eight week duration. A total of 47 tests were performed on the Löffler Target, water blanks and an Approved Reference Material (ARM) glass. The water blanks were done for each duration time and the ARM glass was done in triplicate for the first week. Table VII lists the oxide compositions of the Loffler Target and ARM-1 glasses.

Each glass was ground using a Tekmar grinder with tungsten carbide blades. The ground glass was then sieved and a 100-200 mesh size collected in a beaker. The glasses were then washed by forcibly adding 15-20 ml of de-ionized water to the beaker and then decanting. This process was done three times. The glasses were also washed twice by forcibly adding 15-20 ml of de-ionized water, placing the beaker in an ultrasonic water bath for two minutes and then decanting. The process was repeated with ethyl alcohol. The glasses were then placed in a convection oven over night to dry.

Teflon® vessels were prepared to receive the dried samples. First, the vessels and lids were cleaned by soaking them in 0.16M Nitric Acid (HNO_3) at 90 ± 10°C for approximately one hour on a hot plate. These items were then rinsed with de-ionized water. The vessels were then soaked in fresh de-ionized water at 90 ± 10°C for about an hour on a hot plate. The vessels were filled 80% full with de-ionized water, capped, and placed in a convection oven at 90 ± 2°C for 16 hours. As expected, the pH values of the water after the 16 hour period were between 5.0 - 7.0.

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1 ASTM C 1285-94, Annual Book of ASTM Standards, American Society for Testing and Materials, Committee C-26 on Nuclear Fuel Cycle, Subcommittee C26.13 on Repository Waste Package Materials Testing, Volume 12.01, 1994.

Approximately 3.5 grams of each glass were then added to the cleaned Teflon® vessels and their weights recorded.

An Orion pH meter was calibrated using 4, 7, and 10 pH buffers. De-ionized water was collected at an electrical resistivity of 18 megaohms•cm and then a pH measurement was taken. The initial pH of the ASTM Type 1 water was 6.6. Approximately 35 grams of the de-ionized water was then added to each Teflon® vessel and a total weight of the vessel, water, and glass was recorded. The Teflon® vessels were capped using a CEM® capping station and then placed in a Blue M convection oven at 90 ± 2°C. The following day, the Teflon® vessels were removed and checked to make sure that they were still tightly sealed. The oven temperature was monitored at half an hour intervals during the course of the eight week period, using an Omega Thermocouple Thermometer. The temperature ranged from 90.0°C - 91.7°C during the eight week period.

After each test period was complete, the appropriate vessels were taken out of the convection oven and allowed to cool. The vessels were weighed and the weight recorded. All of the samples had a weight loss of less than 1% over the course of eight weeks. Each vessel was then uncapped and a pH taken. The final pH of the leachate solutions ranged from 5.0-7.5. There were no consistent increases or decreases in pH during the course of the eight week period. The pH measurements for each week are listed in Figure 1. The final pH levels of the ARM glass standards were 10.22, 10.26, and 10.27.

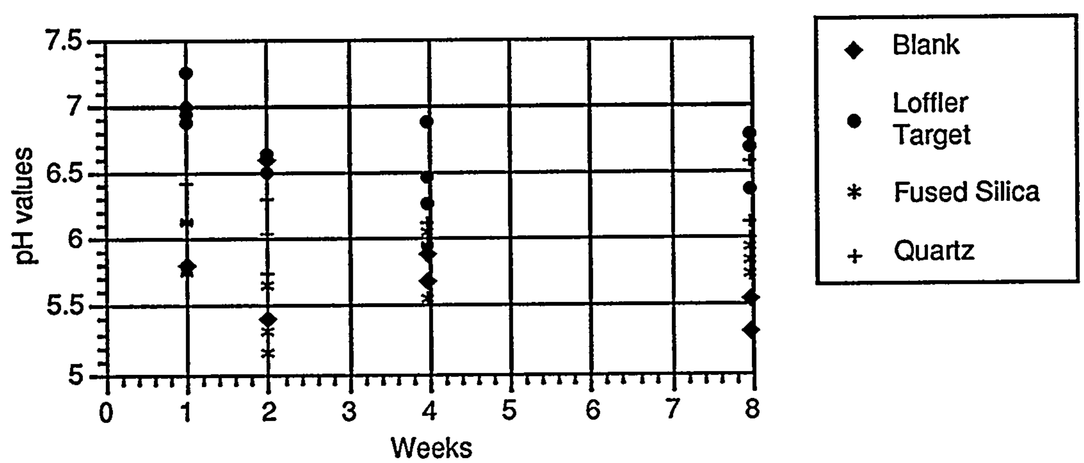

Figure 1. pH values of PCT Leachates at 90°C for various times

Sterilized syringes and filters were used to filter the leachate into pre-sterilized vials. A total of 20 ml was filtered into each vial and then 200 ml of ultrapure nitric acid was added. The samples were then submitted for elemental analyses on an Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES). Elements analyzed for the blanks, ARM glass standard, and Löffler glass leachates included Silicon (Si), Lead (Pb), Boron (B), Aluminum (Al), Neodymium (Nd), Barium (Ba), Europium (Eu), Lanthanum (La), and Cerium (Ce). Silicon was the only analysis run on the quartz and fused silica leachates due to their chemical composition.

Elemental analyses of the leachates for the one, two, four, and eight week duration times are listed in Table I. The elemental concentrations for the Löffler Target glass leachates were consistently lower than the glass standard, fused silica, and quartz. In the next section, dissolution rates are calculated from the data shown in Table I.

Table I. PCT Leachate Concentration Data at 90°C

(Results in ppm)	Si	Pb	B	Al	Nd	Ba	Eu	La	Ce
Week 1									
Blank 1-1	<0.05	<0.20	0.017	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
Blank 2-1	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
ARM 1-1	100	<0.20	48.1	3	0.532	0.186	<0.01	<0.03	0.897
ARM 2-1	106	<0.20	53.2	2.71	0.569	0.203	<0.01	<0.03	1.01
ARM 3-1	102	<0.20	51.3	2.87	0.495	0.182	<0.01	<0.03	0.897
Löffler 1-1	2.15	0.398	0.55	<0.15	<0.30	0.582	<0.01	<0.03	<0.15
Löffler 2-1	2.1	0.419	0.527	<0.15	<0.30	0.559	<0.01	0.05	<0.15
Löffler 3-1	2.17	0.414	0.512	<0.15	<0.30	0.567	<0.01	<0.03	<0.15
Quartz 1-1	37.2								
Quartz 2-1	42.4								
Quartz 3-1	42.9								
Fused Silica 1-1	51.9								
Fused Silica 2-1	52.4								
Fused Silica 3-1	51.7								
(Results in ppm)	Si	Pb	B	Al	Nd	Ba	Eu	La	Ce
Week 2									
Blank 1-2	<0.05	<0.20	0.02	<0.15	<0.30	<0.01	<0.01	0.06	<0.15
Blank 2-2	<0.05	<0.20	0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
Löffler 1-2	2.39	0.418	0.55	<0.15	<0.30	0.582	<0.01	<0.03	<0.15
Löffler 2-2	2.46	0.448	0.56	<0.15	<0.30	0.613	<0.01	<0.03	<0.15
Löffler 3-2	2.38	0.444	0.53	<0.15	<0.30	0.612	<0.01	<0.03	<0.15
Quartz 1-2	55.7								
Quartz 2-2	64.8								
Quartz 3-2	64.6								
Fused Silica 1-2	57								
Fused Silica 2-2	65.6								
Fused Silica 3-2	54.7								
Week 4									
Blank 1-4	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
Blank 2-4	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
Löffler 1-4	3.09	0.291	0.623	<0.15	<0.30	0.701	<0.01	<0.03	<0.15
Löffler 2-4	2.99	0.416	0.603	<0.15	<0.30	0.699	<0.01	<0.03	<0.15
Löffler 3-4	3.91	0.302	0.739	<0.15	<0.30	0.824	<0.01	<0.03	<0.15
Quartz 1-4	77								
Quartz 2-4	90.8								
Quartz 3-4	86.9								
Fused Silica 1-4	75.5								
Fused Silica 2-4	92.2								
Fused Silica 3-4	84.9								

Table I. Continued

Week 8									
Blank 1-8	0.058	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
Blank 2-8	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15
Löffler 1-8	3.64	0.564	0.725	<0.15	<0.30	0.777	<0.01	<0.03	<0.15
Löffler 2-8	3.46	0.607	0.704	<0.15	<0.30	0.741	<0.01	<0.03	<0.15
Löffler 3-8	3.39	0.61	0.704	<0.15	<0.30	0.741	<0.01	<0.03	<0.15
Quartz 1-8	107								
Quartz 2-8	102								
Quartz 3-8	90.8								
Fused Silica 1-8	105								
Fused Silica 2-8	110								
Fused Silica 3-8	105								

Dissolution Rate Calculation

Data obtained from one, two, four, and eight week PCT Tests were analyzed to determine the dissolution rates of the Löffler Target Glass, Fused Silica Glass, and Quartz. The dissolution rate equation can be written as:

(1a)
$$\frac{dC}{dt} = C_0 \bullet \frac{G}{t} \bullet \left[\frac{t}{t_0}\right]^G$$

where C is the concentration at time t, C_0 is the concentration at t_0, t is the time in weeks, t_0 represents one week, and G is the logarithmic release rate.[2] This rate model is based on the doctorate research of W. G. Ramsey and is supported by similar models in the literature.[3] The term G gets its name from its derivation from plotting the log of concentration ratios versus time ratios. More specifically, G is found by plotting $\ln(C/C_0)$ versus $\ln(t/t_0)$. In these studies, the concentrations were represented by ppm analyses. The log-log plots are shown in Figures 2 through 6.

[2]Ramsey, W. G., *Glass Dissolution Chemistry of the System Na_2O-B_2O_3-SiO_2-Al_2O_3-Fe_2O_3-CaO*, Ph.D. Thesis, Clemson University, 1994.
[3]Jantzen, C. M., "Prediction of Glass Durability as a Function of Glass Composition and Test Conditions: Thermodynamics and Kinetics," Proceedings of the First International Conference on Advances in the Fusion of Glass, American Ceramic Society, Westerville, OH, pp. 24.1-24.17, 1988.

Figures 2, 3, and 4 show the concentrations of Si, B, and Ba for the Löffler Target glass over a period of eight weeks. Figures 5 and 6 show the Si concentration in the PCT leachates for Quartz and Fused Silica, respectively, for this study. The numbers in the legends of these graphs refer to the sample vials taken. For each glass, three separate samples were maintained and calibrated against blank standards. The dashed lines in these figures represent the average of the Least Squares (LS) fit to each of the three samples' points. The slopes of these lines are the logarithmic rate terms (G) which are listed in Table II.

Table II. Average Logarithmic Release Rates (G) for Tested Glasses

Glass	Si Basis	B Basis	Ba Basis
Löffler Target	0.258	0.143	0.148
Quartz	0.470	*	*
Fused Silica	0.334	*	*

*not applicable

Using the logarithmic rates (G) found from Figures 2 through 6, the Instantaneous Dissolution Rates for the glasses were calculated using the following form of Equation (1a):

(1b)
$$\frac{dC}{dt} = \frac{ppm_i^0}{mf_i \bullet S_a/V \bullet AW_i} \bullet \frac{G_i}{t} \bullet \left[\frac{t}{t_0}\right]^{G_i}$$

where ppm_i^0 is the concentration of element i at time t_0 in milligrams per liter, mf_i is the moles of element i as an oxide per mole of glass, S_a/V is the Surface area per unit Volume , AW_i represents the Atomic Weight of Element i in milligrams per gram-mole, G_i is the dimension-less logarithmic release rate for element i, and t is the elapsed time in seconds. For the elements analyzed here, the mf_i terms for Loffler glass were determined from experiments to be 0.542 mole of Si as SiO_2 per mole of glass, 0.2112 mole of B as B_2O_3 per mole of glass, and 0.0169 mole Ba as BaO per mole of glass. Since the Fused Silica and Quartz samples are essentially pure SiO_2, the only mole fraction term for them is $mf_{Si} = 1$. The surface area to volume ratios were also determined based on experimental data to be 11,800 cm^2/L for the Löffler Target samples and 23,500 cm^2/L for the Quartz and Fused Silica samples. Equation (1b) gives the dissolution rates normalized to moles of glass reacted per second per cm^2. Table III contains the Löffler Target Dissolution Rates and Table IV contains the Fused Silica and Quartz rates. A plot of Table III is shown in Figure 7 and a plot of Table IV is shown in Figure 8.

Table III. Instantaneous Dissolution Rates normalized to Moles of Löffler Target Glass reacted per cm² per second

Time (weeks)	Si Basis	B Basis	Ba Basis
1	4.963E-15	4.530E-15	4.998E-15
2	2.968E-15	2.501E-15	2.769E-15
4	1.774E-15	1.381E-15	1.534E-15
8	1.061E-15	7.623E-16	8.498E-16

Table IV. Instantaneous Dissolution Rates normalized to Moles of Glass reacted per cm² per second (Si Basis)

Time (weeks)	Löffler Target	Quartz	Fused Silica
1	4.963E-15	4.802E-14	4.347E-14
2	2.968E-15	3.326E-14	2.740E-14
4	1.774E-15	2.303E-14	1.727E-14
8	1.061E-15	1.595E-14	1.088E-14

The raw analysis data used in this study are listed in Table I. Before any calculations were performed, the data was corrected based on the blank samples that were also analyzed. The first number in the sample names in Table I refer to the three vials that were taken while the second number refers to the week of the analysis.

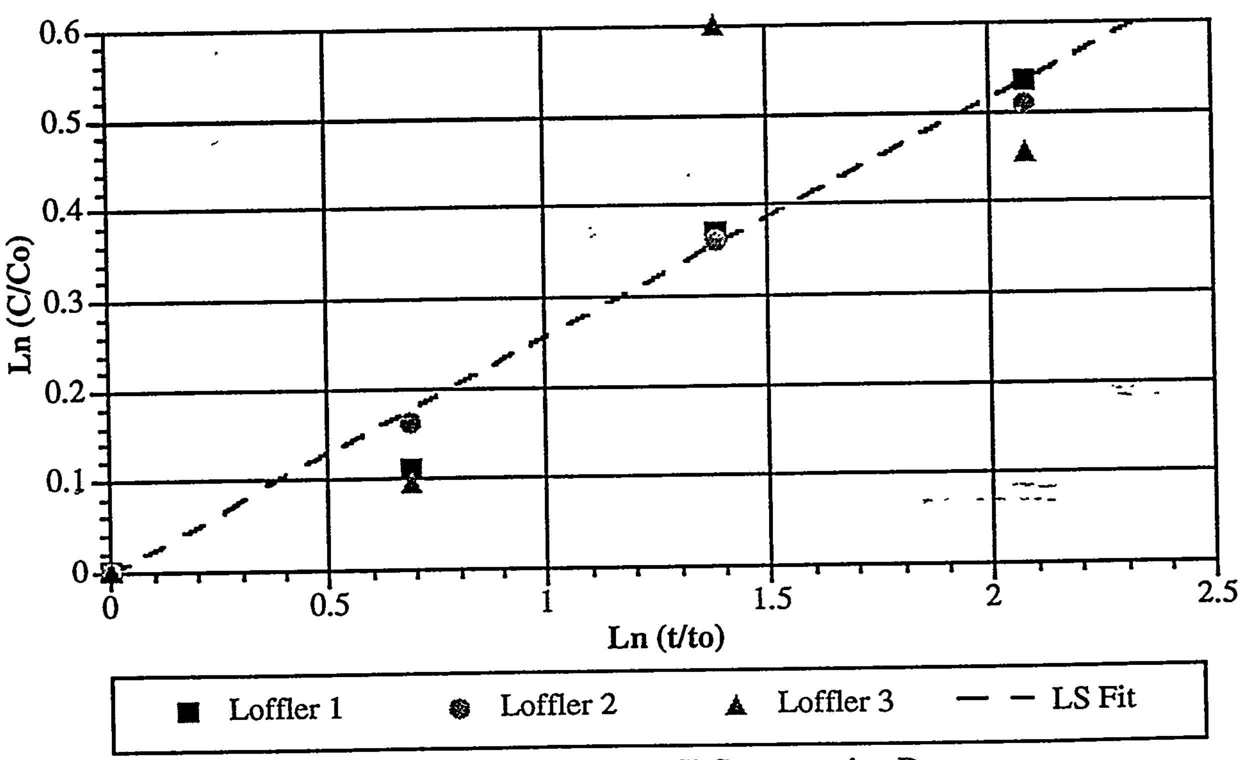

Figure 2. PCT Löffler Target Si Concentration Data

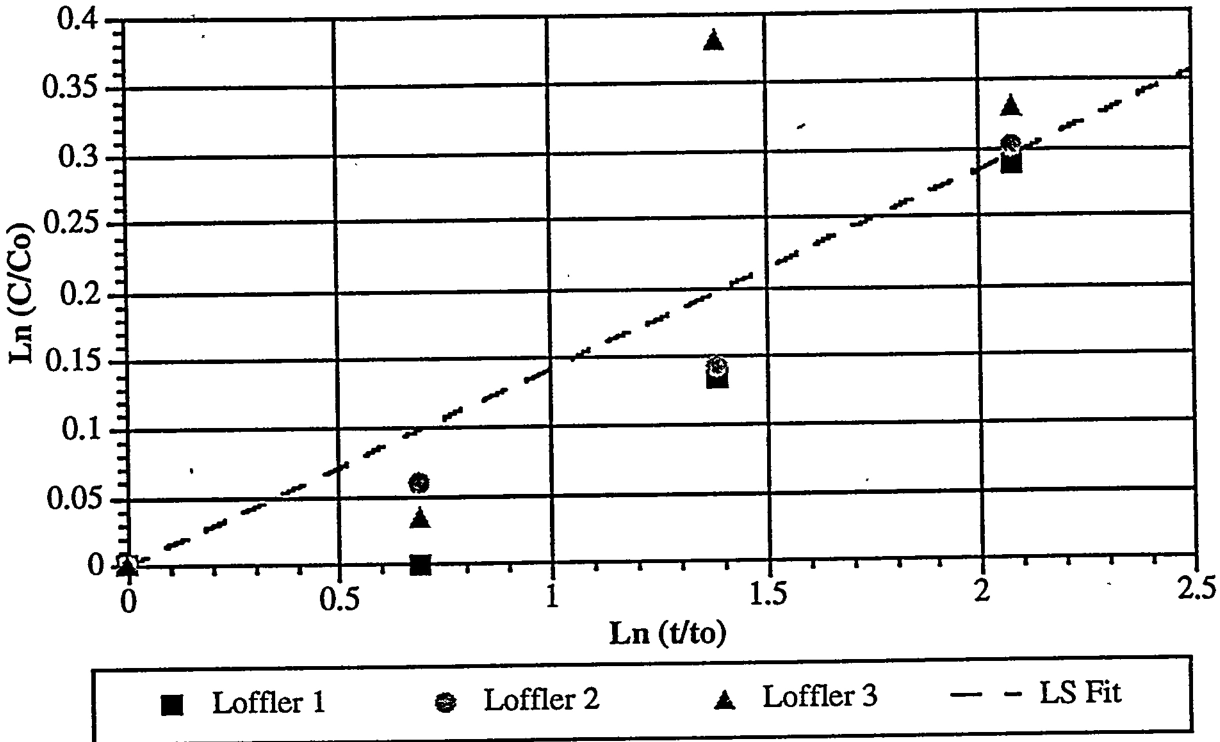

Figure 3. PCT Löffler Target B Concentration Data

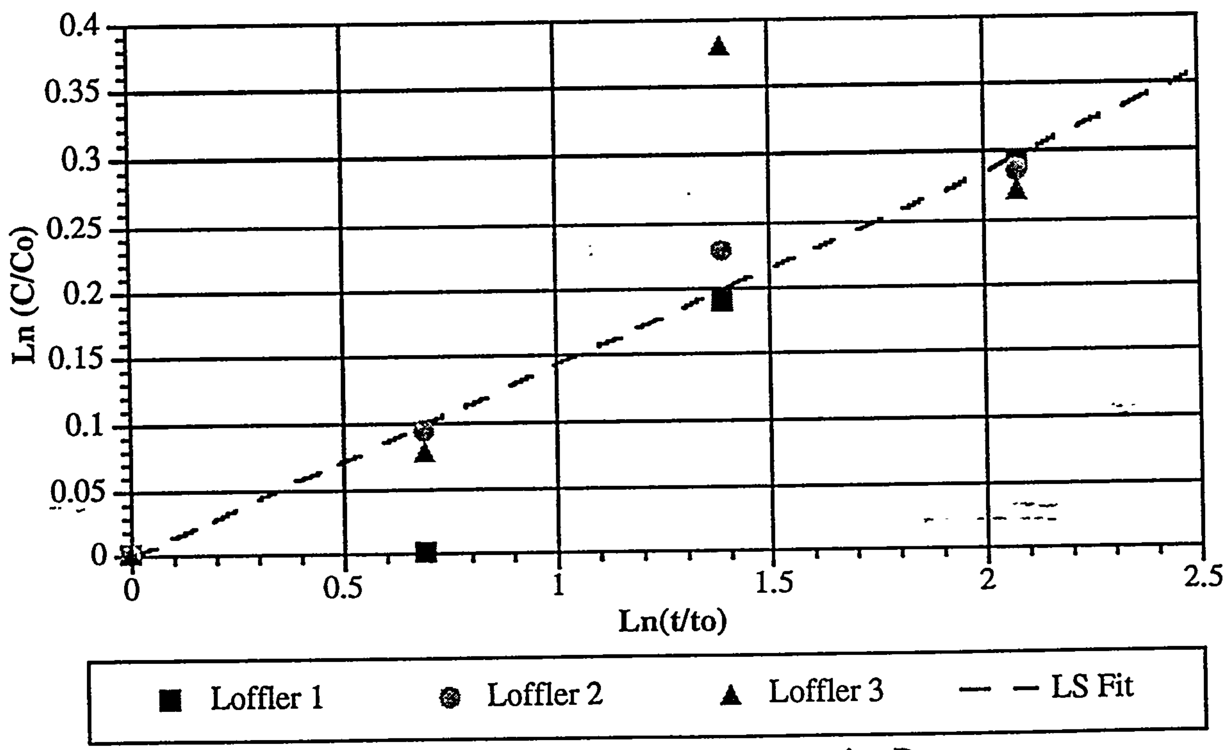

Figure 4. PCT Löffler Target Ba Concentration Data

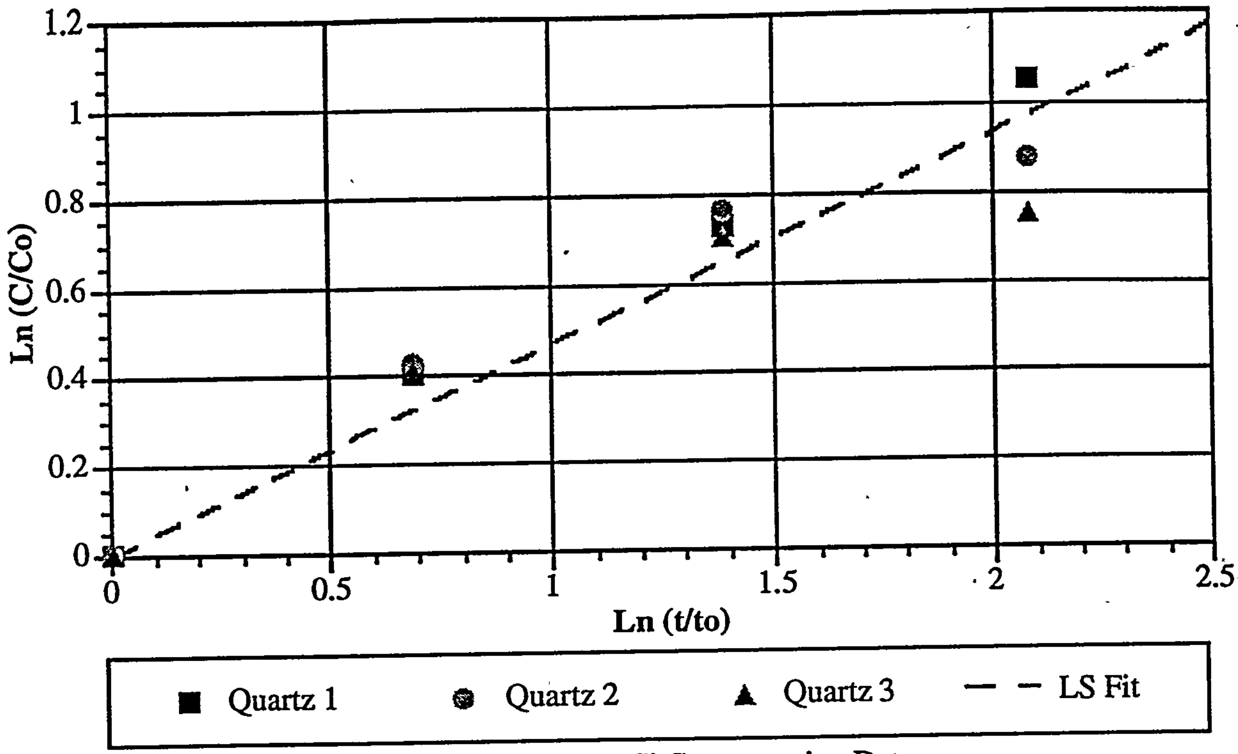

Figure 5. PCT Quartz Si Concentration Data

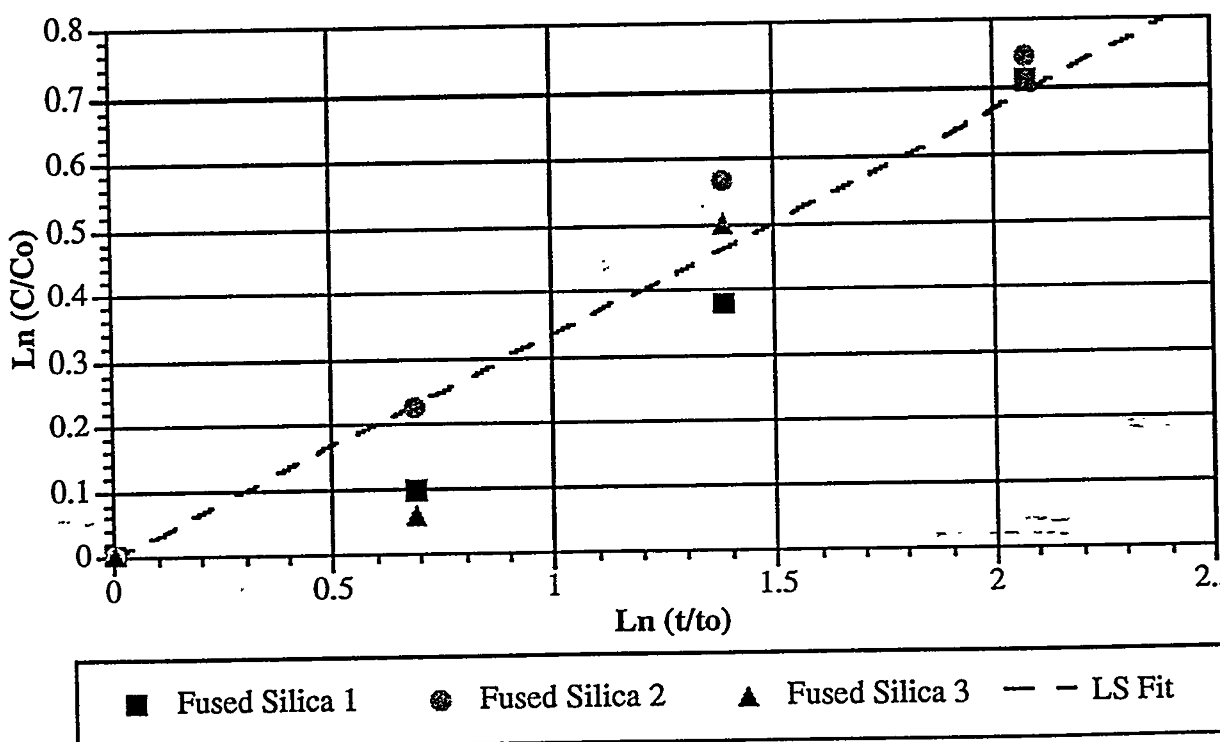

Figure 6. PCT Fused Silica Si Concentration Data

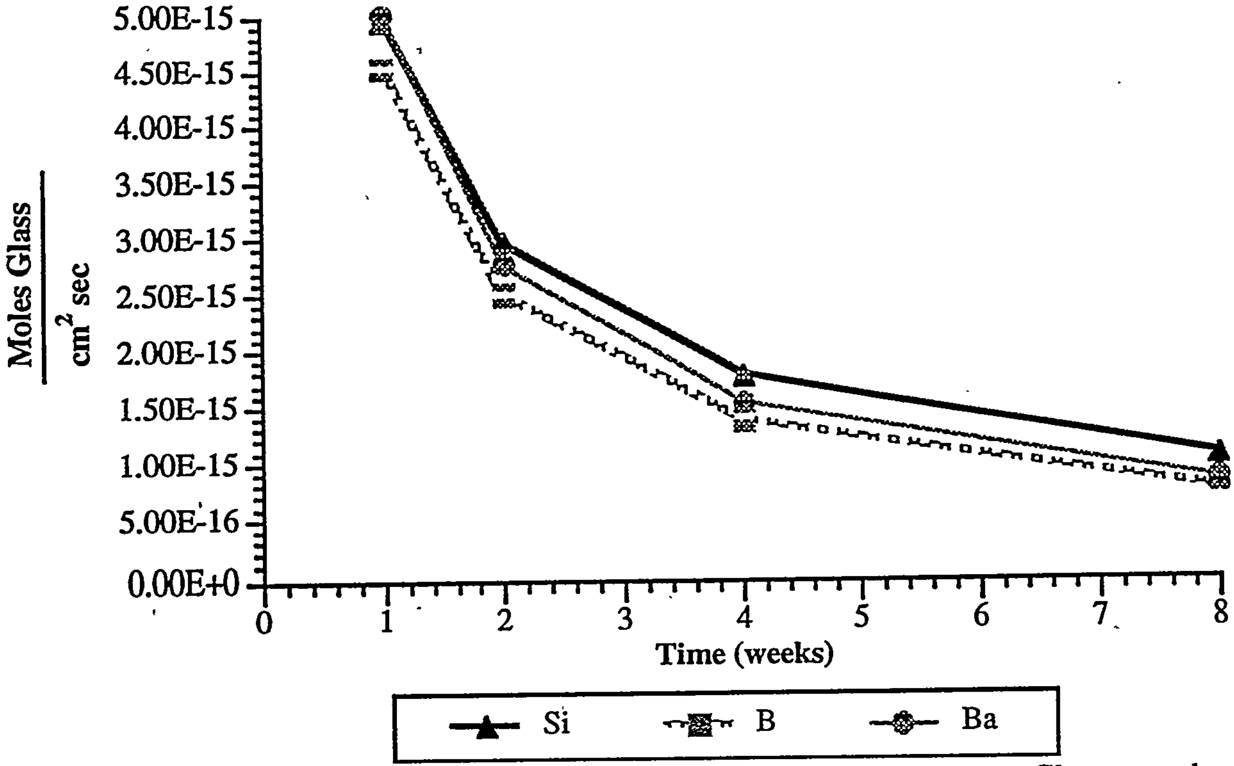

Figure 7. Instantaneous Dissolution Rate normalized to Moles of Löffler Target Glass reacted per cm^2 per second

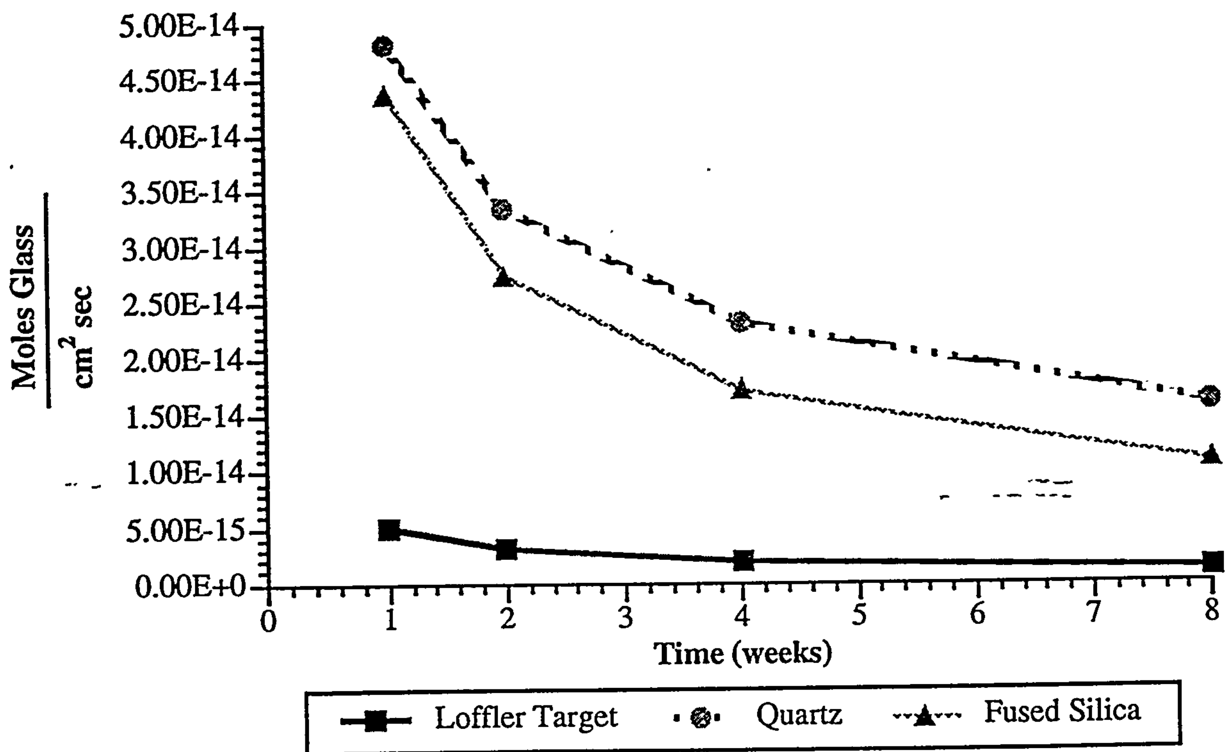

Figure 8. Instantaneous Dissolution Rates normalized to Moles of Glass reacted per cm^2 per second (Si Basis)

Part II: Activation Energies for PCT Dissolution

Temperature PCT Experiment Description

Product Consistency Tests (PCT's) were performed on the Löffler Target glass and reference ARM glass at 60°, 90°, 120°, 150°, 180°, and 210°C using Test Method B. These experiments were performed to the determine the activation energy for the dissolution rate of the actinide glass. A complete description of this PCT method is given in Part I of this document and also in ASTM Test Method C1285-94 *Determining Chemical Durability of Nuclear Waste Glasses: The Product Consistency Test (PCT)*.[1] Each glass was run in triplicate at each temperature for one week. A 10:1 ratio of leachate to glass was placed in PARR© stainless steel vessels instead of Teflon, due to the potential of high pressure build up in the vessels during testing. To prevent a vessel from rupturing, a MAWL (Maximum Allowable Water Level) was calculated to determine the safest volume of leachate to use for each temperature test:

(2) $$MAWL = 0.9 \bullet \frac{V}{V_m}$$

where V is the vessel volume and V_m is the volume multiplier as provided by the manufacturer for various temperatures. The final pH of the leachate for the Loffler glass test ranged from 5.8-7.2 and ARM ranged from 9.6-10.7. The pH values are listed in Figure 9.

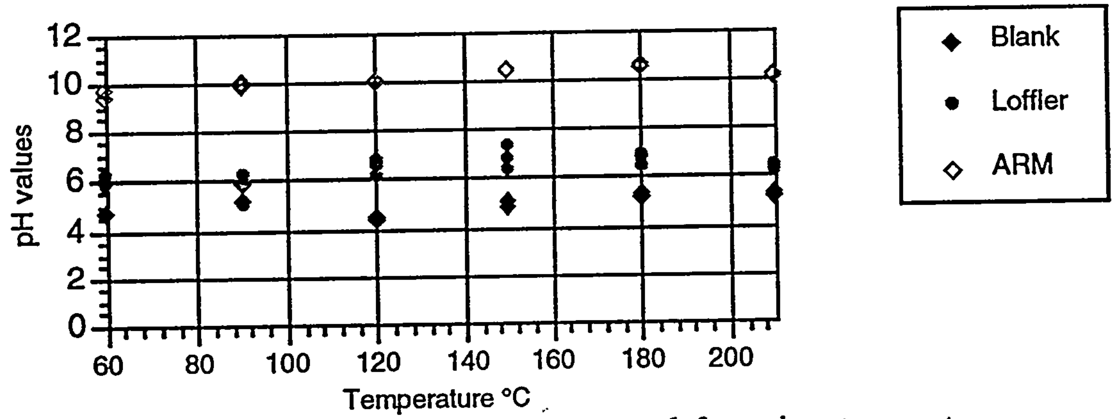

Figure 9. pH values of Leachates at one week for various temperatures.

Elemental analyses were performed on the leachates for Si, Pb, B, Al, Nd, Ba, Eu, La, Ce, Na, and Li. From the data in Table VI, activation energies for the Löffler Target glass and the reference ARM glass were calculated as shown in the next section.

Activation Energy Calculations

The activation energies were found using an Arrhenius type expression[4]:

(3) $$C(T) = A \bullet e^{-\frac{Ea}{RT}}$$

where C is the 7 day concentration of the leachate at temperature T, A is a pseudo-frequency factor, E_a is a pseudo-activation energy, and R is the gas constant.

[4]Perry, John H., *Chemical Engineer's Handbook*, 4th edition, McGraw-Hill Book Company, New York, 1963.

Taking the natural log of each side of this equation gives:

$$\ln C = \ln A - \frac{E_a}{RT} \tag{4}$$

By plotting the natural logs of the 7 day leachate concentrations (C) versus the reciprocal of absolute temperature (1/T), the "activation energy" term (E_a) can be obtained from the slope $-E_a/R$. Plots of the natural log of the concentrations versus the reciprocal temperature are shown in Figures 9, 10, and 11. To obtain the activation energies, a least squares fit of each component's data was performed and the equations from this fit are also shown in Figures 9, 10, and 11. The slopes from these equations were then multiplied by the gas constant 1.987 cal/(gmole·K). Table V contains the calculated activation energies along with their standard errors for the Löffler Target glass and the reference ARM glass. For comparison, activation energies from C. L. Crawford and N. E. Bibler's ARM data of 1992 were also computed.[5] Based on the Boron release, the ARM glass has an activation energy of 5.64 Kcal/gmole and Löffler Target has an activation energy of 5.31 Kcal/gmole.

Table V. Activation Energies of Löffler Target and ARM Glass in Kcal/gmole

Glass	Si Basis	B Basis	Ba Basis
ARM	5.31 ±0.10	5.64 ±0.22	*
ARM (Bibler)	5.83 ±0.21	5.91 ±0.32	*
Löffler Target	6.41 ±0.15	5.35 ±0.32	5.76 ±0.30

*not applicable

At each temperature, three samples were taken and all these individual points were used in the least squares calculations. However, the Arrhenius type expression was applied over certain ranges of the data based on the type of glass being analyzed. For the ARM glass, the Arrhenius expression holds from about 50°C to 180°C. Somewhere between 180°C and 210°C, the ARM dissolution rate increases as evidenced in Figures 9 and 10. This sudden rise indicates that the dissolution mechanism is also changing. A rate change is also observed in the Löffler glass around 150°C but unlike the ARM glass the Löffler dissolution rate appears to level off between 150°C and 210°C. Experiments were attempted at 300°C using Teflon and copper gaskets. However, neither held a seal at this temperature, and all the leachate evaporated. A complete listing of the experimental data is contained in Table VI.[6]

Conclusions

This experimental study has shown that the concentration of PCT leachate species is both time and temperature dependent. As time increases, the instantaneous dissolution rates decrease following a power-law relation. Comparing Löffler Target Glass with Quartz and Fused Silica, the Löffler Glass is more durable by an order of magnitude as shown in Figure 8. The temperature studies showed a similar result. As temperature increases the amount of dissolved leachate component increases following an Arrhenius type expression. The pseudo-activation energy for ARM-1 dissolution is approximately 23 KJ/gmole for temperatures less than 180°C, which agrees with the Crawford and Bibler value of 20 KJ/gmole.[4] The pseudo-activation energy for the Löffler Target Glass is around 23 KJ/gmole for temperatures less than 150°C. These experiments show that the temperature dependence of the PCT dissolution rate is similar between ARM-1 and Löffler glass

[5] Crawford, C. L. and N. E. Bibler, *Effects of Temperature and Radiation on the Nuclear Waste Glass Product Consistency Leach Test*, US DOE Report WSRC-MS-92-505, Westinghouse Savannah River Co., Savannah River Laboratory, Aiken, SC, 1992.

[6] Best, David R., *Product Consistency Testing,* WSRC-NB-92-55, WSRC-SRTC, Aiken, South Carolina, 1995.

which is expected due to their similar compositions as shown in Table VII. However, the ARM-1 glass shows a marked increase in its dissolution above 180°C whereas the Löffler Target glass shows a leveling off effect above 150°C. More temperature experiments are being planned to more fully understand the temperature and time effects on the PCT dissolution rates of the Löffler Target glass. These experiments will be conducted at the Westinghouse Savannah River Company -Savannah River Technology Center TNX laboratory near Aiken, South Carolina.

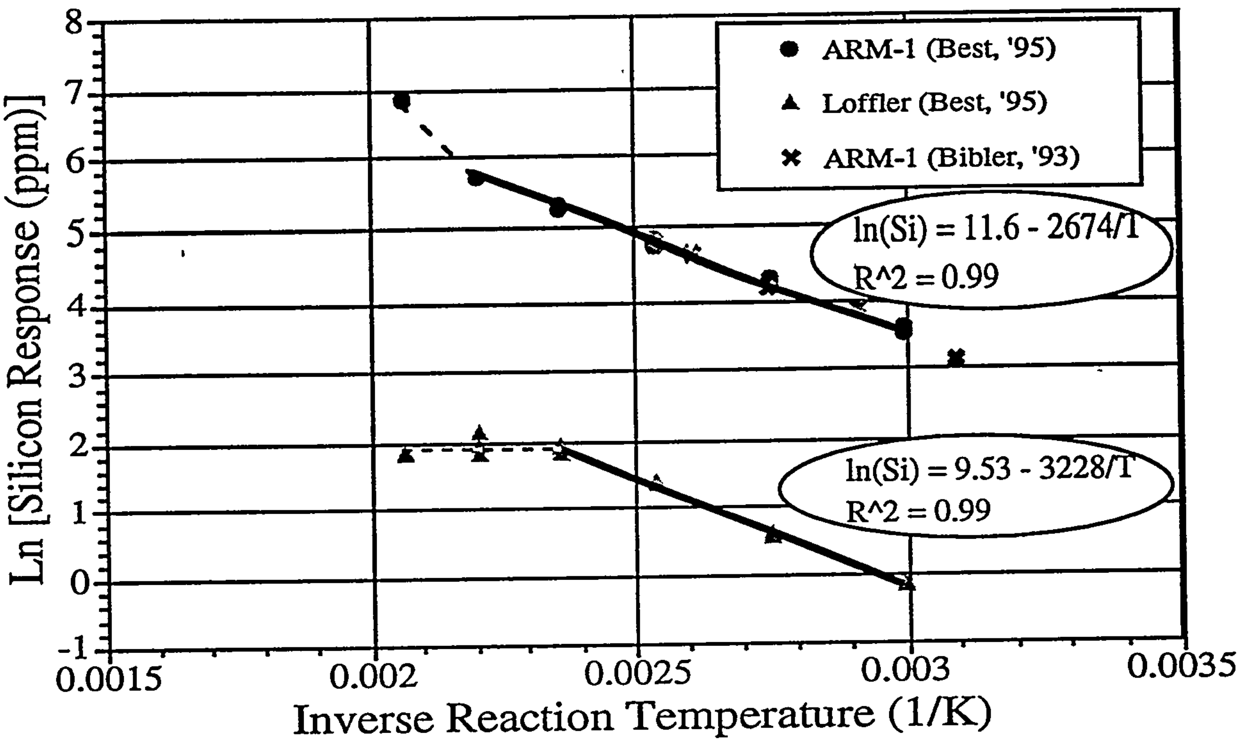

Figure 9. Natural Logarithm of One Week PCT Silicon Leachate Concentration versus Reciprocal of Absolute Reaction Temperature

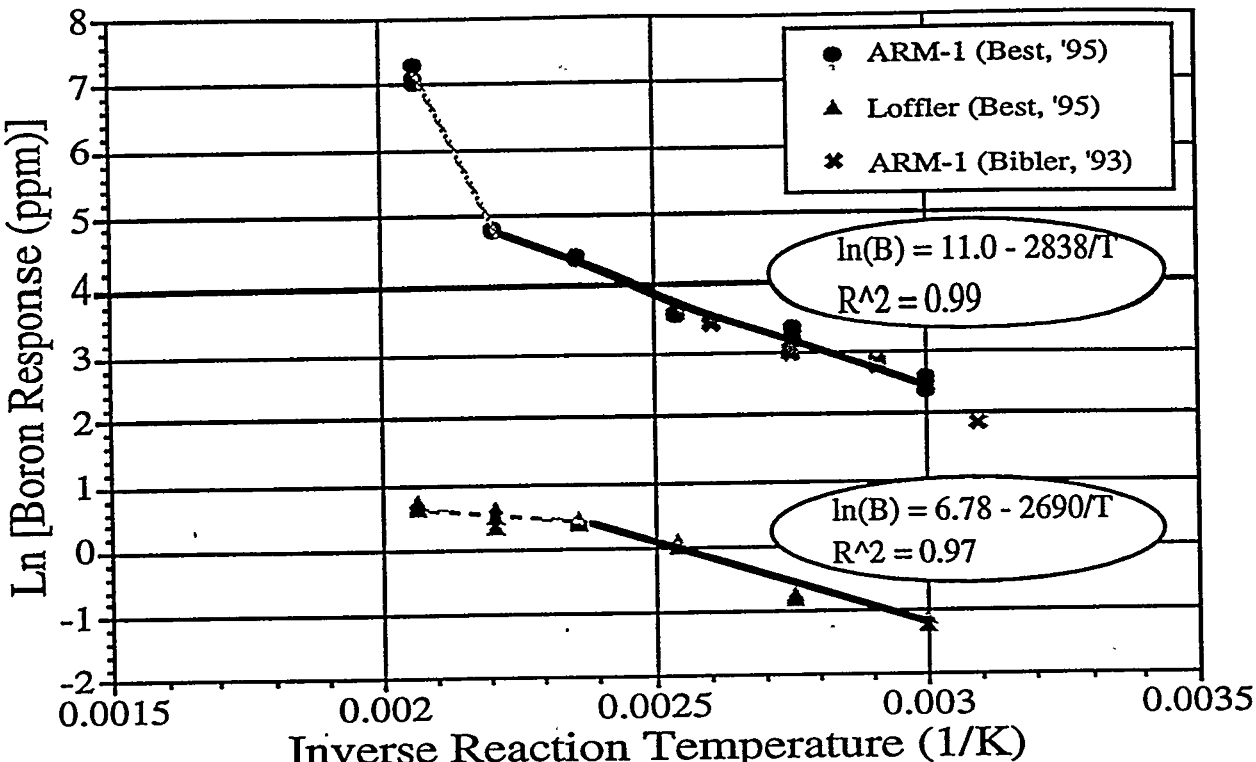

Figure 10. Natural Logarithm of One Week PCT Boron Leachate Concentration versus Reciprocal of Absolute Reaction Temperature

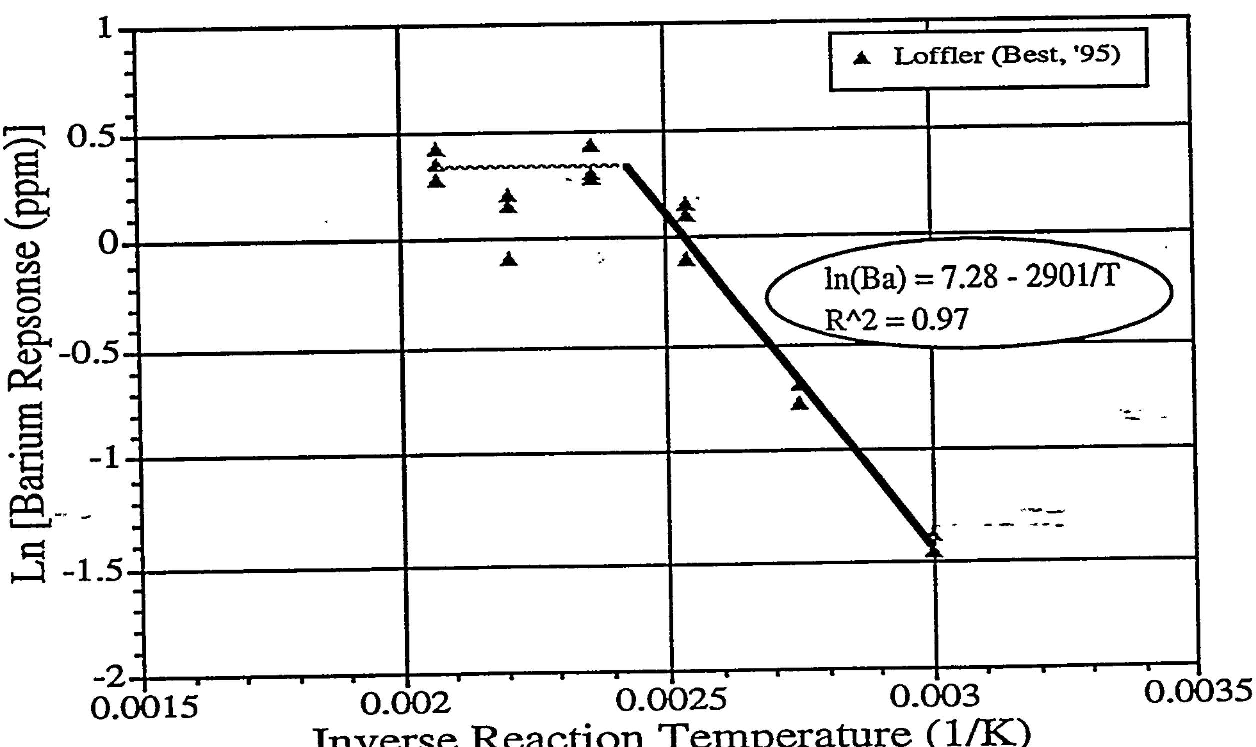

Figure 11. Natural Logarithm of One Week PCT Barium Leachate Concentration versus Reciprocal of Absolute Reaction Temperature

Table VI. PCT One Week Leachate Analyses at Various Temperatures

	Si	Pb	B	Al	Nd	Ba	Eu	La	Ce	Na	Li
60°C	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Blank 1-60	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	0.228	<0.015
Blank 2-60	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	0.569	<0.015
ARM 1-60	34	<0.20	11.9	1.58	<0.30	<0.01	<0.01	<0.03	<0.15	21.3	8.24
ARM 2-60	32.4	<0.20	10.6	1.76	<0.30	<0.01	<0.01	<0.03	<0.15	19.8	7.63
ARM 3-60	36.2	<0.20	13	1.51	<0.30	<0.01	<0.01	<0.03	<0.15	23.5	9.02
Löffler 1-60	0.902	<0.20	0.29	<0.15	<0.30	0.239	<0.01	0.049	<0.15	0.556	<0.015
Löffler 2-60	0.951	<0.20	0.342	<0.15	<0.30	0.239	<0.01	<0.03	<0.15	0.223	<0.015
Löffler 3-60	0.93	<0.20	0.289	<0.15	<0.30	0.258	<0.01	<0.03	<0.15	<0.100	<0.015
90°C											
Blank 1-90	0.059	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	0.519	<0.015
Blank 2-90	<0.05	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	<0.100	<0.015
ARM 1-90	70	<0.20	23.5	4.09	<0.30	<0.01	<0.01	<0.03	<0.15	44.3	17.1
ARM 2-90	75.7	<0.20	28.6	3.56	<0.30	<0.01	<0.01	<0.03	<0.15	51	19.9
ARM 3-90	73.6	<0.20	26.8	3.85	<0.30	<0.01	<0.01	<0.03	<0.15	48.4	18.8
Löffler 1-90	1.83	0.327	0.46	<0.15	<0.30	0.472	<0.01	<0.03	<0.15	<0.100	<0.015
Löffler 2-90	1.91	0.24	0.481	<0.15	<0.30	0.511	<0.01	<0.03	<0.15	<0.100	<0.015
Löffler 3-90	1.77	<0.20	0.437	<0.15	<0.30	0.465	<0.01	<0.03	<0.15	<0.100	<0.015
120°C											
Blank 1-120	1.83	<0.20	0.12	<0.15	<0.30	<0.01	0.02	0.03	<0.15	0.27	<0.015
Blank 2-120	1.12	<0.20	0.04	<0.15	<0.30	<0.01	0.02	0.03	<0.15	0.20	<0.015
ARM 1-120	115	<0.20	35.6	9.37	<0.30	<0.01	<0.01	0.107	<0.15	72.9	27.9
ARM 2-120	116	<0.20	36.2	9.50	<0.30	<0.01	<0.01	0.081	<0.15	74.2	28.1
ARM 3-120	126	<0.20	37.8	10.9	<0.30	<0.01	<0.01	0.091	<0.15	80.1	30.6
Löffler 1-120	5.50	<0.20	1.16	<0.15	<0.30	0.91	0.01	0.03	<0.15	0.39	<0.015
Löffler 2-120	5.47	0.70	1.14	<0.15	<0.30	1.11	<0.01	0.03	<0.15	0.26	<0.015
Löffler 3-120	5.40	0.81	1.09	<0.15	<0.30	1.17	0.01	0.04	<0.15	0.20	<0.015

Table VI. Continued

150°C	Si ppm	Pb ppm	B ppm	Al ppm	Nd ppm	Ba ppm	Eu ppm	La ppm	Ce ppm	Na ppm	Li ppm
Blank 1-150	0.076	<0.20	0.041	<0.15	<0.30	<0.01	<0.01	0.05	<0.15	0.137	<0.015
Blank 2-150	0.119	<0.20	0.092	<0.15	<0.30	0.011	<0.01	<0.03	<0.15	0.256	0.043
ARM 1-150	203	<0.20	80.6	18.2	<0.30	<0.01	0.01	0.06	0.257	156	55.1
ARM 2-150	200	<0.20	78.3	17.6	<0.30	<0.01	<0.01	0.04	0.267	151	53.6
ARM 3-150	186	<0.20	74.3	15.5	0.421	0.034	0.011	0.05	0.309	142	50.4
Löffler 1-150	6.75	0.609	1.6	<0.15	<0.30	1.54	<0.01	<0.03	<0.15	0.428	0.087
Löffler 2-150	7.02	<0.20	1.64	0.262	<0.30	1.35	<0.01	<0.03	<0.15	0.668	0.165
Löffler 3-150	6.38	0.432	1.5	<0.15	<0.30	1.33	<0.01	<0.03	<0.15	0.642	0.122
180°C											
Blank 1-180	0.298	<0.20	0.049	<0.15	<0.30	<0.01	<0.01	0.043	<0.15	0.218	0.025
Blank 2-180	0.163	<0.20	<0.01	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	0.138	<0.015
ARM 1-180	288	<0.20	113	21.6	<0.30	<0.01	<0.01	<0.03	<0.15	230	75.6
ARM 2-180	287	<0.20	112	22.5	<0.30	<0.01	<0.01	<0.03	<0.15	229	74.6
ARM 3-180	303	<0.20	119	21.4	<0.30	<0.01	<0.01	0.035	<0.15	262	79.6
Löffler 1-180	6.32	<0.20	1.43	0.192	<0.30	0.933	<0.01	<0.03	<0.15	1.14	0.238
Löffler 2-180	8.7	<0.20	1.84	<0.15	<0.30	1.22	<0.01	<0.03	<0.15	1.12	0.24
Löffler 3-180	7.14	0.324	1.64	<0.15	<0.30	1.17	<0.01	<0.03	<0.15	0.925	0.201
210°C											
Blank 1-210	0.221	<0.20	0.015	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	0.211	<0.015
Blank 2-210	0.206	<0.20	0.022	<0.15	<0.30	<0.01	<0.01	<0.03	<0.15	0.26	<0.015
ARM 1-210	895	0.278	1100	5.85	<0.30	0.04	0.036	0.05	0.442	1380	387
ARM 2-210	954	0.322	1500	6.16	0.307	0.049	0.044	<0.03	0.483	1750	506
ARM 3-210	888	0.303	1200	5.46	0.301	0.039	0.037	<0.03	0.445	1470	424
Löffler 1-210	6.41	<0.20	1.89	<0.15	<0.30	1.43	<0.01	0.04	0.199	0.819	0.156
Löffler 2-210	6.72	<0.20	1.93	<0.15	<0.30	1.53	<0.01	0.08	0.218	0.852	0.195
Löffler 3-210	6.67	<0.20	2.09	0.276	0.401	1.33	<0.01	0.05	0.305	1.14	0.311

Table VII. Löffler Target and ARM-1 Glass Compositions

Oxide	ARM-1 Wt %	Löffler Target Wt %
Al_2O_3	5.59	6.24
B_2O_3	11.3	6.19
BaO	*	2.25
CaO	2.24	*
CeO_2	1.51	*
Ce_2O_3	*	8.22
Cs_2O	1.17	*
Eu_2O_3	*	0.72
Fe_2O_3	*	*
FeO	*	*
K_2O	*	*
La_2O_3	*	23.3
Li_2O	5.08	*
MgO	*	*
MnO	*	*
MnO_2	*	*
MoO_3	1.66	*
Na_2O	9.66	*
Nd_2O_3	5.96	11.62
PbO	*	13.48
SiO_2	46.5	27.97
TiO_2	3.21	*
ZnO	1.46	*
ZrO_2	1.8	*

*not applicable