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Characterization of Cement and Bitumen Waste Forms Containing Simulated Low-Level Waste Incinerator Ash

Pacific Northwest Laboratory
Operated by
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Incinerator ash from the combustion of general trash and ion exchange resins was immobilized in cement and bitumen. Tests were conducted on the resulting waste forms to provide a data base for the acceptability of actual low-level waste forms. The testing was done in accordance with the U.S. Nuclear Regulatory Commission Technical Position on Waste Form. Bitumen had a measured compressive strength of 130 psi and a leachability index of 13 as measured with the ANS 16.1 leach test procedure. Cement demonstrated a compressive strength of 1400 psi and a leachability index of 7. Both waste forms easily exceed the minimum compressive strength of 50 psi and leachability index of 6 specified in the Technical Position. Irradiation to 10^8 RAD and exposure to 31 thermal cycles ranging from +60° to -30°C did not significantly impact these properties. Neither waste form supported bacterial or fungal growth as measured with ASTM G21 and G22 procedures. However, there is some indication of biodegradation due to co-metabolic processes. Concentration of organic complexants in leachates of the ash, cement and bitumen were too low to significantly affect the release of radionuclides from the waste forms. Neither bitumen nor cement containing incinerator ash caused any corrosion or degradation of potential container materials including steel, polyethlyene and fiberglass. However, moist ash did cause corrosion of the steel.

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EXECUTIVE SUMMARY

The objective of this work is to provide a data base for the U.S. Nuclear Regulatory Commission (NRC) to use to assess the acceptability of cement and bitumen waste forms for the disposal of low-level waste incinerator ashes. The incinerator ash and the cement and bitumen waste-form specimens were prepared with industrial-scale equipment. Tests on the waste forms were conducted in accordance with the NRC's Technical Position on Waste Form. These tests include mechanical strength, leachability, radiation stability, thermal cycling, and biodegradation. In addition, tests were conducted to identify organic complexants in the leachates and to identify potential interactions between the two waste forms and container materials.

The ash used in this study was a mixture of two ashes from the combustion of ion exchange resin and general trash which was composed of paper, plastic, wood, rubber, and cloth. Non-radioactive cesium, strontium, cobalt, and iodine were added to simulate the radionuclides in actual low-level wastes. The iodine was lost during the incineration.

Werner and Pfleiderer Corporation (now WasteChem Corporation) produced the bitumen specimens with an ash loading of 40 wt%. Because of bitumen's relatively large thermal expansion coefficient, four successive pourings were required to completely fill the molds. A larger, 5-gallon specimen showed a concentration gradient from top to bottom and had a spongy layer on top. However, samples taken from throughout the specimen excluding the spongy layer showed no variation in compressive strenth. Smaller 5x10 cm (2x4 in.) cylindrical specimens were used for most testing. Bitumen showed an average compressive strength of 130 psi as measured with the ASTM D1074 procedure. The strengths ranged from 108 to 145 psi for the leached, irradiated, thermal cycled and large-scale samples. These easily exceed the 50 psi minimum required in the Technical Position on Waste Form. The leachability of bitumen is so low that it caused some difficulties with the chemical analyses of the leachates. The leachability index based on cesium and strontium as measured by the ANS 16.1 leach test procedure was 13 compared with a required minimum of 6. The calculated index ranged from 12.2 and 14.3 depending on the test treatments given the specimens prior to leaching. Bitumen did not support bacterial or fungal growth as measured by the ASTM G21 and G22 procedures. However, there is some indication that bitumen may be subject to attack by the byproducts of the metabolism of the organisms (co-metabolism). This needs further study.

Cement waste-form specimens were prepared with a high-shear mixer at the Pacific Northwest Laboratory. The cement/ash mixtures had a tendency to foam, apparently due to the relatively acidic resin-ash component. The foaming could be controlled by adding sodium hydroxide solution to the ash. The large 5-gallon specimen of cement was chemically homogeneous although there was perhaps more porosity near the top. There was a variation in the compressive

strength of the cement with samples from the bottom showing strengths of 2500 psi and 1400 psi at the top. This is probably a result of premature drying of the cement at the exposed top surface. The smaller 5x10 cm (2x4 in.) cylindrical cement test specimens demonstrated an average compressive strength of 1360 psi with a range of 1320 to 1410 psi for the as-prepared, irradiated, and thermal cycled specimens. Specimens that had been leach tested had compressive strengths of 2100 psi. The leachability index for the as-prepared cement was 7.3 based on cesium and 8.7 based on strontium. As with bitumen there were some problems with the chemical analyses of the leachates so it is not possible to make direct comparisons between as prepared and treated cement specimens. However, it is apparent that there were no significant effects of irradiation, thermal cycling or leaching in a simulated Barnwell groundwater on the leachability of the cement. Cement did not support bacterial or fungal growth as determined by the ASTM G21 and G22 procedures. There is some evidence that co-metabolism may increase the rate of radionuclide release but, further study is needed.

In general both cement and bitumen containing incinerator ash meet the requirements outlined in the Technical Position on Waste Form. Areas of concern are the foaming observed with both waste forms, and the potential for biodegradation of the waste forms due to co-metabolism by bacteria and fungi.

A test was conducted to identify organic species released during the leaching of ash, bitumen and cement. Most of the organics were carboxylic acids although three chelating agents (NTA, EDTA, and ED3A) were also identified. Concentrations of the organic species were in the parts-per-billion (ppb) range and are therefore below the concentrations necessary to significantly impact the release and migration of radionuclides.

A screening test was conducted to determine if the bitumen, cement, and/or ash could cause degradation of potential container materials including steel, fiberglass and polyethylene. The cement and bitumen did not react with any of the container materials. There could be a problem if the bitumen or ashes were hot enough to thermally decompose the fiberglass or polyethylene. Dry ash does not present a corrosion problem. However, if the ash becomes wet then corrosion of the steel will occur. Ash saturated with water caused corrosion of carbon steel (AISI-1006) at a rate of 0.7 mm per year. The amount of moisture absorbed by ash in equilibrium with air does not cause a problem.

1. INTRODUCTION

One method for treating combustible low-level radioactive waste is to incinerate the waste and immobilize the resulting ash in a cement, bitumen, or organic polymer. The resulting waste form must comply with federal regulations for low-level wastes as defined in 10 CFR Part 61 "Licensing Requirements for Land Disposal of Radioactive Waste" (Federal Register 1982). The only performance required of the waste form is that it or its container be structurally stable such that it maintains its physical dimensions under disposal conditions and that it contain no more than one volume-percent free-standing liquid. The Nuclear Regulatory Commission has issued a Technical Position on Waste Form (USNRC 1983) that provides guidance on test methods and test results that are acceptable to the NRC for demonstrating performance of the waste form. Included are tests for mechanical strength, radiation stability, leachability, stability to thermal cycling, and resistance to biodegradation.

The primary objective of the work presented here is to provide a data base that the NRC can use to assess the acceptability of proposed waste forms for the disposal of low-level waste incinerator ashes. In the first phase of the project, an ash was produced by the combustion of simulated low-level waste general trash and spent resin in a controlled-air industrial incinerator (Treat, Lokken, and Schliebe 1983). In the second phase, the ash was immobilized in cement and bitumen, again using industrial equipment to produce the waste forms. The waste forms were then subjected to the battery of tests listed in the NRC Technical Position on Waste Form.

In addition, a simple screening test was conducted to identify potential problems due to the interaction of the ash, cement, or bitumen with potential waste-form container materials including steel, fiber-glass, and polyethylene. Also, a test was conducted to identify organic complexants in the leachates of the cement and bitumen.

This report begins with a description of the preparation of the cement and bitumen waste forms containing the incinerator ash. Next, the characterization of the waste forms using the tests specified in the Technical Position is reviewed. The container corrosion tests and the organic speciation tests are then discussed, followed by the conclusions and recommendations.

2. PREPARATION OF CEMENT AND BITUMEN WASTE FORMS

Ashes produced by the incineration of a simulated, light-water-reactor combustible waste were solidified in Portland cement and in bitumen.

2.1 Incineration of Combustible Waste

Combustible wastes were burned in a controlled-air incinerator in two batches, A and B. Materials that comprised the two batches are listed in Table 1. Before incineration, the combustible materials were sprinkled with solutions containing nonradioactive spiking chemicals as indicated in Table 2.

Table 1. Simulated Combustible Waste

Batch A (General Trash)	Weight (pounds)
PVC Plastic	300 (140 kg)
Polyethylene	3300 (1500 kg)
Sulfite Paper	400 (180 kg)
Kraft Paper	800 (360 kg)
Wood (fir)	400 (180 kg)
Rubber (latex)	300 (140 kg)
Cloth (cotton)	100 (45 kg)
Batch B (Resins)	
Cation Exchange Resin	3100 (1400 kg)
Anion Exchange Resin	1100 (500 kg)
Crud (Fe_2O_3)	160 (73 kg)
(CuO)	40 (18 kg)

Table 2. Combustible Waste Spiking Solutions

Compounds	Batch A	Batch B
$CsNO_3$	126 g	710 g
$Sr(NO_3)_2$	204 g	1150 g
$Co(NO_3)_2$	852 g	4824 g
CaI_2	200 g	1123 g
H_2O	41 L	21 L

The spiking chemicals were added to serve as nonradioactive tracers for leaching tests on solidified ashes. Ashes recovered from the incineration of Batches A and B weighed 122 kg and 148 kg, respectively. Details on the incineration and analysis of the ash are provided by Treat, Lokken, and Schliebe (1983).

Prior to solidification, ashes from Batches A and B were thoroughly blended to ensure consistency when preparing solidified samples. First, the partially burned clinkers (approximately 2.5 cm dia.) were removed to assure that they did not hinder the manufacture of small-scale, solidified samples. Then the two ashes were alternately layered into 30-gallon drums to achieve the first stage of blending and to overcome the effects of any possible ash segregation that may have existed in the shipping drums. The ashes were combined in a ratio of 122 weight parts of Ash A to 148 weight parts of Ash B in accordance with their production ratio. The contents of the 30-gallon drums were then placed in a high shear mixer manufactured by Littleford Brothers, Inc. (Figure 1) and were blended at 155 RPM for two minutes. The blended ash was then

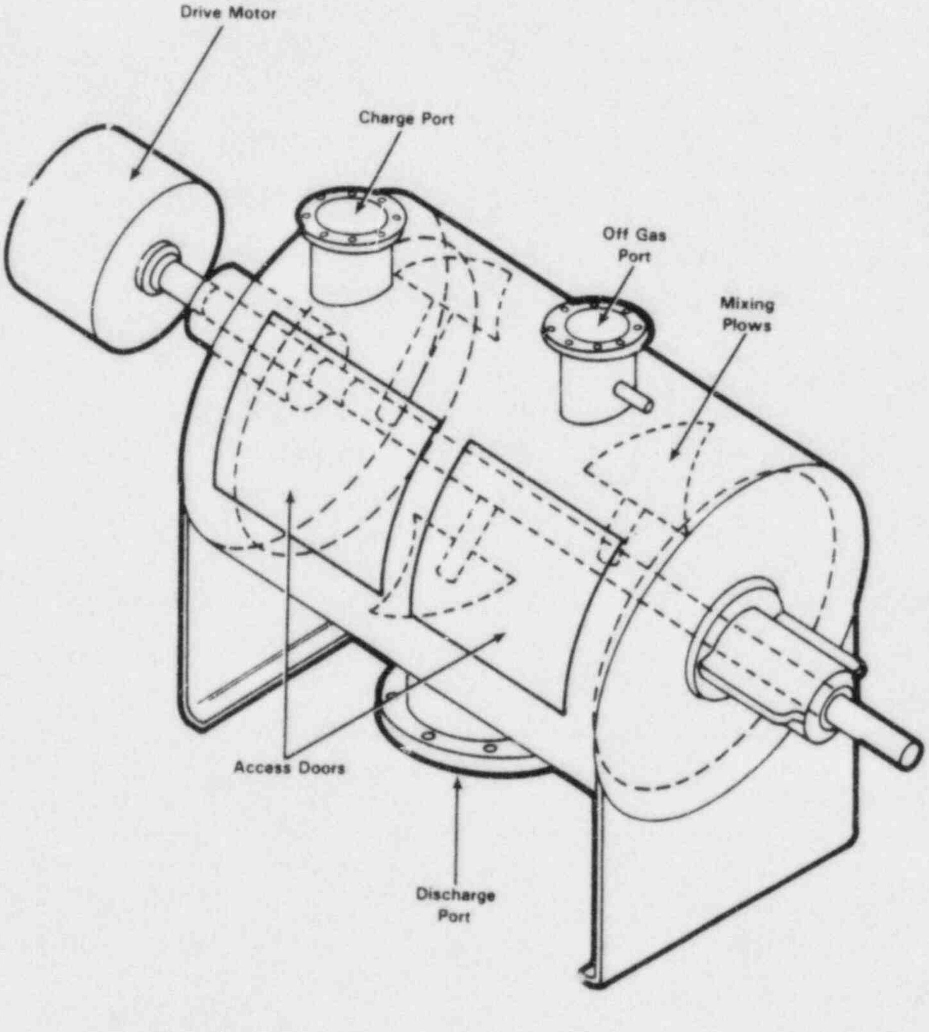

Figure 1. High shear mixer used for blending ashes and preparing cement waste forms

sieved through a 1/4 in. screen to remove any remaining clinkers. The oxide compositions of the individual ashes and the blended ash are shown in Table 3. The true powder density of the blended ash was 2.40 g/cm^3.

Table 3. Oxide Composition of Ashes (weight %)

Oxide [(a)]	Batch A (General Trash)	Batch B (Resin)	Blended Ash
Al_2O_3	20.3	0.18	8.73
B_2O_3	--	0.04	0.05
BaO	0.02	0.01	0.01
CaO	5.45	0.36	2.25
Co_2O_3	0.21	0.69	0.49
Cr_2O_3	0.04	0.04	0.03
CuO	0.13	10.3	5.81
Fe_2O_3	0.94	40.1	20.6
K_2O	0.8	--	0.5
MgO	0.57	0.08	0.24
Na_2O	0.7	0.28	0.6
P_2O_5	0.5	--	0.2
SiO_2	25.1	0.72	11.3
SrO	0.11	0.24	0.19
TiO_2	1.58	0.05	0.68
ZnO	0.08	0.07	0.08
ZrO_2	--	0.01	0.21[(b)]
Cs_2O	0.021	0.071	0.047
TOTAL	56.55[(c)]	53.24[(c)]	52.02[(c)]

(a) Oxidation state is assumed.

(b) Values are high due to contamination from the zirconia grinding media.

(c) The remainder of the ash weight can be attributed primarily to the presence of carbon. Some sulfur is also present.

2.2 Preliminary Solidification Tests

Preliminary ash solidification tests were conducted to determine ash and solidifying media mix ratios that would likely result in adequate waste forms. These tests involved Dow vinyl ester, Portland cement, and bitumen.

A sample of the blended ash was forwarded to the Dow Chemical Company to permit an evaluation of the compatibility of the ash with Dow vinyl ester. Dow reported that it was unsuccessful in its attempts to solidify the ash, but did not provide an explanation. Thus, vinyl ester was dropped from consideration as a solidifying medium. Subsequent discussions with users of vinyl ester revealed that the proper polymerization of vinyl ester is sensitive to the presence of elemental carbon. This suggests that if vinyl ester is to be successfully used for solidifying ashes, the maximum elemental carbon content permissible in an ash/vinyl ester mix must be established, as must the variation in the carbon content of the ashes produced by the particular incinerator used.

A small amount of blended ash was also combined with type II Portland cement with ash contents, on a dry weight basis, ranging from 0% to 60% in 10% increments. The ash and cement were mixed dry and then sufficient water was added to produce a paste with a soft ice cream consistency. The paste was vibrated into plastic pill vials, capped, and set aside. The water-to-solids ratio varied from 0.34 with no ash, to 0.40 with 60 wt% ash. The average water-to-solids ratio was 0.35 for the majority of ash loadings. Soon after casting, the samples underwent a chemical reaction that liberated gas. This caused bloating which increased with ash content. After setting and curing, the samples were removed from their containers. The 50% and 60% ash-content samples were friable and broke apart on removal from their containers. The 10%, 20%, 30% and 40% samples appeared strong and fairly dense. The samples containing up to 40% ash were immersed in water at room temperature for 7 days. None of the immersed samples appeared to suffer any loss of mechanical integrity.

In an attempt to minimize the bloating problems, the ash was mixed with 1 M NaOH solution and allowed to react for one hour at room temperature. The initial experiment used a volume of NaOH solution which corresponded to a water-to-solids ratio in the final product of 0.34. Following the reaction step, an appropriate amount (70% on a dry weight basis) of cement was added, blended, and cast as before. After about two hours, the paste again showed signs of reaction and foaming. Additional pre-reaction studies used four times the volume of NaOH solution with the solution heated to 70°C for 1/2 h. The ash was allowed to react overnight (16 h) and then was mixed with cement. This product was apparently free from reaction and the resulting foaming. Thus, it appears that the high pH of cement (>12) causes reactions with the ash (pH ≈ 5). Subsequently, Batch A and B ashes were individually mixed with Portland cement and water. No foaming occurred in the Batch A mix, but foaming was severe in the Batch B mix. Because the source of Batch B ash was largely a sulfonated polystyrene, it is postulated that the foaming was caused by the release of a sulfur-bearing gas.

A small amount of ash (35 wt%) was also mixed with bitumen and cast into molds lined with aluminum foil. The castings appeared sound, except that some small bubbles were present. Refrigeration of the molds enabled the foil to be fairly easily peeled from the castings.

2.3 Solidification of Ash in Portland Cement

As a result of preliminary testing, a mixture of 30 weight parts of ash to 70 weight parts of cement was selected for further testing. This ratio is reasonably consistent with loadings tested at Brookhaven National Laboratory (Columbo and Nielson 1979) and elsewhere (USERDA 1976), and enabled the production of waste forms with a reasonably low level of foaming.

Mixing was conducted in the same mixer used to blend ashes (see Figure 1). The mixer drum contains a concentric shaft to which plows are attached. This mixer design produces a blending action that is similar to the action achieved by the in-drum mixer produced by Hittman Nuclear and Development Corp.

The ash, cement, and water mixtures were produced in two batches. Originally it was planned that three batches would be produced, but an inspection of the first batch after mixing for approximately five minutes revealed that the mix had a thinner consistency than expected and desired. The mixing action achieved by the Littleford mixer revealed that the mixture is thixotropic. This had not been evident when preparing samples by hand. Hence, the ash and cement that had been weighed out for the second batch were added to the mixer, and water was added gradually over several minutes until a thicker, but still pourable mixture was attained. This finally resulted in a water-to-dry solids ratio of 0.33, instead of 0.38 as had been originally planned. After the last water was added, the mixer was operated for an additional two or three minutes to ensure good blending of ingredients. This batch was then cast into one hundred 2-in. dia x 4-in. high (5 x 10 cm) cylindrical molds fabricated from polyvinyl chloride (PVC) pipe and plate. Also, a 5-gallon steel container was filled. Batch 2 was prepared using the same 30 wt% ash loading and 0.33 water-to-dry solids ratio. Mixing time was about five minutes. The mixture was cast into three PVC containers having the following dimensions; 2 in. dia x 2.3 in. high (5.1 x 5.8 cm), 6 in. dia x 6.8 in. high (15.2 x 17.3 cm), and 12 in. dia x 13.6 in. high (30.5 x 34.5 cm). All of the PVC containers used for both batches were cleaned with trichloroethane prior to casting.

All of the castings were prepared by simply pouring the mixture into the molds. No attempt was made to rod or vibrate the mixture in the molds nor to smooth the surfaces after casting. Within minutes after casting, bubbles appeared on the surfaces, just as they did during the preliminary tests. This resulted in the formation of a dense froth on the surface which caused the volume of the castings to increase by 15 to 20%. Molds were purposely filled about 1/2 in. below their tops in anticipation of this foaming. Still, in some cases, the mixture frothed above the rim of the mold, although none of the mixture ran down the sides of the molds. Within two days, the castings had hardened. After 28 days, the PVC containers were removed from their bases and were cut nearly through using a table saw. A screw-driver inserted and twisted in the cut caused the molds to pop open and the castings to drop out freely. The samples were then packaged and moved to the laboratory for testing.

2.4 Solidification of Ash in Bitumen

Ash/bitumen waste forms were produced at the Werner and Pfleiderer Corporation (WPC) (now WasteChem Corporation) facility in Ramsey, New Jersey. At the time this work was conducted, WPC was supplying the bitumen solidification equipment for ashes and other low-level wastes that were to be generated at the Hope Creek nuclear power reactor in New Jersey. This program's bitumen specimens were produced in a pilot-scale solidification process that represents the solidification process to be used at Hope Creek. The process is depicted in Figure 2.

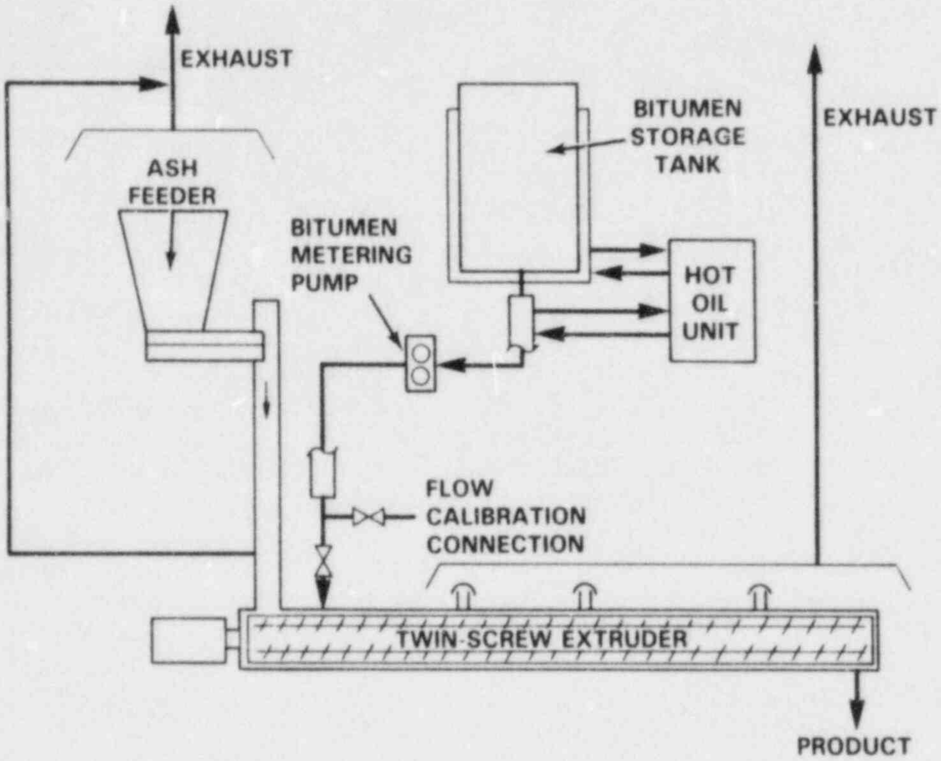

Figure 2. Schematic of the solidification process for bitumen

The bitumen used in this study is a medium-softening-point asphalt identified as "Pioneer 221 Laminating and Industrial Asphalt" and is produced by Witco Chemical Corporation. Some of its characteristics are shown in Table 4.

An ash loading of 40 wt% was selected for bitumen waste forms. Although WPC stated that higher loadings were probably achievable and demonstrated that fact following production of the required samples, the 40% level was chosen because it was the level specified by Bechtel Group, Inc., the architect engineer for the Hope Creek solidification facility.

Table 4. Properties of Asphalt Used to Make Bitumen Waste Forms

Softening Point	88-99°C (190 - 210°F)
Ductility @ 25°C	$\geq$2.5 CMS
Flash Point	288°C (550°F)
Density	0.99 g/cm^3 (8.3 lbs/gal)
Viscosity @ 204°C	0.94 secs.
Viscosity @ 177°C	0.36 secs.

The ash and bitumen were mixed in Werner and Pfleiderer Corporation's heated, twin-screw compounding extruder. The extruder reduced the particle size of the ash while homogeneously dispersing the ash particulate in a matrix of bitumen. Molten bitumen at 185°C was metered to the extruder at a fixed rate from a heated storage tank. Ash was simultaneously fed to the extruder by a K-Tron, T-20 weight-loss-differential feeder. The relative feed rates of bitumen and ash were proportioned to yield the desired 40 wt% ash loading. The actual feed rates were 45 lb/h (20 kg/h) and 30 lb/h (14 kg/h) for the bitumen and ash, respectively. The molten product was discharged from the end of the extruder into molds of the same size and number used in casting cement specimens (5 x 10 cm). However, the molds were constructed of heavy-duty aluminum foil and thin-walled extruded aluminum tubing. Aluminum was selected because it was found to be easy to peel from samples cooled to below 0°C. Molds were filled in the following order:

Filling Order	Number of Samples
1. 5-gal steel pail	(1)
2. 12 in. dia x 13.5 in. high (30.5 x 34.5 cm)	(1)
3. 6 in. dia x 6.8 in. high (15.2 x 17.3 cm)	(1)
4. 2 in. dia x 2.3 in. high (5.1 x 5.8 cm)	(1)
5. 2 in. dia x 4 in. high (5.1 x 10.2 cm)	(109)

Clinkers jammed the ash feeder during the filling of the 12-in. (30.5 cm) diameter container. Because continued interruption of the process might result in non-representative samples, the ash was screened through an 18-mesh sieve to remove the larger pieces. The 6-in. (15.2 cm) and 2-in. (5.1 cm) diameter molds were filled without further interruptions using only 18-mesh sieved ash. Three successive pourings were required after the initial filling to completely fill the molds because of shrinkage of the bitumen caused by loss of entrained air and thermal contraction. Sample shrinkage was the most pronounced in the

2-in. (5.1 cm) diameter molds because of the relatively high surface-to-volume ratio that caused rapid hardening and a deeper shrinkage void (see Figure 3).

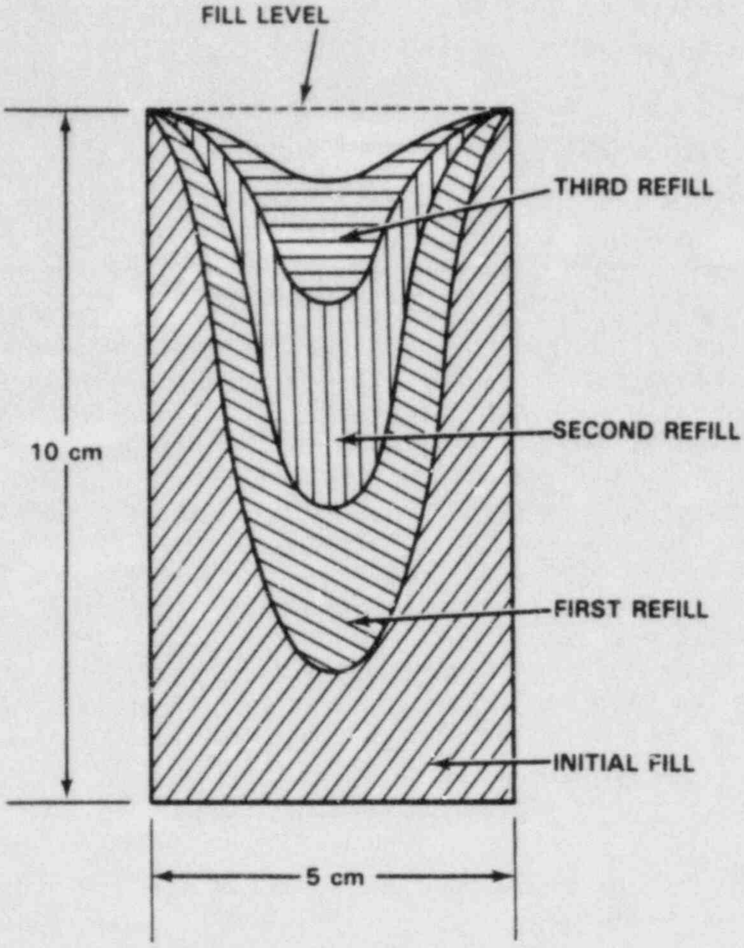

Figure 3. Shrinkage of ash/bitumen blend castings due to thermal contraction

The successive pourings occurred approximately 45 minutes apart and in the same sequence used when the molds were initially filled. The only exception was the 5-gallon pail which was used to catch excess production between individual fillings.

Nine extra samples were produced that contained ash at higher loadings, including 50, 60, and 66 wt% ash contents. All of these samples were produced with a single fill. The problem-free production of these samples indicates that Bechtel's selection of a 40 wt% ash loading may be somewhat conservative. A much broader testing program involving ashes of different compositions and physical properties would be required to determine an optimum ash loading, however. The castings were shipped in their molds to PNL where they were placed in a freezer for several hours to facilitate removing the molds. Samples were stored in plastic bags while awaiting testing.

2.5 Effect of Ash Solidification on Waste Volume

One of the intended purposes of ash solidification is reduction of waste volume for disposal. Waste disposal costs are strongly dependent upon volume and, thus, methods of reducing waste volumes may be very cost-effective. The effects of ash immobilization on volumes of waste for disposal were calculated using the following pertinent data.

- Density of general trash ash (as produced): 0.3 g/cc
- Density of general trash (after mixing): 0.9 g/cc
- Nominal loading of ash in ash/bitumen: 40 wt%
- Nominal loading of ash in ash/cement/water: 22.5 wt%
- Density of ash/bitumen: 1.2 g/cc
- Density of ash/cement: 1.3 g/cc
- Maximum loading of ash in ash/bitumen: 60 wt%
- Maximum loading of ash in ash/cement/water: 30 wt%

Results are shown in Table 5.

Table 5. Waste Volume Reduction for Bitumen and Cement

Bitumen

Conditions	Volume Ratio (ash:ash/bitumen)
40 wt% loading, 0.3 g/cc ash;	1.6:1
60 wt% loading,* 0.3 g/cc ash;	2.4:1
40 wt% loading, 0.9 g/cc ash;	0.5:1
60 wt% loading,* 0.9 g/cc ash;	0.8:1

Cement

Conditions	(ash:ash/cement/water
22.5 wt% loading, 0.3 g/cc ash;	1.0:1
30 wt% loading,* 0.3 g/cc ash;	1.3:1
22.5 wt% loading, 0.9 g/cc ash;	0.3:1
30 wt% loading,* 0.9 g/cc ash;	0.4:1

*These waste loadings provide little, if any, flexibility for producing solidified wastes of acceptable quality.

These results indicate that some reduction of waste volume can be achieved when solidifying ashes in bitumen and cement, assuming that the ash is not pre-densified. The volume reduction is greater for bitumen. However, when the ash is pre-densified by simply mixing the ash for a few minutes in a conventional dry solids blender, immobilization in cement or bitumen actually increases waste volumes. Mixing the ash breaks down high-porosity and flakey particles into small, dense particles that pack more readily. This probably increases the potential for dispersion of the ash, however. If ash is an acceptable waste form for disposal, "mixing" may be a cost-effective means of significantly reducing waste volumes.

The volume reduction ratio achieved by incinerating the general trash (paper, plastic, etc.) was 22:1 (Treat, Lokken, and Schliebe, 1983). The net volume reduction from the general trash to the immobilized ash was 35:1 for the 40 wt% ash loading in bitumen and 22:1 for the 22.5 wt% ash loading in cement.

3. CHARACTERIZATION OF BITUMEN AND CEMENT WASTE FORMS

The NRC Technical Position on Waste Form recommends a series of tests to demonstrate the stability of the waste form. Radiation, thermal cycling, leaching, and biodegradation and their effect on the mechanical strength of the waste form are the basis for the tests to be used. Laboratory scale samples are permitted for the tests but specimens taken from full-scales products should be tested to verify the results.

In general the work described in the following sections is based upon the tests recommended in the Technical Position. However, the program was started before the final version was issued. Therefore not all test conditions are exactly as recommended and some additional tests were conducted.

3.1 Thermal Cycling

The Technical Position on Waste Form recommends that the waste form be tested for thermal stability by exposing the waste form to 30 temperature cycles from 60°C to -40°C. This would represent the range of temperatures the waste form might experience during transportation and while awaiting burial. Ground temperatures remain relatively constant such that the wastes should not vary in temperature once buried.

3.1.1 Thermal Cycling Procedure

The procedure used is based on ASTM B553-79 "Standard Test Method for Thermal Cycling of Electroplated Plastics" and incorporated modifications suggested by Brookhaven National Laboratory (BNL).

Bitumen samples were die pressed and concrete samples were cut to standard length to give the right cylindrical configuration needed for future compressive strength testing. The samples were then weighed, measured and sealed in 7.8-cm diameter by 11.4-cm high metal cans. The nominal size of the samples was 5 cm x 10 cm so the metal can provided no support for the sample. A thermocouple was placed in the center of one sample of each waste form so that centerline temperatures could be monitored. The hole through the can lid for the thermocouple lead was sealed with RTV silicon rubber.

A temperature cycle consisted of removing the samples from the constant temperature (20°C) bath where they had been stored at least overnight and placing them in a 60°C chamber for one hour. The samples were returned to the 20°C bath and allowed to cool. After the centerline temperature had been at the bath temperature for at least one hour, the samples were placed in the cold chamber. Due to equipment limitations the cold chamber was set at -30°C rather than -40°C recommended in the Technical Position. After one hour in the cold chamber, the samples were returned to the 20°C bath. The samples were randomly placed in the chambers to minimize the effect of temperature gradients that may have existed. Only one cycle per day was possible and no cycles were done on weekends. The extreme centerline temperatures for cement ranged from 50 to 54°C and -24 to -18°C; for bitumen the temperatures were 43 to 47°C in the hot chamber and -15 to -11°C in the cold.

At the conclusion of 31 cycles, the metal cans were opened and examined for the presence of free liquid. The specimens were visually inspected, dimensionally measured, and weighed. Five samples were then tested for compressive strength and three were leach tested.

3.1.2 Results

The effect of thermal cycling on the cement was minimal. The samples had released no observable liquid. The samples had lost from 40 to 220 mg weight with an average of 120 mg, which represents an average decrease of only 0.04%. Two samples had some small chips out of the top edge, otherwise there was no visible change in the cement specimens.

The bitumen samples gained from 51 to 72 mg in weight with an average of 67 mg or only 0.025%. The samples had swelled an average of 0.15 cm in diameter on the top edge, 0.05 cm at the mid-section and 0.33 cm on the bottom edge and were an average 0.05 cm shorter. The sample surfaces, which originally were very smooth, were covered with bumps (see Figure 4). The bumps were caused by ash inclusions which, after thermal cycling, lay near the surface. This most likely was caused by the flow of bitumen away from the inclusions.

3.2 Irradiation Stability

According to the NRC Technical Position on Waste Form, waste forms must exhibit acceptable properties after being subjected to a minimum dose of 10^8 Rad, or, if the expected maximum dose exceeds 10^8 Rad, to the higher value. Total doses to the cement and bitumen waste forms containing a representative commercial LLW ash were estimated using curie content data obtained from Technology for Commercial Radioactive Waste Management, (USDOE 1979) and are shown in Tables 6 and 7. The activity contents of the cement and bitumen waste forms at the time of solidification were determined to be 3.7×10^{-5} and 6.6×10^{-5} Ci/g, respectively. Assuming that all of the radiation is absorbed and that all of the species have undergone total decay, the total doses for cement and bitumen waste forms are 8×10^6 and 14×10^6 Rads, respectively. Since these levels are below the minimum 10^8 Rads standard for radiation stability testing, both cement and bitumen waste forms were tested for leachability and compressive strength after receiving gamma doses of 10^8 Rad.

The waste form specimens showed no visible physical changes such as cracking of the cement or embrittlement of the bitumen. Irradiation caused no significant changes in the leachability or mechanical strength of the cement (see Sections 3.3 and 3.4). Bitumen also showed no significant changes in leachability, but it did show an eight percent increase in mechanical strength, probably due to increased cross-linking induced by the radiation.

To determine the effect of gamma radiation on gas generation from the waste forms, specimens of cement and bitumen were irradiated in a closed system and the gases generated were analyzed by quadrupole mass spectrometry. One set was irradiated at 10^6 R/h to a total dose of 10^8 Rad and a second set was irradiated at 7×10^6 R/h to a total dose of 1.4×10^8 Rad. The latter irradiation was conducted with equipment to measure the gas pressures generated during

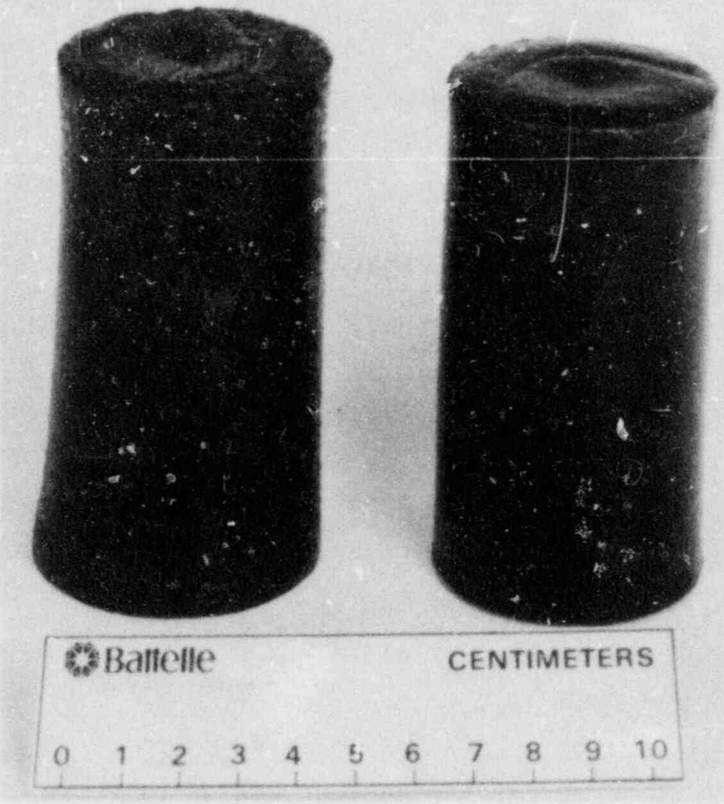

Figure 4. Bitumen specimens showing effects of thermal cycling (before on right, after on left)

irradiation. Temperatures during irradiation were approximately 54°C. Table 8 lists the gas compositions resulting from the gamma irradiation of the cement and bitumen specimens. Both waste forms yielded high levels of hydrogen and almost complete depletion of oxygen. The difference in the gas compositions between the two cement samples may be due to the fact that the second sample was dried in a vacuum oven prior to irradiation while the first was dried in a convection oven. The pressure increase for the cement was less than the detection limit of 14 KPa (2 psi). The pressure increase for the bitumen was 224 KPa (32.5 psi) corrected for temperature increase.

3.3 Leach Testing

Three leach test procedures were used in this study. The NRC Branch Technical Position on Waste Form recommends using the draft leach test procedure being prepared by the American Nuclear Society Working Group ANS-16.1 and recommends extending the test to 90 days. We conducted the test for a year to generate longer term leach data for the cement and bitumen waste forms. The 90-day test was used to determine the effects of irradiation and thermal cycling on the release of radionuclides from the waste forms. In addition to the ANS 16.1

Table 6. Dose to LLW Cement Waste Forms With Initial Activity of 3.7×10^{-5} Ci/g

Isotope	Activity (Ci/g)	Half Life(s)	Decay Energy (MeV)	Total Disintegrations (d/g)	Total Energy (MeV/g)	Dose (Rad)
51Cr	1.61 E-8	2.40 E6	0.752	2.06 E9	1.55 E9	2.49 E1
54Mn	7.11 E-7	2.62 E7	1.379	9.94 E11	1.37 E12	2.20 E4
55Fe	1.50 E-5	8.20 E7	0.232	6.56 E13	1.52 E13	2.44 E5
59Fe	1.27 E-7	3.89 E6	1.573	2.64 E10	4.14 E10	6.65 E2
58Co	4.49 E-6	6.16 E6	2.309	1.47 E12	3.41 E12	5.46 E4
60Co	9.36 E-6	1.66 E8	2.819	8.29 E13	2.34 E14	3.74 E6
89Sr	3.41 E-8	4.49 E6	1.463	8.18 E9	1.20 E10	1.92 E2
90Sr	5.99 E-8	8.86 E8	2.816(a)	2.83 E12	7.98 E12	1.28 E5
95Zr	1.80 E-9	5.62 E6	2.046(b)	5.40 E8	1.10 E9	1.77 E1
103Ru	8.99 E-11	3.42 E6	0.74	1.64 E7	1.21 E7	1.95E-1
106Ru	3.59 E-9	3.17 E7	3.579(c)	6.08 E9	2.17 E10	3.49 E2
127mTe	1.54 E-8	9.42 E6	0.78	7.74 E9	6.04 E9	9.68 E1
129mTe	1.80 E-9	2.94 E6	1.59	2.82 E8	4.49 E8	7.19 E0
124Cs	3.74 E-6	6.46 E7	2.062	1.29 E13	2.66 E13	4.27 E5
137Cs	3.59 E-6	9.46 E8	1.176	1.81 E14	2.13 E14	3.42 E6
141Ce	1.80 E-10	2.85 E6	0.581	2.74 E7	1.59 E7	2.55 E-1
144Ce	8.99 E-09	2.45 E7	3.309(d)	1.18 E10	3.90 E10	6.25 E2
TOTAL	3.72 E-5	---	---	---	---	8.04 E6

(a) includes 2.27 MeV of 90Y daughter.
(b) Includes 0.925 MeV of 95Nb daughter.
(c) Includes 3.54 MeV of 106Rh daughter.
(d) Includes 2.989 MeV of 144Pr daughter.

Table 7. Dose to LLW Bitumen Waste Forms With Initial Activity of 6.6 x 10^{-5} Ci/g

Isotope	Activity (Ci/g)	Half Life(s)	Decay Energy (MeV)	Total Disintegrations (d/g)	Total Energy (MeV/g)	Dose (Rad)
51Cr	2.84 E-8	2.40 E6	0.752	3.64 E9	2.74 E9	4.39 E1
54Mn	1.26 E-6	2.62 E7	1.379	1.76 E12	2.43 E12	3.89 E4
55Fe	2.64 E-5	8.20 E7	0.232	1.15 E14	2.68 E13	4.30 E5
59Fe	2.25 E-7	3.89 E6	1.573	4.67 E10	7.35 E10	1.18 E3
58Co	7.93 E-6	6.16 E6	2.309	2.61 E12	6.02 E12	9.65 E4
60Co	1.65 E-5	1.66 E8	2.819	1.46 E14	4.12 E14	6.60 E6
89Sr	6.01 E-8	4.49 E6	1.463	1.44 E10	2.11 E10	3.38 E2
90Sr	1.06 E-7	8.86 E8	2.816(a)	5.014 E12	1.41 E13	2.26 E4
95Zr	3.17 E-9	5.62 E6	2.046(b)	9.50 E8	1.94 E9	3.12 E1
103Ru	1.59 E-10	3.42 E6	0.74	2.90 E7	2.15 E7	3.44 E-1
106Ru	6.34 E-9	3.17 E7	3.579(c)	1.07 E10	3.84 E10	6.16 E2
127mTe	2.71 E-8	9.42 E6	0.78	1.36 E20	1.06 E10	1.70 E2
129mTe	3.17 E-9	2.94 E6	1.59	4.97 E8	7.90 E8	1.27 E1
134Cs	6.61 E-6	6.46 E7	2.062	2.28 E13	4.70 E13	7.54 E5
137Cs	6.34 E-6	9.46 E8	1.176	3.20 E14	3.77 E14	6.04 E6
141Ce	3.17 E-10	2.85 E6	0.581	4.83 E7	2.80 E7	4.49 E-1
144Ce	1.59 E-8	2.45 E7	3.309(d)	2.08 E10	6.89 E10	1.11 E3
TOTAL	6.55 E-5					1.42 E7

(a) Includes 2.27 MeV of 90Y daughter.
(b) Includes 0.925 MeV of 95Nb daughter.
(c) Includes 3.54 MeV of 106Rh daughter.
(d) Includes 2.989 MeV of 144Pr daughter.

Table 8. Gas Composition Resulting From Gamma Irradiation of Cement and Bitumen

	Cement		Bitumen	
Gas	10^8 Rad	1.4×10^8 Rad(a)	10^8 Rad	10^8 Rad(a)
H_2	21.96	10.0	77.10	60.5
H_2O	1.38	ND(b)	2.90	1.3
N_2	75.80	88.2	19.60	37.5
O_2	0.06	0.5	0.0	0.14
Ar	0.63	1.0	0.27	0.38
CO_2	0.18	0.2	0.16	0.25

(a) With pressure transducer.
(b) Not determined.

procedure, the IAEA procedure as applied at Brookhaven National Laboratory (BNL) was used as a basis for comparing results on other waste forms tested at other laboratories. BNL has done extensive testing of waste forms for resin beads and boric acid wastes. The third test used was a static or equilibrium test which gives an indication of solubility and steady state effects on the release of radionuclides from the cement and bitumen containing incinerator ash.

3.3.1 Experimental

Many of the conditions for the leach tests used were the same for the three procedures. Deionized water at room temperature (23 +/- 5°C) was the standard leachant. A synthetic groundwater simulating conditions at the Barnwell site was also used in one test using the ANS 16.1 procedure. This was substituted for the seawater suggested in the ANS 16.1 procedure since the groundwater is probably more relevant to low-level waste disposal. Table 9 shows the groundwater composition. Cement and bitumen specimens approximately 5-cm diameter by 10-cm high were used throughout the tests; some cement samples were cut and some bitumen samples were pressed to form the right circular cylinders needed for the compressive strength testing after leaching. A set of samples approximately 5 x 6 cm, 15 x 17 cm and 30 x 35 cm were tested using the equilibrium procedure to determine the effects of sample size. The solution-volume-to-specimen-surface-area (V/SA) ratio was maintained at 10 cm in all tests. Table 10 shows the test matrix.

The three leach test procedures differ in the sampling and sampling frequency. In the ANS 16.1 and IAEA tests, an aliquot of the leachate was removed,

Table 9. Composition of Barnwell Groundwater

Component	Range(a)	Average	Composition of Synthetic Groundwater Batch 1	Batch 2
SiO_2	6.3 - 14.5(b)	10.3(b)	12(b)	11(b)
Fe	0.11 - 0.24	0.15	0.27	0.19
Ca	16.0 - 74.4	35.1	28	41
Mg	1.9 - 15.6	8.3	3.3	15
Na	4.2 - 9.9	6.9	13	12
K	2.3 - 21.2	8.7	5.1	14
Carbonates	9.6 - 175.7	76		
Bicarbonates	0 - 85.4	26.4		
Sulfates	3.4 - 20.6	12		
Nitrates	0.01 - 1.18	0.32		
pH	9.1 - 11.7	10.2		

Makeup of Simulated Barnwell Groundwater

100 Liters Deionized Water
8.8 g Magnesium Carbonate (Basic)
2.2 g Potassium Bicarbonate
1.24 g Sodium Bisulfate
0.069 g Ferric Nitrate
4.8 g Sodium Silicate

(a) Barnwell Nuclear Fuel Plant Environmental Report Docket - 50332-22.
(b) Concentration values are in parts per million.

acidified, and submitted for chemical analyses. The remaining leachate was discarded and the waste-form specimen was placed in fresh leachant. In the equilibrium test, a 5-ml aliquot was removed, acidified, and submitted for analyses. However the waste form remained in the old leachant for the duration of the test. At 56 days of leaching, 120 ml of deionized water was added to the equilibrium test to compensate for the leachate removed.

The leachate was sampled and changed 10 min, 100 min, 6 h and 24 h after the start of leaching; and then daily during the work week for the first four weeks

Table 10. Leach Test Matrix

Waste Form Condition	ANS 16.1 Deionized Water	ANS 16.1 Barnwell Groundwater	IAEA	Equilibrium
As-Generated	6[a]	3	5	5
Irradiated	3			
Thermal Cycled	3			
Pre-Compressive Strength	5 cement 4 bitumen			
Larger Sizes				1 each size

(a) Numbers indicate number of replicates for each waste form.

and weekly thereafter for a total of 91 days of leaching using the IAEA procedure. In the ANS 16.1 tests, the leachate was sampled and changed 30 sec. 2 h, 7 h, and 24 h after the start of leaching; and then daily including weekends for three weeks and weekly thereafter for a total leaching time of 91 days. In the ANS 16.1 tests conducted for a year, weekly samples were taken to the 168th day of leaching and thereafter samples were taken once every four weeks. Sampling for the equilibrium test followed that of the IAEA test except that no samples of the leachate were taken during the first day of testing. After 91 days of leaching, samples were taken at the same intervals used in the ANS 16.1 test.

The leachate samples were analyzed for cesium using a graphite furnace atomic absorption spectrometer. Aluminum, calcium, cobalt, copper, iron, silicon, sodium, and strontium concentrations were measured using an inductive-coupled plasma spectrometer (ICP). The solution concentrations for the bitumen samples in the IAEA and long-term ANS 16.1 tests were below the detection limits for the analytical equipment. Therefore the solutions from late in the long-term tests and from all other non-equilibrium tests of both bitumen and cement were concentrated a factor of 100 by evaporating a one liter volume of leachate to 10 ml prior to submitting for chemical analyses.

3.3.2 Data Analysis

From the raw data, the ANS 16.1 leach test procedure requires that the incremental fraction leached, a_n/Ao; the incremental leaching rate, $(a_n/Ao)/\Delta t_n$; and the cumulative fraction leached, $\sum_1^n a_j/Ao$ be calculated where a_n = quantity of element release during the leaching interval n

$\sum_{1}^{n} a_j$ = total quantity of element released over the entire leaching time t

Ao = initial quantity of the element in the specimen

Δt_n = duration of the n leach interval

An effective diffusion coefficient, D (cm^2/sec), is then calculated.

$$D = \frac{\pi}{4} \left[\frac{a_n}{Ao} \times \frac{V}{S} \times \frac{1}{t_n^{1/2} - t_{n-1}^{1/2}} \right]^2 \qquad (1)$$

where V = volume of specimen (cm^3)
S = geometric surface area of the specimen (cm^2)

Equation 1 is based upon the assumptions that 1) the release is controlled by diffusion through the waste form, 2) the waste form can be modeled by a semi-infinite medium with the boundary conditions of constant initial concentrations throughout the sample at $t<0$ and the concentration at the surface of the sample is zero at $t>0$, 3) the diffusion coefficient is constant, and 4) less than 20% of the element has been leached from the waste form (ANS 1981,1982; Crank 1956).

Finally, a "Leachability Index" is calculated for the elemental release from the waste form. The leachability index (L) is simply the negative logarithm of the effective diffusion coefficient.

$$L = -\log(D)$$

The Technical Position on Waste Form requires a minimum leachability index of 6.

The assumption that release is controlled by diffusion could be a problem with the ANS 16.1 procedure and the Technical Position on Waste Form. There must be some method specified to verify that diffusion is controlling release and alternate methods provided for analyzing the cases where diffusion is not controlling.

3.3.3 Results

A diffusion coefficient and the leachability index for each waste form was calculated based on the cesium and strontium behavior. These results are shown in Tables 11 and 12 for the bitumen and cement waste forms. The diffusion coefficients are the average of the diffusion coefficients calculated at each leach interval beginning with the second day of leaching for each replicate used in each test. The diffusion coefficients were not constant with time and this then results in large standard deviations (see Figure 5). Because incremental release data are not available from the equilibrium tests, the values are calculated using integral rather than incremental techniques (ANS 1984).

TABLE 11. Cesium Diffusion Coefficients and Leachability Index

	Bitumen			Cement		
	Diffusion Coefficient		Leachability	Diffusion Coefficient		Leachability
Test	Mean	St. Dev	Index	Mean	St. Dev	Index
IAEA	Not Determined			7 E-8*	2 E-[illegible]	7.2
Equilibrium	4 E-13*	2 E-13	12.4	4 E-8*	1 E-8	7.4
ANS 16.1						
As-formed	1 E-13	1 E-13	13	5 E-8*	1 E-8	7.3
Irradiated	6 E-14	1 E-13	13.2	3 E-9	3 E-9	8.6
Thermal cycled	2 E-13	4 E-13	12.6	2 E-9	3 E-9	8.6
Pre-compressive strength	1 E-14	1 E-14	14	1 E-9	2 E-9	9.0
Barnwell groundwater	5 E-14	2 E-13	13.3	2 E-9	2 E-9	8.8

* Average of 2, 3, 4, 7, 18, 49 and 91 day values.

TABLE 12. Strontium Diffusion Coefficients and Leachability Index

	Bitumen			Cement		
	Diffusion Coefficient		Leachability	Diffusion Coefficient		Leachability
Test	Mean	St. Dev	Index	Mean	St. Dev	Index
IAEA	3 E-13	4 E-13	12.6	1 E-9	7 E-10	9.0
Equilibrium	3 E-13*	1 E-13	12.6	8 E-10*	4 E-10	9.1
ANS 16.1						
As-formed	1 E-13	1 E-13	13	2 E-9	5 E-10	8.7
Irradiated	2 E-14	3 E-14	13.7	5 E-11	3 E-11	10.3
Thermal cycled	7 E-14	9 E-14	13.2	3 E-11	5 E-11	10.5
Pre-compressive strength	5 E-15	6 E-15	14.3	2 E-11	3 E-11	10.6

* Average of 2, 3, 4, 7, 18, 49 and 91 day values.

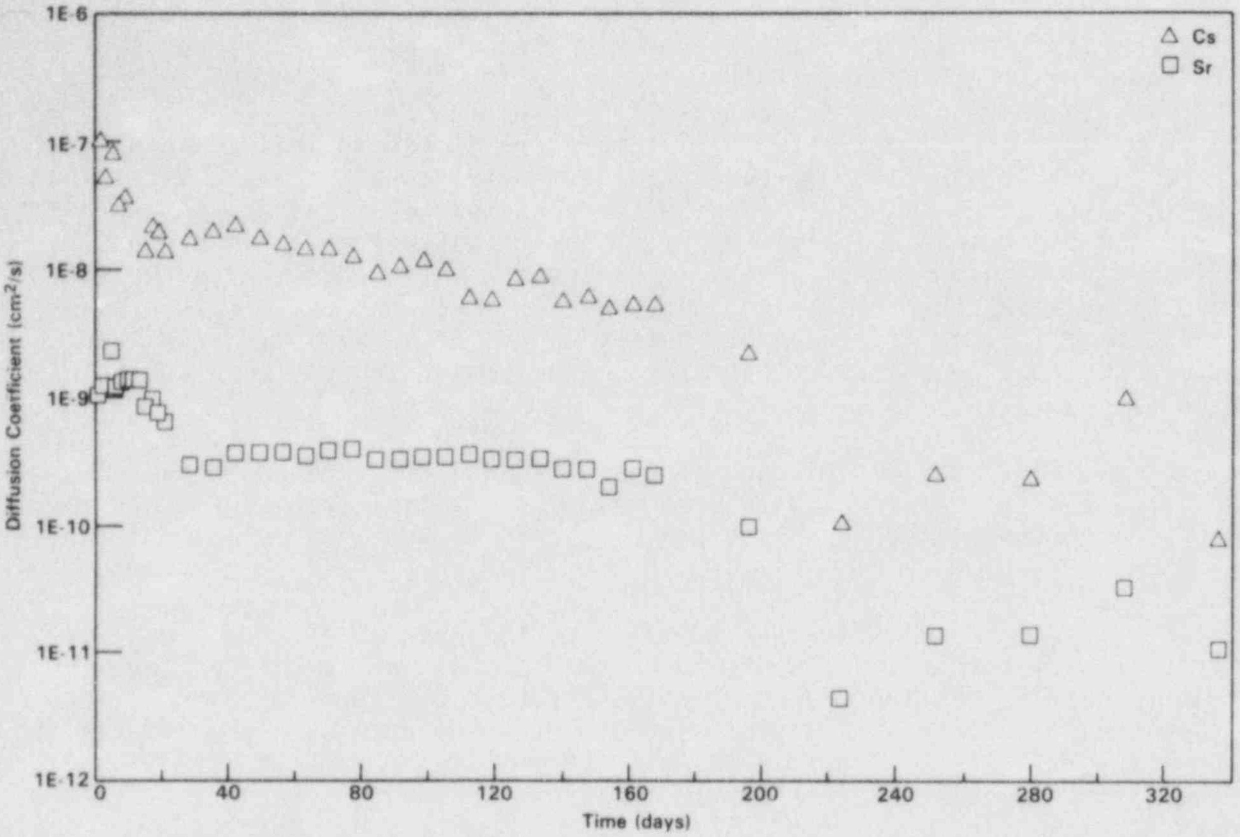

Figure 5. Cesium and strontium diffusion coefficients from cement

The leachability indicies easily exceeded the minimum of 6 required in the Technical Position on Waste Form.

One problem exists in the leach data. After the ANS 16.1, IAEA, and equilibrium tests were well underway, it was discovered that the leachate concentrations for bitumen were frequently below detection limits. Therefore the leachates from the tests on the irradiated, thermal cycled and pre-compressive strength bitumen and cement specimens and from the Barnwell groundwater tests were concentrated a factor of 100 prior to analyses. The concentration procedure was originally shown to yield results the same as for non-concentrated solutions. However, in practice the results appear to be lower by a factor of two to five for the concentrated solutions. The pre-compressive strength specimens were essentially the same as those used in the ANS 16.1 test such that the leach test results should be the same. Comparison of the two reveals the effect of the leachate concentration step. The cause of the discrepancy is not known. Saturation is a possibility although one would not expect it to be important for cesium.

The leach test results are discussed further below. Fractional release data are tabulated in Appendix A.

Bitumen

The leachability of bitumen is very low with fractional release rates typically less than 10^{-5} fraction/day. This caused some problems in the ANS 16.1 and IAEA tests because the concentrations of Al, Ca, Co, Cs, Fe, Na, Si, and Sr were below the detection limits. Only copper was detected in the leachates. This would not be a problem if radiotracers were used but it was not possible to use industrial equipment to produce the test specimens and still incorporate the radionuclides into the waste forms. Thus it was necessary to concentrate the leachates a factor of 100 prior to analyses. This was done for the tests of the irradiated, thermal cycled, and pre-compressive strength specimens and was also done for the last half of the 1-year ANS 16.1 samples. This then provided the data necessary to estimate the diffusion coefficients shown in Tables 11 and 12.

The leachability index for bitumen ranges from 12.2 to 14 based on cesium and 12.3 to 14.3 based on strontium. Even allowing for the large scatter in the calculated diffusion coefficients, the Leachability Index is well above the minimum of 6.

Theoretically the results for the ANS 16.1 test specimens and the pre-compressive strength specimens should be the same since the only difference in the specimens is that the pre-compressive strength ones were pressed to form right circular cylinders. As discussed above, there were some problems in the concentrating of the leachates such that the results are not the same. However, the pre-compressive strength test specimens can serve as a reference to compare the effects of irradiation, thermal cycling, and Barnwell groundwater leachate. Figure 6 shows the cumulative fraction of cesium released for the four sets of specimens. There is an effect of the various treatments on the release from bitumen. Again the effects are not large enough to significantly impact the performance of the bitumen waste form.

The best way to examine the behavior of the other elements released from bitumen is to look at the results of the equilibrium test as shown in Figure 7. The cumulative fraction releases after a year were of the order of 10^{-3} for Cs, Sr, Co, Ca, Cu, and Na and about two orders of magnitude lower for Al, Si, and Fe. The pH ranged from 5.5 to 4.4. At a pH of 5; Al, Si, and Fe are close to the minimum concentrations for their stable hydrolysis products (Baes and Mesmer 1976) which would limit their concentration in solution and thus their cumulative fractional releases.

Cement. Cement is much more leachable than bitumen as evidenced by the leachability indices of 7.3 and 8.7 based on cesium and strontium releases from cement respectively. However these values still exceed the minimum value of 6. Irradiation, thermal cycling and leaching in Barnwell groundwater do not significantly impact the release from the cement. This is easily seen by comparing the diffusion coefficients for the treated samples with those calculated for the pre-compressive strength samples. As with the bitumen, the leachates for the thermal cycled, irradiated pre-compressive strength and Barnwell groundwater test samples were concentrated a factor of 100 prior to analyses. Due to some unidentified problems in the concentration step it is not possible

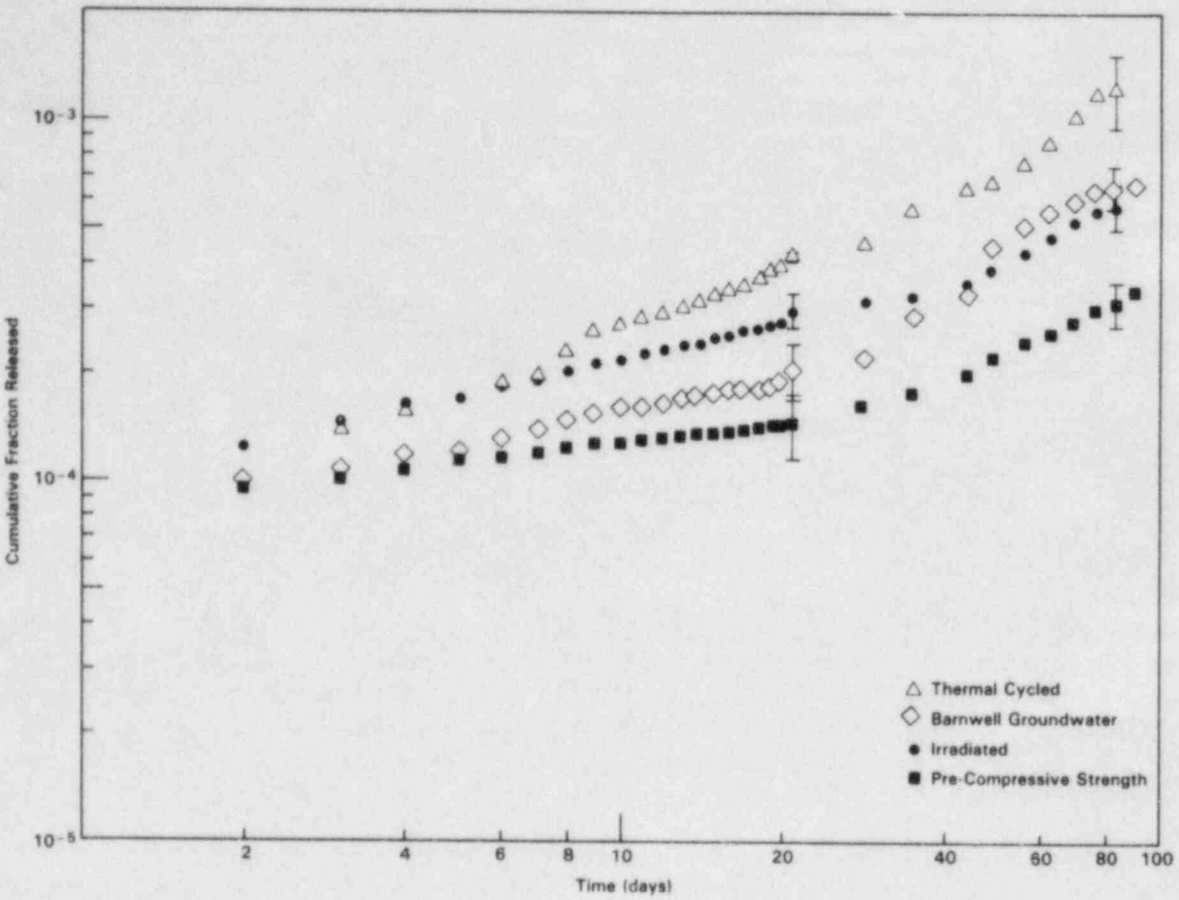

Figure 6. Cumulative fraction of cesium released from bitumen in ANS 16.1 tests

to compare concentrated and non-concentrated solution. Comparison among concentrated leachates is still acceptable.

The results of the ANS 16.1, IAEA, and equilibrium tests warrant further discussion. First, the cumulative fraction release of cesium exceeded 20% of initial cesium inventory in the waste forms such that Equation 1 was no longer applicable. The diffusion coefficients are based upon the diffusion from a right circular cylinder (Nestor 1980) rather than from a semi-infinite solid. The diffusion coefficients reported in Table 11 are therefore based on the cumulative release at 90 to 100 days rather than on the incremental releases and Equation 1.

It is particularly interesting to compare the cumulative releases from the ANS 16.1 and IAEA tests with the cumulative release from the equilibrium test. Cesium, strontium and sodium cumulative releases are the same as measured by each of the three tests. Figure 8 illustrates this for cesium. Aluminum, calcium, iron and silicon releases in the equilibrium test reach a constant

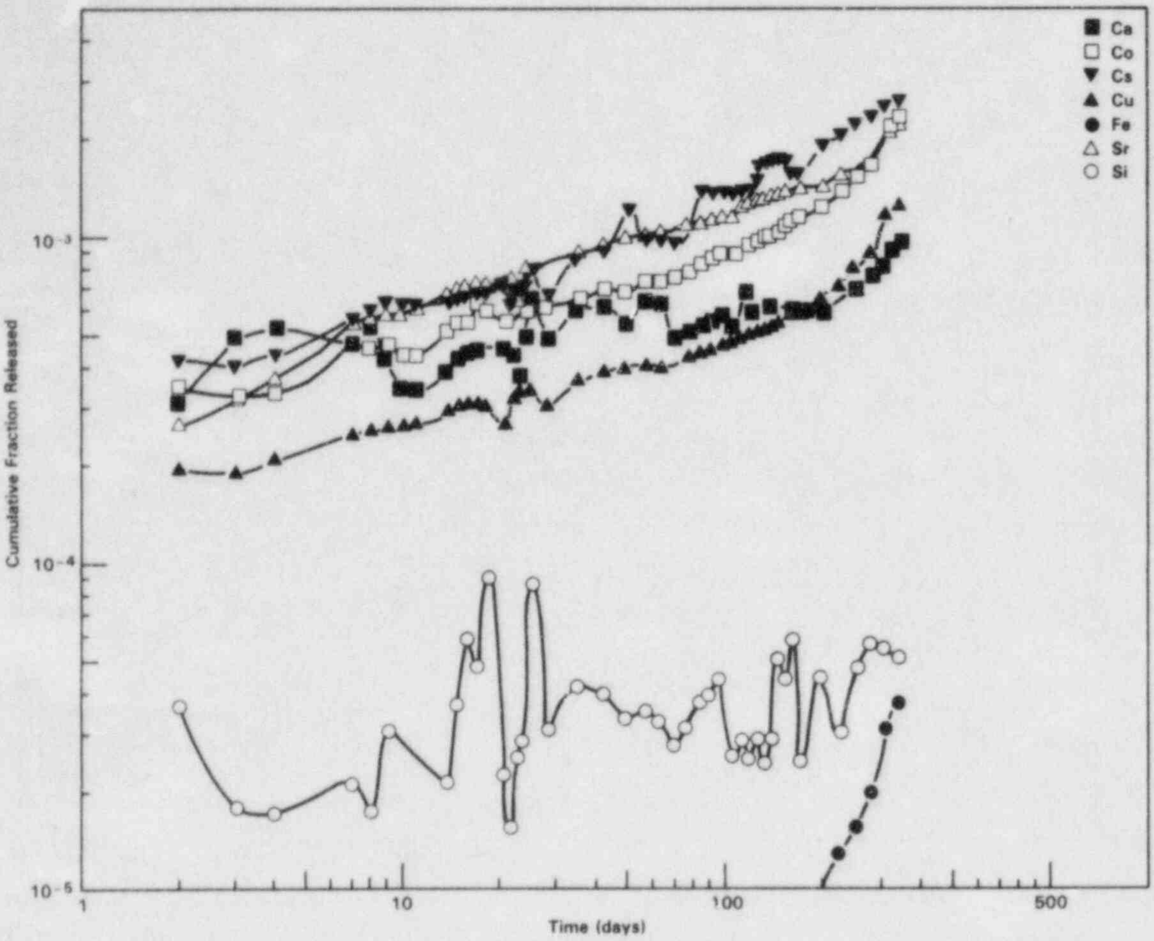

Figure 7. Cumulative fraction released from bitumen in equilibrium test

value while the releases in the other two tests continue to increase. Figure 9 shows this for silicon. The results for cobalt and copper are scattered and no trends are immediately obvious.

The pH for the equilibrium test leachates are in the range of 12 to 12.5 and the pH for the IAEA and ANS 16.1 tests are in the range of 10.5 to 11.3. At these pHs silicon rapidly forms silicic acid which can rapidly react with the Al, Fe, and Ca in solution to form silicates (Iler 1979). In addition, Ca is reacting with CO_2 from the air and is precipitating as calcium carbonate. These reactions may have a long term effect on the release from cement, particularly if a film forms on the cement surface that could slow the release.

3.4 Mechanical Strength

The mechanical strength is the critical property of the waste form as described in 10 CFR 61. The Technical Position on Waste Form requires that the mechanical strength be determined for specimens that have been irradiated, thermal cycled, leached and biodegraded as well as the as-formed material. In

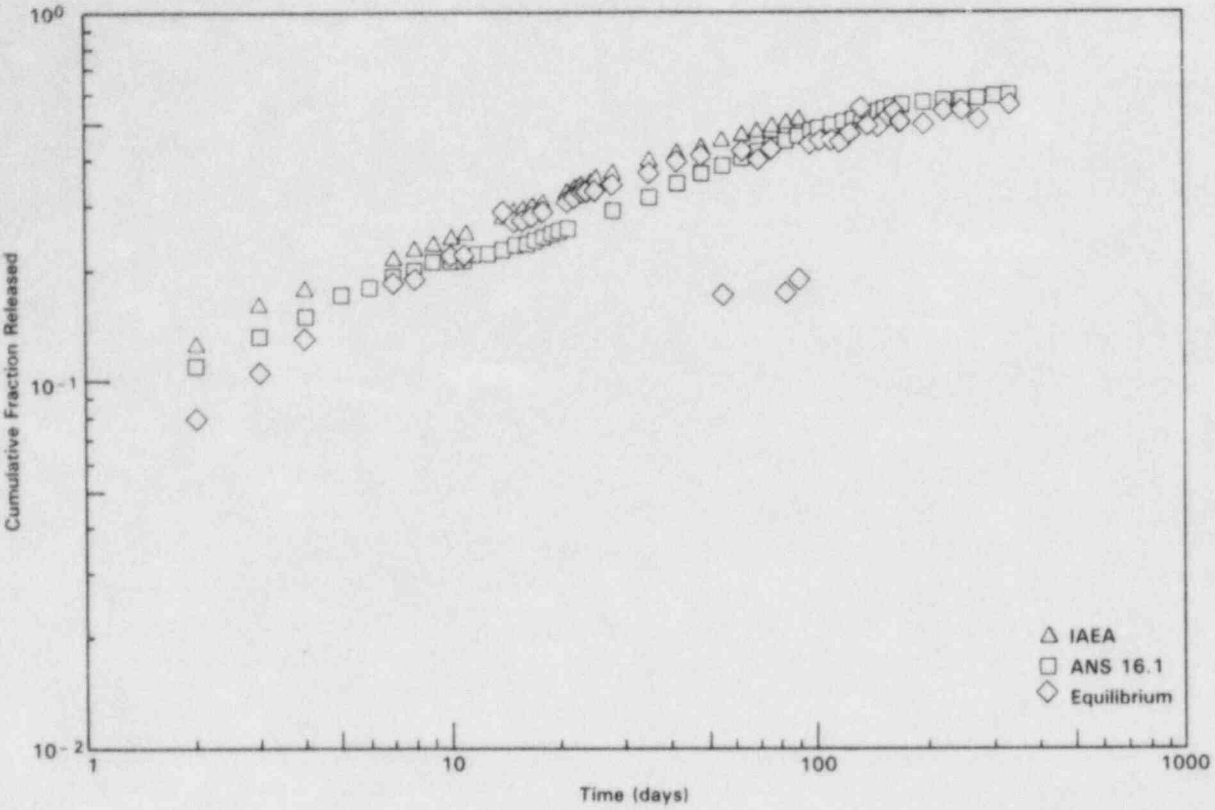

Figure 8. Cumulative fraction cesium released from cement in IAEA, ANS 16.1 and equilibrium test

addition, specimens from full-scale samples should be tested to verify the results from smaller samples.

3.4.1 Procedure

Cement. The tests on the cement waste forms were conducted according to ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens". While the testing and calculation procedures were followed per ASTM C39, the sample preparation deviated because of the intent of the program to produce samples in a manner consistent with anticipated commercial processes. The samples were cast into 2-in (5 cm) diameter PVC molds, cured, and then centerless ground prior to leaching, irradiation, and thermal cycling. The final sample dimensions were approximately 2-in. diameter by 4-in. high (5 x 10 cm). The samples were tested by applying a continuous load with the cross head traveling at a rate of 0.05 in/min (0.13 cm/min). The loading continued until the specimen failed. The compressive strength was then calculated by dividing the maximum load carried by the specimen during the test by the average cross-sectional area determined by the physical dimensions.

Bitumen. The bitumen samples were tested according to ASTM D1074, "Standard Test Method for Compressive Strength of Bituminous Mixtures". This method,

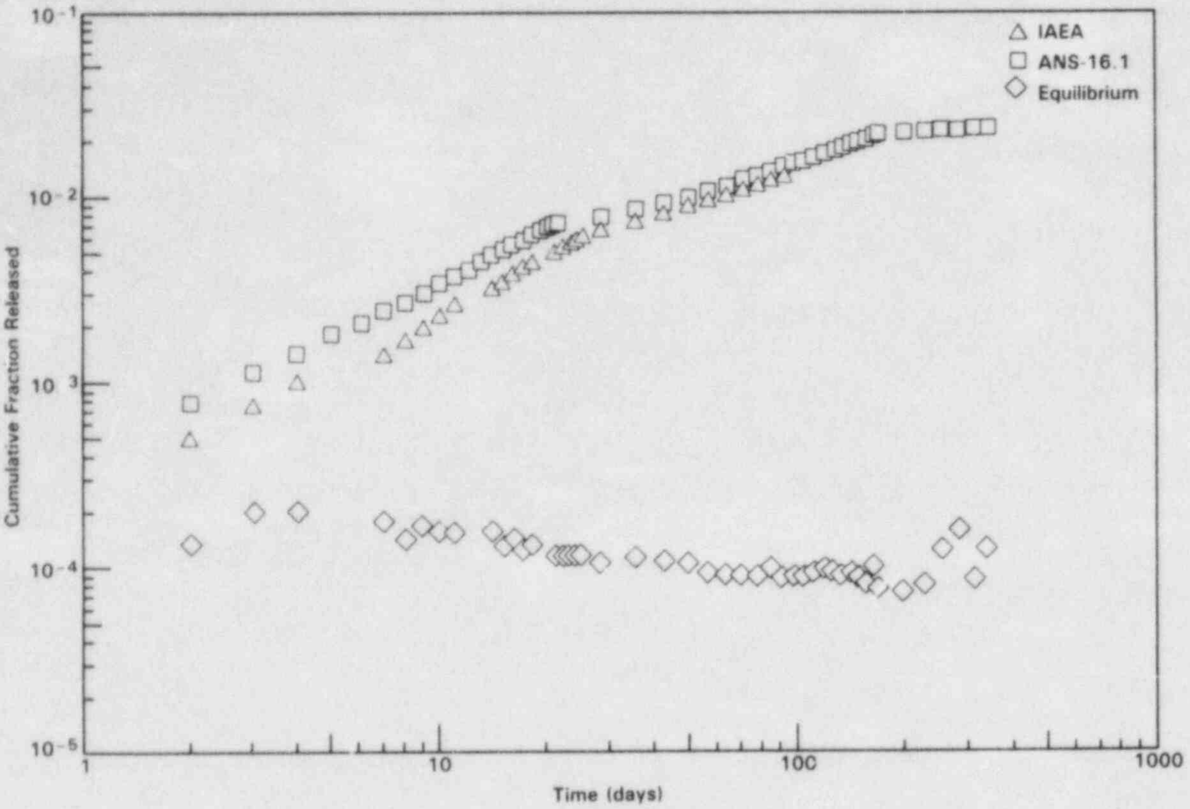

Figure 9. Cumulative fraction silicon released from cement in IAEA, ANS 16.1 and equilibrium tests

like ASTM C39, specifies specimen preparation techniques; however, the samples were produced to approximate production processes. Sample preparation, described in Section 2, yielded samples approximately 2-in. diameter by 4-in. high (5 x 10 cm). The specimen dimensions specified in ASTM D1074 are right circular cylinders with a length to diameter ratio of 1. To obtain samples meeting this requirement, the samples were cut in half and then pressed within a 2-in. (5 cm) diameter die at ~7000 psi (48 MPa), allowing 30 minutes for the bitumen to conform to the shape and size of the die cavity. The compressive strength was determined by loading the samples at a constant axial deformation rate of 0.1 in/min (0.25 cm/min), and dividing the maximum load attained by the original cross-sectional area.

In response to a concern expressed regarding the sample preparation procedure mentioned above, particularly the 7000 psi (48 MPa) pressure, the procedures outlined in ASTM D1074 were attempted. However, the bitumen used in these waste forms is not amenable to the prescribed molding temperatures. Therefore, a modification to the molding procedure was necessary to obtain satisfactory samples for testing. The samples were heated to 35°C instead of the 124 or 104°C as specified. The samples were then pressed in a 2-in (5 cm) die for 30 min at 3000 psi (1400 MPa). The longer time period was used because of the lower temperature and subsequent higher viscosity of the samples.

3.4.2 Results

The results of the compression tests are presented in Table 13. As seen in the table, four sets of samples were tested for each of the cement and bitumen waste forms -- as-received, leached, irradiated, and thermal cycled. Biodegraded samples were not tested since the samples used were too small.

Table 13. Compressive Strength Values for Cement and Bitumen Waste Forms

Condition		Compressive Strength, psi[a,b] Cement		Bitumen	
As-Received		1413 ± 93	(5)	134 ± 1 119 ± 4	(4) (5)[c]
Leached		2066 ± 160	(4)	126 ± 3	(3)
Irradiated		1366 ± 207	(3)	145 ± 2	(2)
Thermal Cycled		1323 ± 176	(5)	131 ± 7	(5)
Large Scale 1	Top	1424		124	
	Middle	--		122	
	Bottom	2350		127	
Large Scale 2	Top	1400		108	
	Middle	--		127	
	Bottom	2700		127	

(a) The values are averages of the number of samples in parentheses. The numbers following the "±" are one standard deviation from average.

(b) 1 psi = 6.98 x 10^3 Pa.

(c) Samples were prepared by pressing at 3000 psi instead of 7000 psi.

Cement. Comparing the strengths of the four cement samples, it is seen that the only condition that resulted in markedly different strengths than the as-received samples were those that had been leached. These samples were approximately 30% stronger. The higher strengths are most likely due to increased hydration of the cement compounds that occurred during the leaching process. While the average strength of those samples that were irradiated and thermal cycled are less than the as-received, the large spread in values would tend to indicate that these conditions have a minor effect on the overall strength of the cement waste forms.

The strengths of the samples from the top of the large, 5-gallon castings were about the same as the small-scale samples, while the samples from the bottom of the castings were almost twice as strong as the top. This increase in strength is most likely due to a greater degree of hydration since the bottom of the casting remains moist longer than the top, and because of the greater amount of porosity in the top due to the gas generation during casting.

Bitumen. The average strength of the bitumen waste forms are approximately 10 times less than the cement samples as seen in Table 13. Leaching has the opposite effect on the bitumen as it did on the cement, resulted in slightly lower strengths. Irradiation produced slightly higher strengths than the as-received samples, possibly due to cross-linking of molecules of the bitumen caused by the gamma radiation. Thermal cycling did not appear to result in any major detrimental effects on the strength of the bitumen even though the values listed are lower than the as-received samples.

The compressive strengths of the second set of as-received bitumen samples (pressed at 3000 psi) were slightly lower than the first, yet were still greater than the 50 psi (345 KPa) requirement. With the exception of the sample from the top of the second large, 5-gallon bitumen sample, there appears to be no significant difference between position within the castings or in sample size.

3.5 Homogeneity

In addition to the tests to characterize laboratory-scale specimens, the NRC Technical Position on Waste Form recommends destructive examination of full-scale specimens to verify homogeneity and mechanical strength. The largest samples available in this study were the 5-gallon specimens of each waste form. These were cut in half, examined visually for gross inhomogeneities, and sampled at a number of locations for chemical analyses and mechanical strength measurements.

3.5.1 Bitumen

The bitumen specimen was 28-cm diameter by 29-cm high at the edges and 20-cm high in the center due to the thermal contraction during cooling. The specimen also was smaller in diameter about half way up the sides where the bitumen had pulled away from the container wall. It is not clear what caused this contraction although it may be related to the fact that the specimen was not prepared in one pour but in several over the time that the other specimens were being prepared. The top surface was rough, and while not porous, it was spongy. Examination of the specimen in cross section revealed a foamy layer near the top surface about 1.3 cm thick in the center and 7.0 cm thick near the edge. Individual ash particles could be identified but there were not large pockets of ash.

Chemical analyses of samples taken 2.5, 10, and 18 cm from the bottom at the centerline and at 2.5 cm from the edge showed concentrations of Al, Co, Cu, Fe, Na, Si, and Sr increased from top to bottom. This trend extended up into the foamy layer on the top of the specimen. The variation was at most about a factor of two from top to bottom although it depended upon the element. Cesium concentrations were constant throughout the specimen. The cause of the concentration gradient is not evident. It may be a result of settling of the ash while the bitumen is relatively fluid or it may be an artifact of making the specimen by a number of pours during the sample preparation.

Despite the variations in the chemical composition of the bitumen, the mechanical strength was consistent throughout. Three samples were taken from each half of the specimen. Their mechanical strength was 120 psi as shown in Table 13. These samples did not include the foamy layer which could easily be compressed with a finger.

3.5.2 Cement

The cement specimen was 30-cm diameter by 27-cm high at the center and 25-cm high at the edge. The specimen had a rounded top apparently a result of the foaming described in Section 2. In cross section, the specimen appeared homogeneous. Individual ash particles could be identified and there were small bubbles throughout the specimen. No large ash pockets or voids were visible.

Samples for chemical analyses were taken at the top, middle and bottom along the edge, 25 cm from the edge and at the centerline. No concentration gradients were observed. One sample from the top and one sample from the bottom of each half of the specimen were removed for mechanical strength measurement. As shown in Table 13, the specimens from the top had a slightly lower compressive strength of 1400 psi, probably due to the top being exposed to air and therefore drying faster while the cement was curing. The two bottom samples had strengths of about 2500 psi.

3.6 Biodegradation

The NRC Technical Position on Waste Form recommends that ASTM G21 "Determining Resistance of Synthetic Polymeric Materials to Fungi" and ASTM G22 "Determining Resistance of Plastics to Bacteria" be used to determine the susceptibility of waste forms to biodegradation. The Technical Position also recommends measuring compressive strengths after testing for biodegradation. However this was not done because at the time the biodegradation tests were conducted the strength measurements were not required.

The ASTM tests are limited in that they look only for direct metabolism of the waste forms by the bacteria and fungi. Another mode of attack would be what is referred to as as co-metabolism where the organisms use other materials in the soil for a food source and the byproducts of metabolizing those materials cause degradation of the waste form. An experiment was conducted to evaluate the effect of co-metabolism on the cement and bitumen.

3.6.1 ASTM Procedures

These procedures, ASTM 21 and G22, involve placing wafers of the waste forms on a nutrient salt agar in a Petri dish, inoculating the media with the desired organism and incubating for 21 days. The specimens are then observed visually and rated on a 0 to 4 scale where:

0 = no growth
1 = traces of growth (<10% coverage)
2 = light growth (10 to 30%)
3 = medium growth (30 to 60%)
4 = heavy growth (>60% coverage)

A single bacterial strain and 4 fungal strains were used. The bacterium was *Pseudomonas aeruginosa* (ATCC 13388). The fungal strains were as follows: *Aspergillus niger* (ATCC 9642), *Chaetomium globosum* (ATCC 6205), *Aureobasidium pullulans* (ATCC 9348), and *Gliocladium virens* (ATCC 9645).

Cement. The cement samples caused the pH of the agar to shift from about 6.5 to greater than 10. Fungal and bacterial growth is not possible at this pH. Therefore, unless the burial site is highly buffered, the cement should not support growth of these microorganisms.

Bitumen. The slightly acidic conditions provided by the bitumen samples were well suited to the ASTM tests. However, there was only slight, if any, growth supported by the bitumen. Data are shown in Table 14. Three of five ASTM

Table 14. ASTM Biodegradation Test Results for Fungi

Organism	Test Material	ASTM Rating[(a)]	Comments
Aspergillus niger	cellulose bitumen	1 or 0 1 or 0	Very slight indication of growth. Difficult to score
Chaetomium globosum	cellulose bitumen	4 1 or 0	Difficult to score for bitumen but weak growth, at best
Aureobasidium pullulans	cellulose bitumen	1 or 0 1 or 0	Poor growth on both positive controls and bitumen
Gliocladium virens	cellulose bitumen	2 0	No growth on bitumen
Mixed Spores[(b)]	cellulose bitumen	2 0	No growth on bitumen

(a) Rating scale 0-4 with 0 indicating no growth and 4 indicating heavy growth.
(b) Spores from all for fungi used as innoculum.

tests exhibited more growth on the control medium, cellulose filter paper, than on bitumen. Aspergillus niger and Aureobasidium pullulans grew poorly or not at all on both the control and the bitumen. Therefore, these tests cannot be interpreted.

To provide an independent means for assessing fungal growth at the expense of bitumen, microscopic examination of the ASTM Chaetomium globosum (ATCC 6205) assay plate was conducted. In this procedure, sections of the plate were taken, wet mounts prepared, and the level of growth observed directly. Sections were taken at the border of the bitumen and at increasing distances from the bitumen. It was reasoned that bitumen-dependent growth would have shown a gradient, being more dense near the bitumen sample and much less dense farther away. For comparison, similar examinations of wet-mount samples from the positive controls were carried out. Globules of material on the bitumen samples that might have represented fungal growth were also examined by wet-mount.

Microscopic observation confirmed the ASTM test rankings. There was no indication of gradient of growth radiating outwards from the bitumen sample. The globules on the bitumen were not fungal mats indicating foci of heavy growth, but rather were ill-defined organic material. Thus, we conclude that bitumen is not a carbon source, or at best, a poor carbon source for complete growth of the fungi tested and is unlikely to undergo extensive biodegradation via primary microbial metabolism. However, these tests do not allow a clear distinction between very slight biodegradation and no biodegradation. They also fail to address the possibility that bitumen could be biodegraded indirectly through co-metabolism of a nearby carbon source.

3.6.2 Co-Metabolism

To determine the effects of co-metabolism, wafers of cement and bitumen were placed in a total growth media containing the organism of interest. Three organism were used in the study: Penicillium notatum, Pseudomonas aeruginosa, and Clostridium pasteurianum. The first two are obligate aerobes common to soil and the third is an anaerobic, spore-forming, soil bacterium. The growth media was buffered to maintain the pH. After incubating for seven days, the wafer was removed, treated with 90% ethanol to disinfect the surface, and placed in fresh inoculated growth media. This cycle was repeated for eight weeks. The spent growth media and associated microorganism were then filtered through a 0.45 µm filter and the filtrate and residue were chemically analyzed. The residue included the organic material. These results were compared with solutions and residue from similar tests except the growth media was not inoculated with the microorganism.

The results are shown in Tables 15 through 17 and Figures 10 through 15. The figures show the total release as concentrations of Ca, Co, Cu, Fe, Si, Sr and Cs for each of the eight weeks of the tests. Total release includes the elemental concentrations in the spent growth media plus the amount in the filter residues divided by the volume of growth media. The error bars indicate the standard deviation for the three replicates each week. The tables show the mean of the total release for all replicates over the entire test period for the inoculated and uninoculated cases. The tables also show the results of an

Table 15. Effect of Penicillium notatum on the Release from Bitumen and Cement

	Bitumen		
	Mean Concentration (µg/ml)		
Element	Inoculated	Not Inoculated	Effect Probability
Ca	3.60	0.74	0.0000
Co	2.97	2.92	0.6392
Cu	3.52	4.87	0.0005
Fe	24.07	41.90	0.0006
Si	4.40	4.07	0.0004
Sr	0.21	0.01	0.0000
Cs	0.14	0.10	0.2240

	Cement		
	Mean Concentration (µg/ml)		
Element	Inoculated	Not Inoculated	Effect Probability
Ca	27.04	10.17	0.0031
Co	2.99	2.87	0.3866
Cu	4.13	5.13	0.0033
Fe	26.75	27.67	0.8396
Si	10.12	4.54	0.0001
Sr	0.31	0.04	0.0000
Cs	0.10	0.80	0.0002

analysis of variance for repeated measures. This statistical analysis was used to evaluate the hypothesis that the inoculated test results equal those from the uninoculated tests. The results are shown as an effect probability. If the probability is less than 0.05 the hypothesis is not true and there is therefore a statistically significant difference between the inoculated and uninoculated tests.

Penicillium notatum. The results of the co-metabolism tests using P. notatum are shown in Table 15 and Figures 10 and 11. The releases of Ca and Sr from both cement and bitumen were higher in the inoculated than in the uninoculated tests. The releases of Co from either waste form, Cs from bitumen, and Fe from cement were not affected by the growth of P. notatum. Although the releases of

Table 16. Effect of *Pseudomonas aeruginosa* on the Releases from Bitumen and Cement

	Bitumen		
	Mean Concentration (μg/ml)		
Element	Inoculated	Not Inoculated	Effect Probability
Ca	2.26	4.38	0.0256
Co	0.21	0.09	0.0584
Cu	0.88	0.88	0.9986
Fe	0.54	0.57	0.7953
Si	1.10	1.18	0.4236
Sr	0.10	0.07	0.1418

	Cement		
	Mean Concentration (μg/ml)		
Element	Inoculated	Not Inoculated	Effect Probability
Ca	540.81	108.23	0.0001
Co	0.20	0.004	0.0000
Cu	1.28	0.54	0.0124
Fe	2.42	0.39	0.0024
Si	51.86	11.07	0.0004
Sr	1.02	0.39	0.0030
Cs	0.48	0.22	0.0015

Cu and Si in the two tests are statistically different, the differences from week to week of testing are greater than the difference between the inoculated and uninoculated tests.

Pseudomonas aeruginosa. As shown in Table 16 and Figures 12 and 13, the effect of *Ps. aeruginosa* on the releases from bitumen was insignificant but it had a large effect on the releases from cement. The releases from bitumen were small and essentially the same for both the inoculated and uninoculated systems. In the tests with cement, the systems with the *Ps. aeruginosa* showed significantly higher releases than those without. For most elements, the trends were toward increasing releases with time with maximum levels reached in two to four weeks.

Table 17. Effect of *Clostridium pasteurianum* on Releases from Bitumen and Cement

	Bitumen		
	Mean Concentration (μg/ml)		
Element	Inoculated	Not Inoculated	Effect Probability
Ca	4.53	4.83	0.0046
Co	0.63	0.89	0.0019
Cu	0.54	1.05	0.0102
Fe	6.01	6.39	0.4552
Si	1.37	1.28	0.5341
Sr	0.27	0.31	0.2360
Cs	0.31	0.36	0.1768

	Cement		
	Mean Concentration (μg/ml)		
Element	Inoculated	Not Inoculated	Effect Probability
Ca	413.50	327.88	0.0084
Co	0.28	0.20	0.1051
Cu	0.17	0.44	0.0404
Fe	15.78	11.82	0.0497
Si	42.05	27.99	0.0089
Sr	1.35	0.87	0.0097
Cs	0.41	0.34	0.0055

Clostridium pasteurianum. In contrast with the results obtained for *P. notatum* and *Ps. aeruginosa*, *Cl. pasteurianum* did not have a strong effect on the releases from the cement and bitumen. While the effect probabilities in Table 17 indicate that the releases for Ca, Cu, Fe, Si, Sr and Cs from cement and Ca, Co, and Cu from bitumen are statistically different for the inoculated and uninoculated systems, Figures 14 and 15 suggest that the differences caused by the presence of the organism were less than the week to week variations observed in the tests.

In summary, the co-metabolism effects induced by the three microorganisms were different for each organism. The growth of the fungus *Penicillium notatum* selectively increased the releases of Ca and Sr from both cement and bitumen. *Pseudomonas aeruginosa*, an aerobic soil bacterium significantly increased the

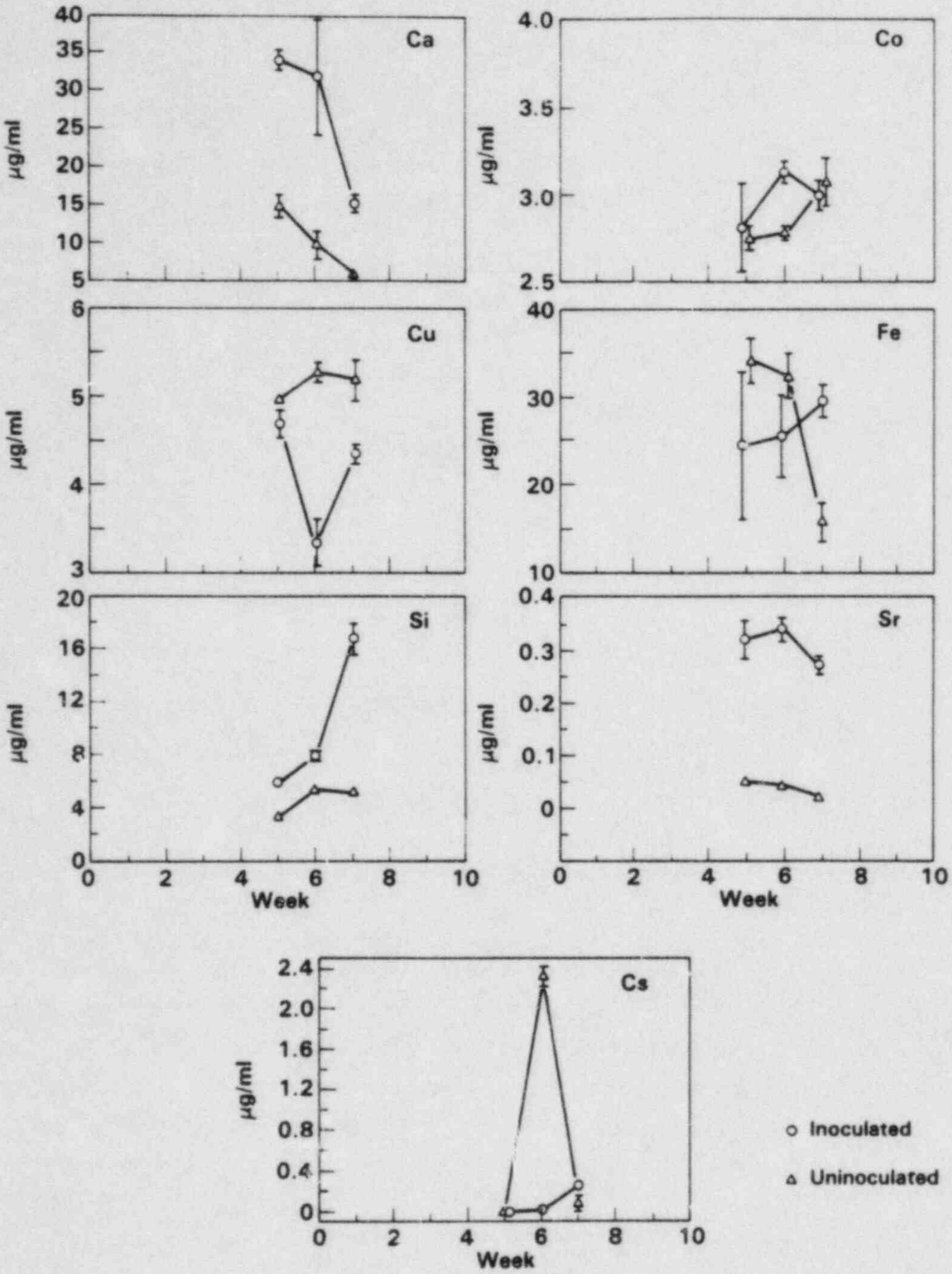

Figure 10. Releases from cement in systems with and without *Penicillium notatum*

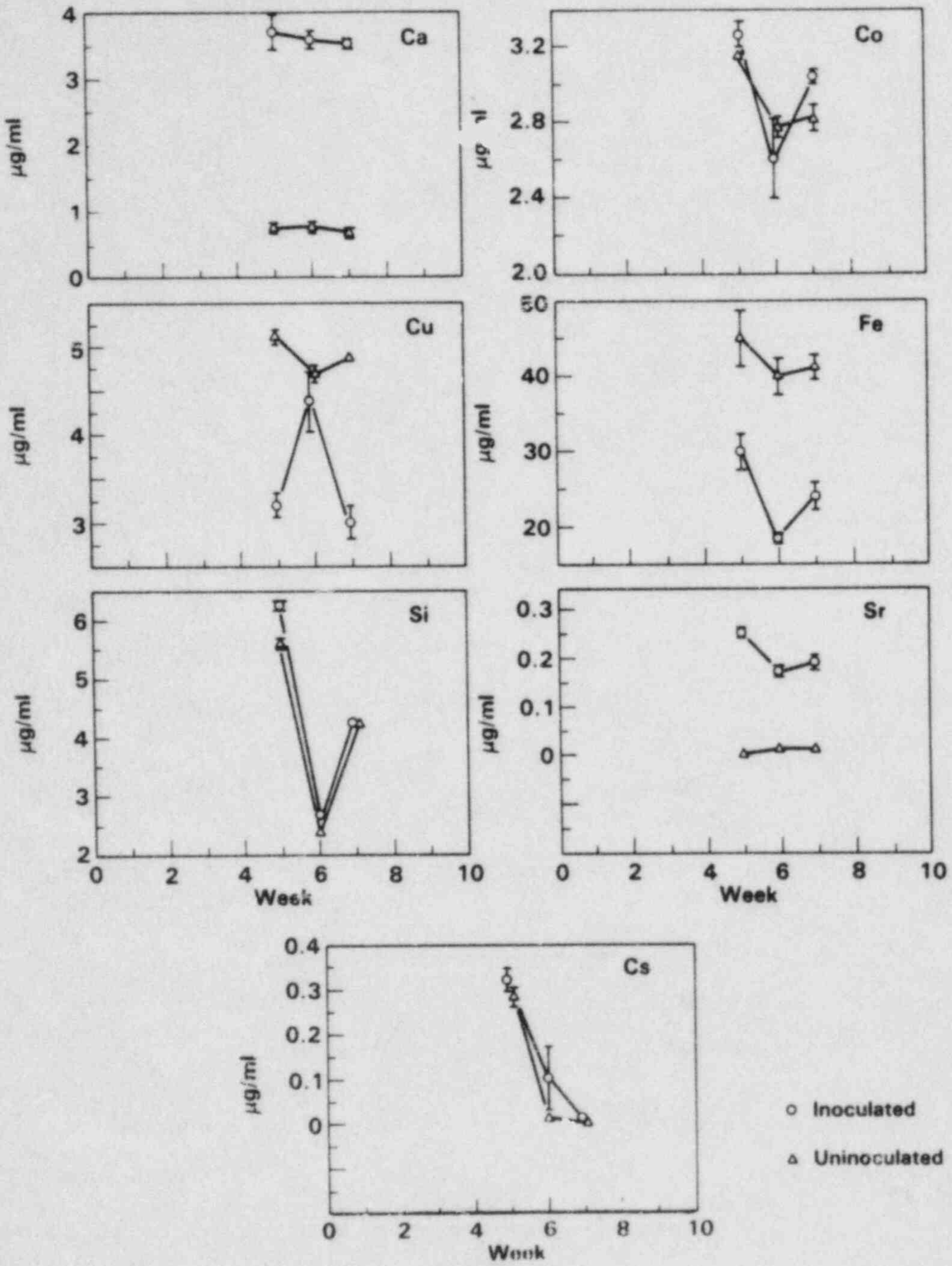

Figure 11. Releases from bitumen in systems with and without Penicillium notatum

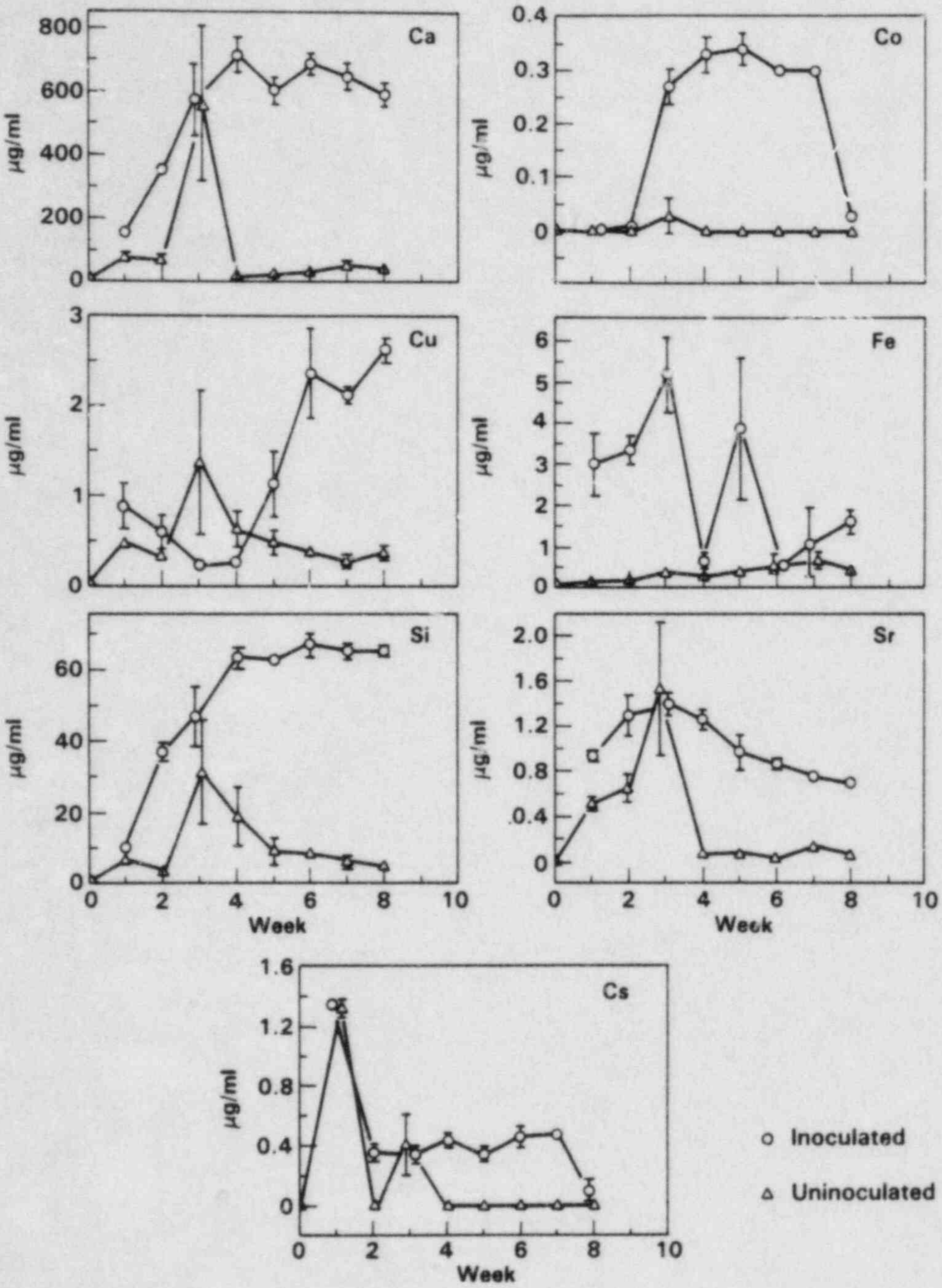

Figure 12. Releases from cement in systems with and without *Pseudomonas aeruginosa*

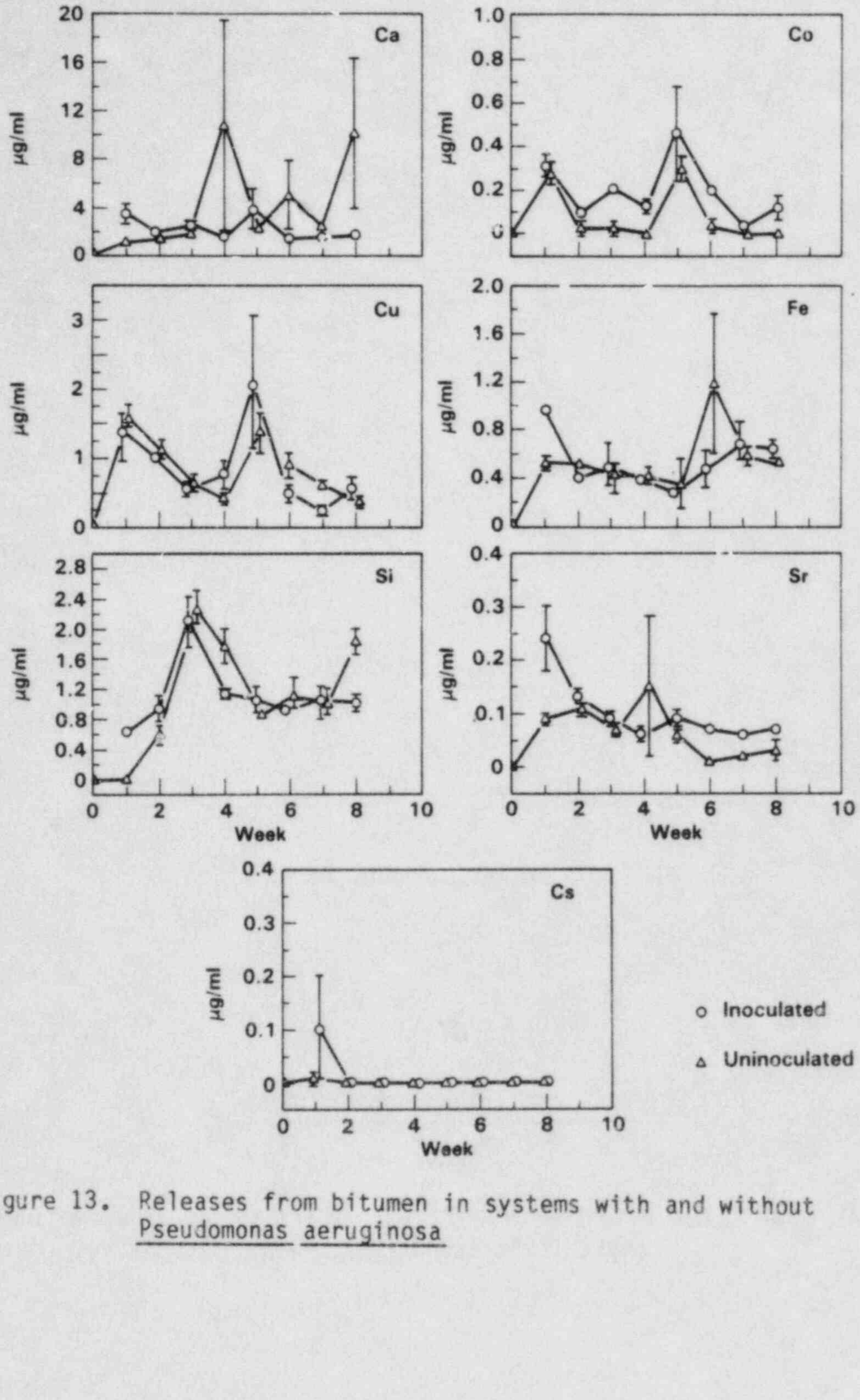

Figure 13. Releases from bitumen in systems with and without *Pseudomonas aeruginosa*

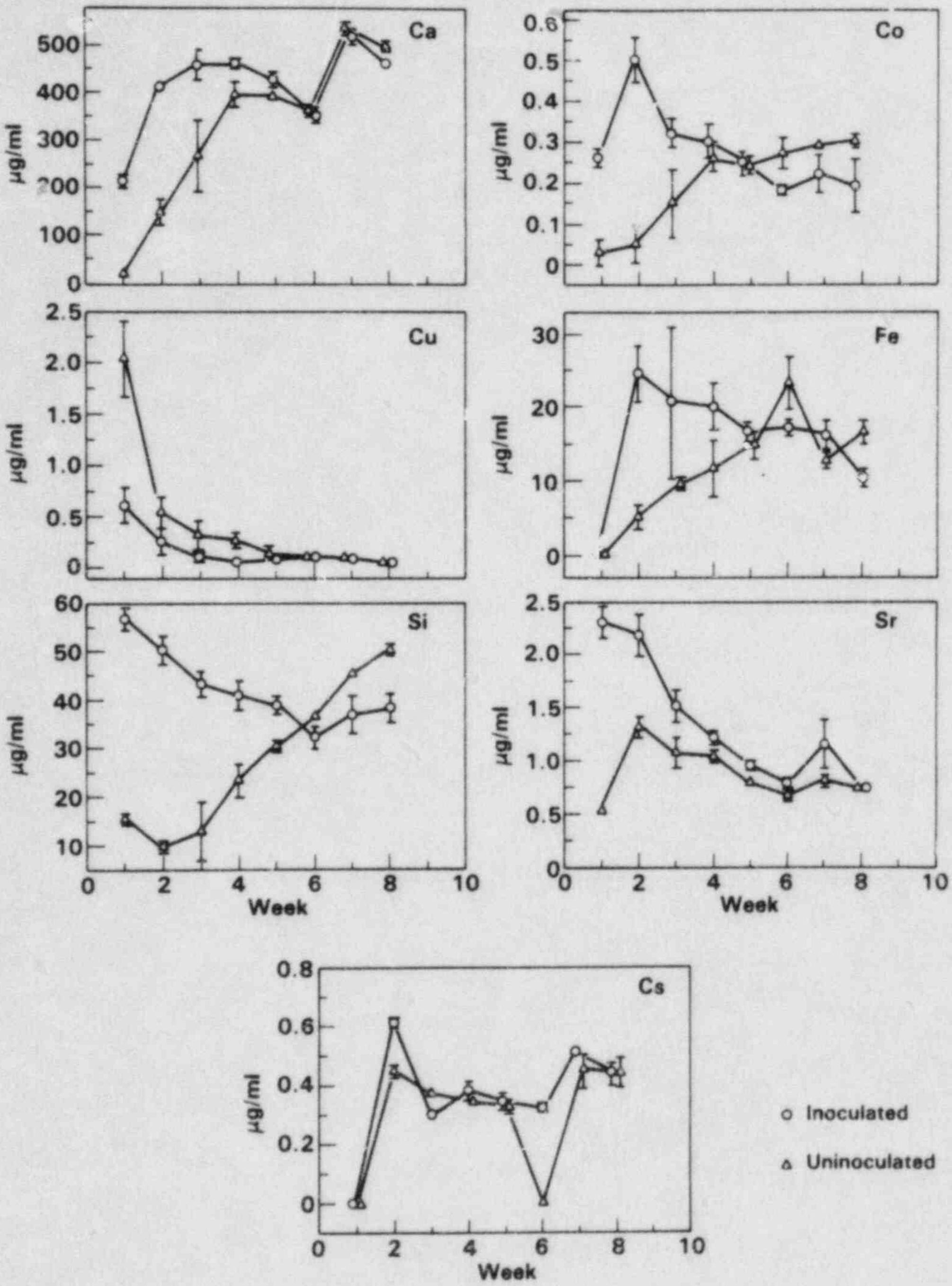

Figure 14. Releases from cement in systems with and without *Clostridium pasteurianum*

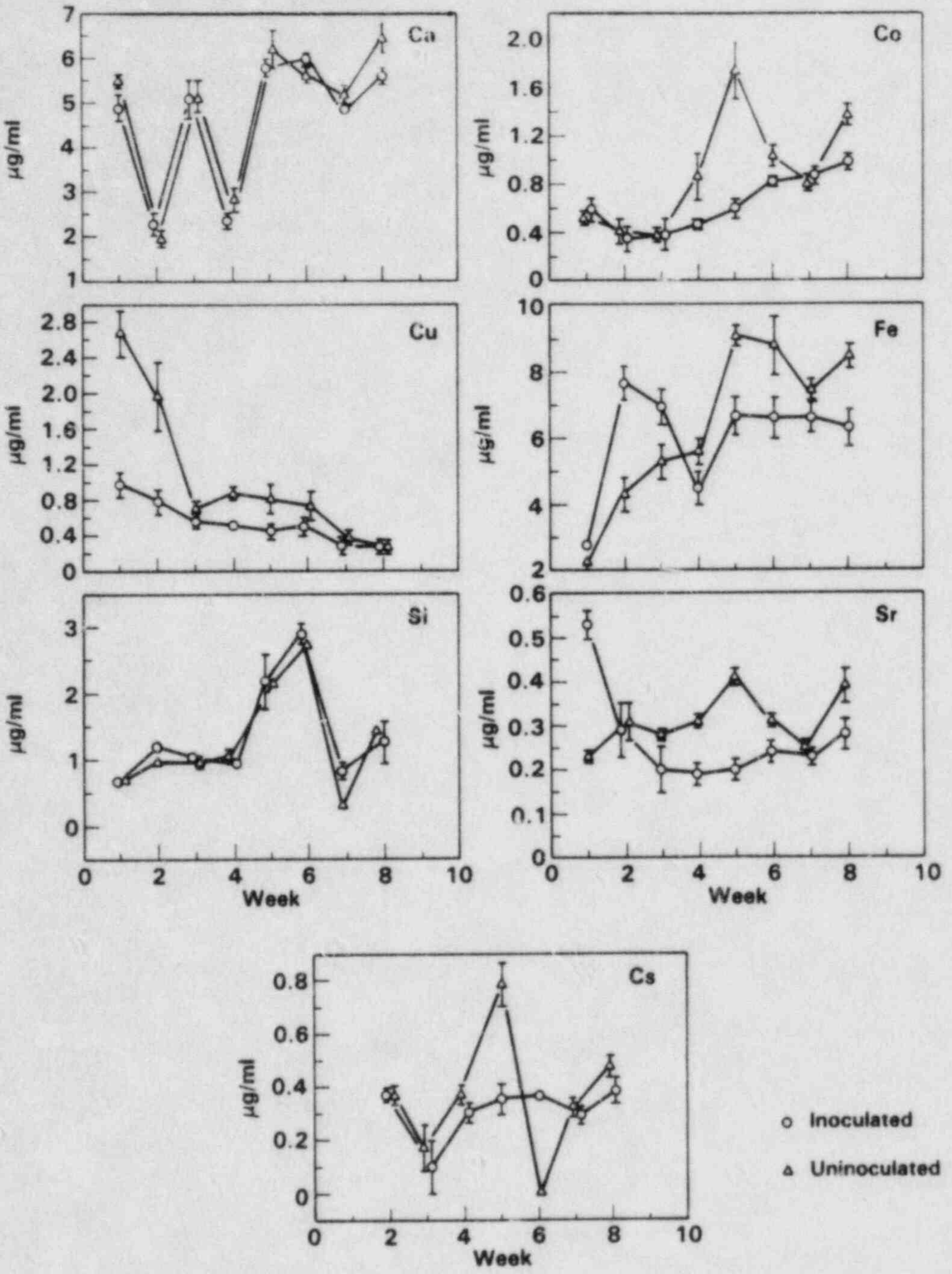

Figure 15. Releases from bitumen in systems with and without Clostridium pasteurianum

releases of Ca, Co, Cu, Fe, Si, Sr and Cs from cement. The anaerobic bacterium, Clostridium pasteurianum, did not induce large increases in the releases from either cement or bitumen.

Co-metabolism does not have a large effect on the releases from bitumen for the organisms studied. Cement was more affected. However, the system was highly buffered to maintain a pH in which the organisms could grow. Disposal sites will not be as well buffered, and as seen in the ASTM tests, the organisms may not grow. Additional work is needed to better understand the effects of co-metabolism on the releases from cement.

4. ORGANIC SPECIATION

One concern in the disposal of low-level wastes is the effect of organic complexants on the release and migration of radionuclides from the waste form. These complexants could originate with the waste form or in the disposal environment. Tests were conducted to identify the organic species in the leachates of the cement, bitumen and the ash itself.

4.1 Experimental

Four leachates were analyzed for their organic content. Two of the samples consisted of the 91 day leachates from the equilibrium leach tests of the 15 x 17 cm specimens of cement and bitumen. The third sample consisted of an aqueous (purified water) extract of the ash itself. A fourth leachate was generated by extracting a sample of the ash (2853 grams) with 500 ml of alkaline, purified water (pH 10) for 191.5 h. Purified water has been deionized and passed through a charcoal filter. A pH probe was dipped into the stirred slurry and the pH was adjusted periodically to keep it at pH 10.

Sample Preparation. Samples of the aqueous leachates (generally 3-4L) were stored at 4°C in acid-cleaned glass bottles. Each sample was filtered through a prewashed 0.45-μm silver membrane filter (Selas Corp.). A specific amount of each leachate, ranging from 419-1500 ml, was concentrated to near dryness by rotary evaporation.

Each concentrated sample was extracted with chloroform to remove hydrophobic organic compounds. This extract, the hydrophobic organic fraction, was concentrated and set aside for analysis by gas chromatography (GC) and combined GC-mass spectrometry (GC-MS). The extracted water sample, containing hydrophilic organic compounds, was evaporated to dryness under nitrogen. The residue of each aqueous fraction was then methylated in a sealed reaction vial with 1 ml of BF_3/methanol (14% w/v) at 100°C for 40 minutes. After cooling, 1 ml of chloroform was added and the mixture was mixed in a test tube containing 3 ml of 1M KH_2PO_4 buffer solution (pH 7) and a 0.2 ml chloroform rinse. Part of the chloroform layer (0.6 ml), which contained the methylated hydrophilic organic compounds, was then evaporated under nitrogen. The residue was redissolved in chloroform and analyzed by GC and GC-MS.

GC Analysis. GC analyses were performed on a Hewlett-Packard 5880 gas chromatograph equipped with a 60-m x 0.25-mm I.D. fused silica capillary column coated with a 0.25-μm film of SE-52 and a splitless injection system. From an initial value of 40°C, the column temperature was increased at programmed rates of 20°C per minute for 3 minutes to 100°C followed by 8°C per minute for 25 minutes to 300°C, and finally maintained isothermally at 300°C for 10 minutes.

GC-MS Analysis. GC-MS analyses were performed on a Hewlett-Packard 5985 GC-MS instrument in the electron-impact (70-eV) mode. The gas chromatograph on the 5985 instrument was equipped with a 60-m x 0.25-mm I.D. fused silica capillary column coated with a 0.25 μm of SE-54; the column was programmed from 400°C to 300°C at 5°C per minute, where it was maintained isothermally for 8 minutes. A splitless injection system was used to introduce the sample onto the GC-MS instrument. A mass range of 50 to 400 amu was scanned every 1.0 sec.

Quantification. The organic species identified by the GC-MS analyses were quantified by GC analysis using internal and external standardization methods. Pure compounds representative of the various compound classes identified by GC-MS were selected as standards and were methylated. A specific amount of each standard was co-injected with each sample to confirm the GC-MS identifications. For quantification purposes, each standard was injected onto the gas chromatograph prior to and following sample analyses. The response factor of each standard was calculated under analytical conditions identical to those of the sample analyses.

4.2 Results

Cement Leachate

A variety of carboxylic acids were identified in the hydrophilic organic fraction of the cement leachate (Table 18). Two classes of acids were represented: monocarboxylic and dicarboxylic acids. These acids were typical bioorganic compounds and also arise from microbial diagenesis. The concentrations of the acids were extremely low (ppb), and in some cases, the concentrations approached the detection limit for the combined gas chromatography-mass spectrometry analysis, 0.1 ppb. A very small amount of the chelating agent EDTA was identified; but its concentration was at the analytical detection limit, suggesting that this compound might be a background contaminant. No organic compounds were detected in the hydrophobic organic fraction.

Bitumen Leachate

The two classes of carboxylic acids identified in the hydrophilic organic fraction of the cement leachate were also present in the bitumen leachate; but only two compounds were present: hexadecanoic acid and hexanedioic acid (Table 18). Three chelating agents were also identified in this sample: NTA, EDTA, and ED3A. NTA and EDTA are commercially available and are widely used in nuclear operations. ED3A is presumably a chemical and/or environmental degradation product of EDTA. The concentrations were quite low at ppb levels. No hydrophobic organic compounds were detected in the hydrophobic fraction.

An extensive variety of aromatic species, mainly aromatic carboxylic acids, were identified in the bitumen leachate. Most of the compounds were polynuclear aromatic (PNA) carboxylic acids ranging in molecular weight from 164-324, or a ring size of 1 to ~4. Some of the aromatic acids existed as several isomers. A likely source of such compounds is the pyrolysis or burning of wood or wood products, as well as microbial diagenesis of wood products. The cumulative concentration of these compounds, based on GC-MS quantification, was 20.1 ppb, which is quite low.

Table 18. Hydrophilic Organic Compounds(a) in Leachate Samples

	Concentration (ppb)(b)			
	Waste Form Leachates		Ash Leachates	
	Bitumen	Cement	Deionized Water	Alkaline Water (pH 10)
Monocarboxylic Acids				
Decanoic Acid		6.4		
Dodecanoic Acid		6.0		
Tetradecanoic Acid		2.5	0.3	
Hexadecanoic Acid	3.96	4.7		4.2
Octadecanoic Acid			0.1	
Dicarboxylic Acids				
Butanedioic Acid		1.9		1.5
Pentanedioic Acid		3.3		
Hexanedioic Acid	1.1	25.8		<0.1
Heptanedioic Acid		1.0		
Octanedioic Acid		7.4		
Nonanedioic Acid		12.3		
Chelating Agents				
Nitrilotriacetic Acid (NTA)	0.4		<0.1	
Ethylenediamine-tetraacetic Acid (EDTA)	4.0	0.1	<0.1	
Ethylenediamine-triacetic Acid (ED3A)(c)	0.5			
Aromatic Species				
Polynuclear Aromatic Carboxylic Acids (PNA Acids)(d)	~20.1			
Benzoic Acid	1.0			
Phthalic Acid	7.7			
t-Butyl Phenol	trace			

(a) Methylated (BF_3/Methanol), acids identified as methyl esters.
(b) No entry indicates compound is below the detection limit of GC-MS analysis (0.1 ppb).
(c) Identified as Dimethyl Lactam (MW 244).
(d) Numerous (~80) PNA acids identified (many as isomers), ring sizes 1-4.

Ash Leachates

The incinerator ash itself was leached in two ways: 1) with purified water, and 2) with alkaline purified water (pH 10). Virtually nothing in the way of organic compounds leached from the ash after extraction with the purified water (Table 18). Small amounts of four compounds were detected at or near the analytical detection limit. Extracting with alkaline water yielded slightly higher concentrations of carboxylic acids, but again the concentrations were quite low (ppb). No hydrophobic organic compounds were detected in the hydrophobic organic extract.

4.3 Discussion

The concentration of organic compounds in the ash leachates were quite low (ppb levels) even after leaching with alkaline water, suggesting that incineration of the waste was quite effective in destroying the organic content. Past experience in our laboratory indicates that the concentration of organic compounds, particularly chelating agents, must be in the ppm range or higher before such compounds will exert any significant effect on solubilizing radionuclides.

The concentrations of organic compounds in the leachates from the cement and bitumen were also quite low (ppb levels), much lower than the concentrations of radionuclides leached (ppm levels). It is quite unlikely, therefore, that the organic compounds are exerting much, if any, role in solubilizing the radionuclides in the waste.

5. ASH/CONTAINER AND WASTE FORM/CONTAINER INTERACTIONS

The purpose of this screening test is to determine if the incinerator ashes and bitumen and cement containing the ash pose a corrosion problem to potential waste-form container materials.

As a first step, the literature was reviewed for previous data. Very little information was located, none of which was pertinent to the question raised. Typical references included Kramer et al. (1982) and Laser (1980) who, respectively, discussed the corrosion of the glass formed from low-level waste and the corrosion of the incinerator off-gas system. Indeed, as Hamner (1983) points out, current Environmental Protection Agency regulations do not provide a comprehensive description of the data needed nor precautions to be reviewed. A recent review for transuranic waste by Guenther et al. (1983) points out a similar lack of data there.

After the literature review, a short, four month long, screening test was conducted to determine whether these waste/container interactions were realistic concerns.

5.1 Test Parameters

The ash types used in this study include those made from general trash, resin, and a mixture of the two. Immobilization of the ashes is accomplished by mixing with cement or bitumen.

Typical waste storage containers include drums or waste liners constructed of steel (bare, painted, or coated with bitumen), polyethylene, or fiberglass. Common industrial practice for the bitumen process is to mix bitumen and waste and then fill the waste container. The cement/ash process can be performed similarly or as is more common, the ash, cement, and water are placed separately into the waste container and mixed in place.

The materials tested were:

- Carbon steel - AISI-1006
- Epoxy coated carbon steel - Epoxy type "Concresive #1170 White"
- Polyethylene - Marlex CL-100
- Polyethylene - GPEP-805
- Bitumen coated carbon steel
- Hetron 197 fiberglass
- Hetron 922 fiberglass.

Rectangular coupons of the bare and coated steel specimens as well as the fiberglass coupons were tested. The specimens were weighed and examined prior to testing. After testing they were reexamined and, where ash and other materials could be removed (and corrosion occurred), reweighed. Bare steel and polyethylene stress (U-bend) specimens were also included in the tests. These tests were used to determine possible problems due to stress in manufacture of the drums or in loading them, either from the dead weight of the waste.

5.2 Test Matrix

The test conditions included a number of unusual cases. These were selected because they represent possible excursions in the operating procedures during waste handling. A total of eleven test conditions were defined. These were:

- Dry ash with no additives, (to simulate poor mixing or failure to add cement or bitumen)
- Hot ash (at a temperature ~>500°F) placed in direct contact with the specimens (to simulate filling of drums with fresh ash and no cement or bitumen)
- Ash saturated with deionized water (to simulate failure to add cement to an in-container mixing process or poor mixing)
- Ash with an amount of water equivalent 10% of saturation (similar to the above but less water)
- Ash mixed with cement according to specifications
- Ash mixed with cement - using one half the proper amount of ash (to simulate improper mixing or insufficient ash)
- Ash mixed with cement - using a 50% excess of ash (similar to the above)
- Ash mixed with bitumen
- Ash mixed with bitumen - using 50% excess ash (similar to the cement can)
- Ash allowed to equilibrate with the atmosphere before packaging (to simulate use of ash that might contain adsorbed moisture)
- A test with nothing in the container but coupons to act as a reference.

After sealing, one set of containers was stored at 25° ± 5°C. A duplicate set was exposed to two thermal cycles between -30 and +60°C. After the temperature cycles, the test vessels were placed adjacent to the room temperature set. The total exposure period ranged from 140 to 161 days because of the time required to start and terminate the large number of tests.

The tests were performed as planned, except the hot ash test was heated to 500°C rather than 500°F. This caused severe reactions with the organic materials. Similar though not as severe results could occur with 500°F ash - in the case of a large container, the temperature would not drop as rapidly as in the laboratory and heat would be applied to the container for a longer period.

5.3 Results

All bare metal specimens in moisture-free environments were unaffected. Water in the cement-ash mixtures caused no problems during curing. The epoxy on coated specimens in many cases came loose on the edges and in extreme cases peeled off in sheets. The bitumen-coated specimens were virtually unaffected by all environments. The Hetron, GPEP and Marlex specimens had a slightly dulled luster but were otherwise unaffected by all environments, except for the hot ash where they were burned. The corrosion rates for the steel generally were less than 0.001 mils per year (mpy) (0.025 μm/y) except for the "dry" ash which had one unexplained case of 0.02 mpy (0.5 μm/y). None of the stress coupons cracked. No attack was observed on the 316 stainless steel hardware used to hold the stress coupons.

The water-saturated ashes caused very severe corrosion of the bare metal specimens. Based on weight loss, corrosion rates of up to 28 mpy (700 μm/y) were observed. The pitting was severe and may have exceeded 200 mpy (5000 μm/y). Corrosion of the epoxy-coated specimens also occurred in areas where the coating came loose. The bitumen-coated specimens were unaffected because of better adherence of the coating.

The 10% of saturation ashes exhibited corrosion on the bare metal specimens, up to 3.1 mpy (79 μm/y), but to a much lesser degree than the saturated ashes. No pitting was observed.

The corrosion rates for all environments appear in Table 19. Observations appear in Table 20. Figure 16 illustrates the results of the extreme corrosive environment, Figure 17 shows mild corrosion, Figure 18 illustrates no corrosion and Figure 19 is a magnified view of U-bends from the extreme corrosion conditions.

The thermal cycled specimens were not significantly different from the static specimens.

5.4 Discussion

The dry waste, including that put in bitumen is non-corrosive because of the lack of an electrolyte. However as is clear from the wet-ash tests, if water gets into these containers, severe corrosion of bare steel will occur.

The corrosion caused by the wet ash appears to have been accelerated by the presence of metallic copper in the resin ash. The corrosion rate in the wet trash ash is not quite as bad as in the resin or mixed ashes.

Corrosion in the cement/ash mixes is inhibited by the high pH of the cement. This could be negated if the acid concentration in the ash were too high.

In no cases were the non-metals observed to be attacked beyond a mild surface discoloration except in the case of the hot ash. As noted, the epoxy coating failed to adhere to the steel. Pretreatment of the polished, 120 grit, finish of the steel is expected to be the cause.

Table 19. Corrosion Rates, mils/year (mpy)

SPECIMEN ENVIRONMENT	NO EFFECT			MILD CORROSION			SEVERE CORROSION		
	I (IX RESIN ASH)	II (TRASH ASH)	III (ASH MIX)	I	II	III	I	II	III
DRY ASH	<0.0006 <0.0006	<0.0008	0.0006 <0.0006		0.012 TO 0.024				
*HOT ASH + CEMENT	<0.0008 *	<0.0006 *	<0.0006 *						
ASH SATURATED W/DIW							0.5 TO 2.8 13.8 TO 28.0	0.02 TO 0.56 4.0 TO 28.9	0.16 TO 0.81 5.4 TO 11.8
ASH 10 w/o SATURATION				<0.0006 0.027 TO 0.059				0.02 TO 0.10 0.7 TO 1.0	0.01 TO 0.02 1.5 TO 3.1
30 w/o ASH + 70 w/o CEMENT	<0.0006 **	<0.0006 TO 0.0086 **	<0.0006 TO 0.0012 **						
15 w/o ASH + 85 w/o CEMENT	<0.0006 TO 0.0094 **	<0.0006 **	<0.0006 **						
60 w/o ASH + 40 w/o CEMENT	<0.0006 **				0.021 TO 0.028 **	0.0030 TO 0.0036 **			
40 w/o ASH + 60 w/o BITUMEN	<0.0006 <0.0006	<0.0006 <0.0006	<0.0006 <0.0006						
60 w/o ASH + 40 w/o BITUMEN	<0.0006 <0.0006	<0.0008 <0.0006	<0.0006 <0.0006						
ASH EQUILIBRATED w/ATMOSPHERE	<0.0006 <0.0006	<0.0006 <0.0008	<0.0006 <0.0006						
CONTROLS			<0.0006 <0.0006						

*ASH RESIDUE BURNED ON TO SURFACE OF BARE SPECIMENS (NO WT LOSS DATA) PLUS CEMENT RESIDUE
**CEMENT RESIDUE (NO WT LOSS DATA)
1. THE HETRON 197-3 & 922 COUPONS AND Gpap 805, MARLEX CL-100 U-BENDS INDICATED NO CORROSION
2. THE BITUMEN COATED COUPONS INDICATE NO CORROSION

EPOXY COATED / BARE METAL

Table 20. Summary of Corrosion Test Observations

SPECIMEN ENVIRONMENT	NO EFFECT			MILD CORROSION			SEVERE CORROSION		
	I (IX RESIN ASH)	II (TRASH ASH)	III (ASH MIX)	I	II	III	I	II	III
DRY ASH					BARE METAL-SMOOTH BROWN RUST COLOR				
*HOT ASH + CEMENT	CEMENT VERY HARD - BARE METAL SPECIMENS HIGH TEMPERATURE AIR OXIDIZED GRAY-BROWN COLOR. EPOXY AND BITUMEN BURNED ONTO SPECIMENS. HETRON SEVERLY BURNED								
ASH SATURATED W/DIW							BARE METAL SPECIMENS SEVERELY CORRODED EPOXY COATED SPECIMENS SEVERELY CORRODED WHERE EPOXY PEELED OFF		
ASH 10 w/o SATURATION				BARE METAL DARK BROWN BLOTCHY FILM.				——— SAME AS ABOVE ———	
30 w/o ASH + 70 w/o CEMENT	CEMENT VERY HARD - EPOXY PEELED OFF SPECIMENS IN SHEETS								
15 w/o ASH + 85 w/o CEMENT	CEMENT EXTREMELY HARD - EPOXY PEELED OFF SPECIMENS IN SHEETS								
60 w/o ASH + 40 w/o CEMENT	CEMENT VERY HARD YELLOW→ RED AREA ON TOP OF CEMENT				MIXTURE DAMP AND CRUMBLED EASILY	CEMENT VERY HARD			
40 w/o ASH + 60 w/o BITUMEN	H_2O ON TOP OF MIXTURE IN THERMAL CYCLED JARS		H_2O ON TOP MIXTURE IN THERMAL CYCLED JARS						
60 w/o ASH + 40 w/0 BITUMEN		MOISTURE PRESENT IN THERMAL CYCLED JARS							
ASH EQUILIBRATED w/ATMOSPHERE		BARE METAL THERMAL CYCLED SPECIMENS SMOOTH BRN RUST							
CONTROLS									

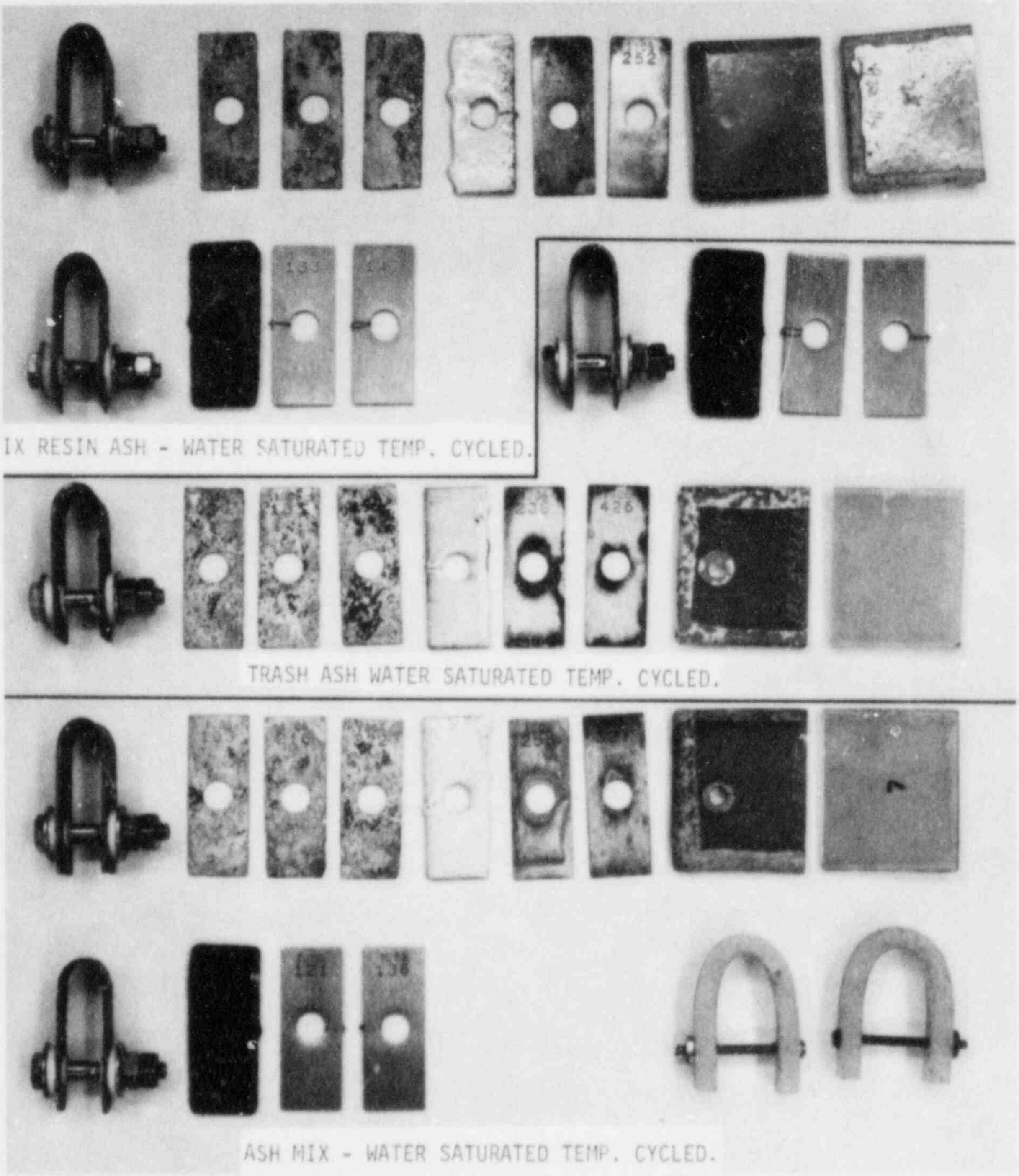

Figure 16. Examples of severe corrosion

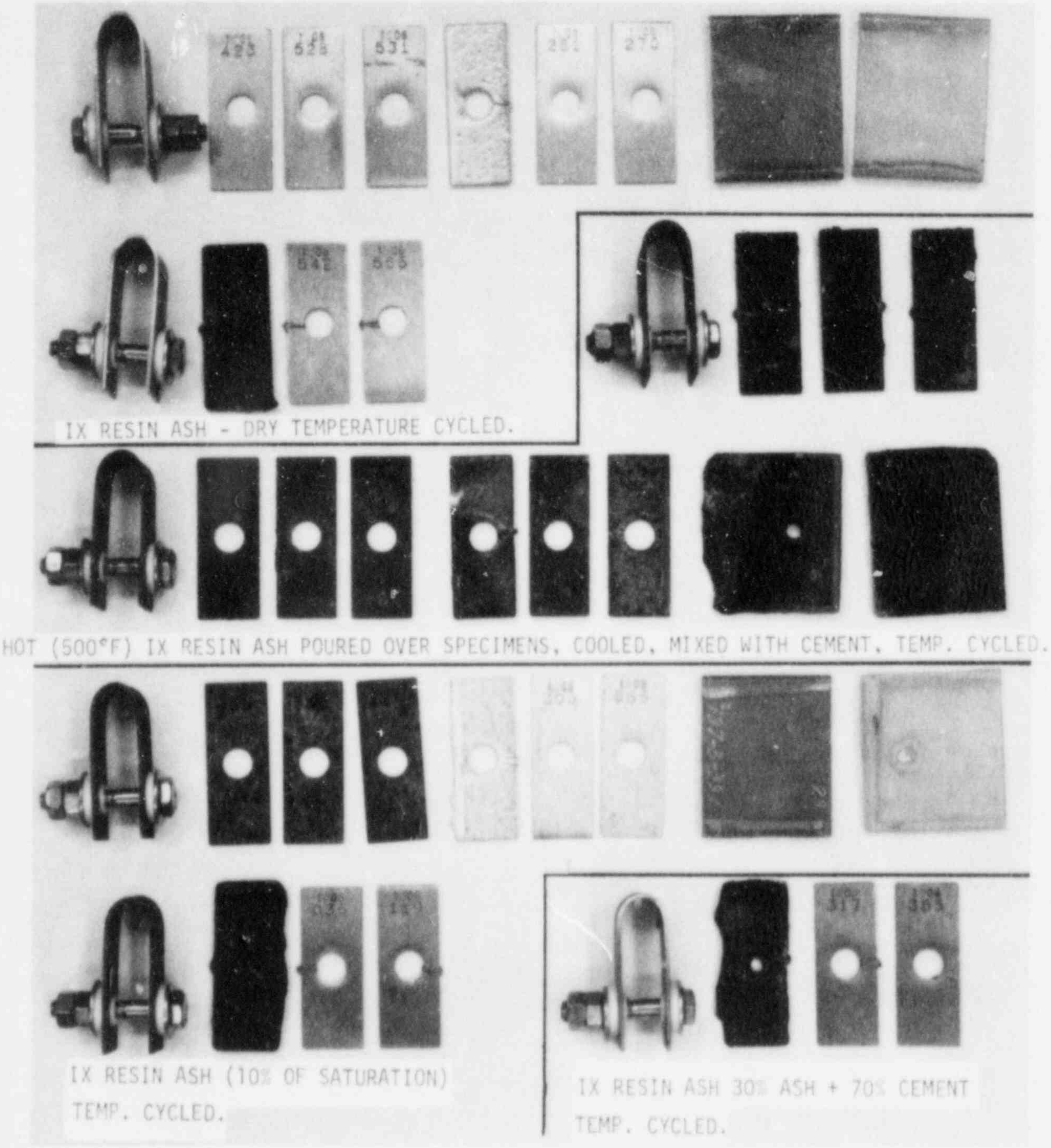

Figure 17. Examples of mild corrosion

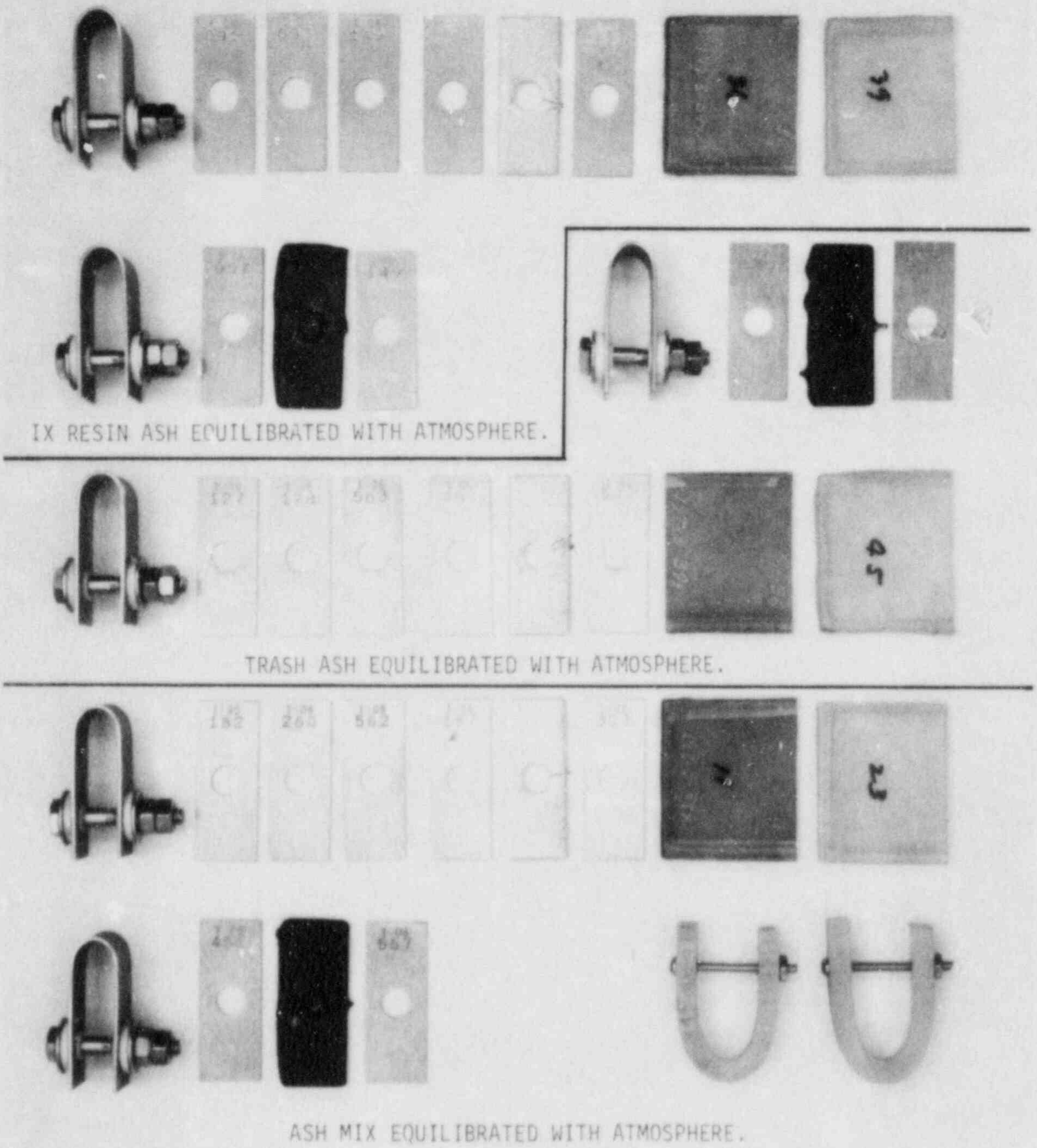

Figure 18. Examples of no corrosion

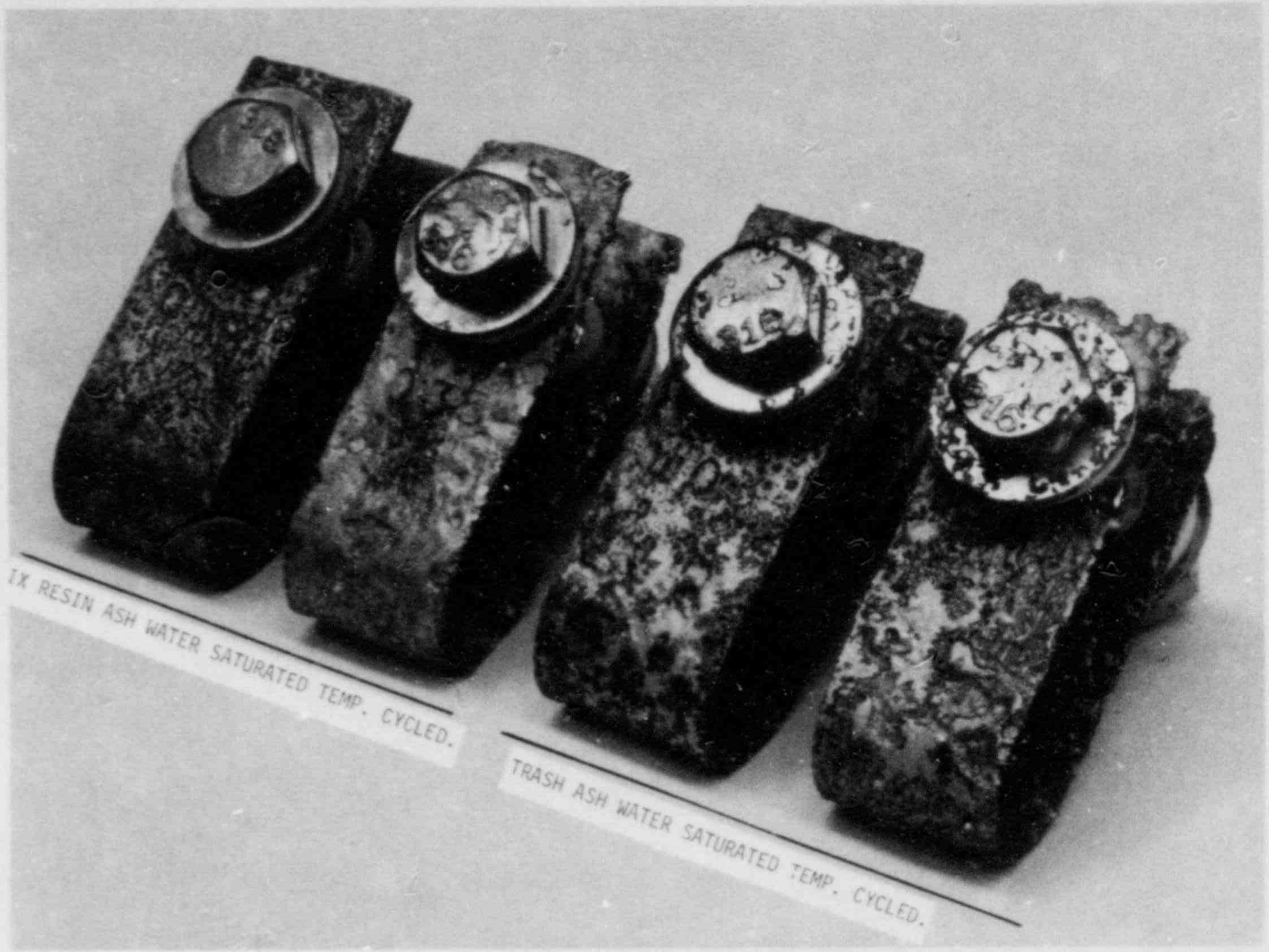

Figure 19. U-bend specimens from severe corrosion environment

6. CONCLUSIONS AND RECOMMENDATIONS

Incinerator ash from the combustion of the low-level wastes including paper, plastic and ion exchange resin can be immobilized in a cement or bitumen matrix. The resulting waste forms meet the requirements outlined in the NRC's Technical Position on Waste Form.

Some foaming was observed with both the cement and bitumen waste forms. Interactions between the resin component of the ash and the cement is probably the cause of the foaming in cement. The cause of the foam in the bitumen is unknown. Its source should be identified and a decision made regarding its acceptability for bitumen since the foam portion of bitumen does not meet the 50 psi minimum compressive strength.

Bitumen had a measured compressive strength of 130 psi and cement had a strength of 1400 psi. Irradiation and thermal cycling did not significantly change the compressive strength of either waste form. Leaching, or more appropriately, exposure of the cement to water caused a significant increase in the strength of the cement to 2100 psi. Curing the cement without allowing it to dry should result in compressive strengths above the 1400 measured here.

Irradiation of the cement and bitumen to a total dose of 10^8 Rad caused no visible changes in either waste form. There was slight pressurization caused by the irradiation, producing high levels of hydrogen and almost complete consumption of oxygen.

Thirty-one temperature cycles from +60°C to -30°C had no visible effect on the cement specimens. The bitumen specimens did tend to slump during the thermal cycling. This slumping probably left the ash particles less protected which probably accounted for the small increase in the leachability of the bitumen. This slumping may not be observed if the bitumen is tightly contained.

The leachability of the cement and bitumen exceed the minimum requirements identified in the Technical Position on Waste Form. The leachability index as calculated in the ANS 16.1 leach test procedure is 13 for bitumen and 7.3 and 8.7 for cement based on cesium and strontium respectively. The leachability index should be a minimum of 6. Irradiation and thermal cycling had no significant impact on the leachability of cement. Nor did leaching in a simulated Barnwell groundwater. The leachability of bitumen was impacted by the irradiation and thermal cycling; decreasing the leachability index by as much as one and a half points. The releases from bitumen are still very low relative to cement.

Neither cement nor bitumen supported bacterial or fungal growth as measured by the ASTM G21 and G22 procedures. Tests to determine if the byproducts of microorganism metabolism impact the waste forms indicate that there may be some effect on the radionuclide release from the waste forms due to this cometabolism. The solutions needed to support growth of the organisms were not representative of those at a burial site, however. More work is needed in this area to understand biodegradation and to develop tests to effectively measure its significance.

Small concentrations (ppb) of carboxylic acids and chelating agents including NTA, EDTA, and ED3A were measured in the leachates of ash and the cement and bitumen waste forms. The concentrations were too low to significantly affect the release and migration of radionuclides from the waste forms.

In a screening test, cement and bitumen were shown to have no significant interactions with potential waste form containers including carbon steel (AISI 1006), fiberglass and polyethylene. Dry ash and ash in equilibrium with air do not interact with the container materials. However, wet ash caused corrosion of the steel to occur.

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APPENDIX A

LEACH TEST DATA

Table A.1. Fractional Releases from Thermal Cycled Cement

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	1.51e-05	2.53e-06	1.96e-06	2.82e-07
8.30e-02	1.33e-03	4.42e-05	3.06e-05	6.95e-06
2.92e-01	1.84e-03	1.65e-04	5.01e-05	4.01e-05
1.00e+00	7.05e-04	4.70e-04	2.41e-04	1.23e-04
2.00e+00	1.29e-03	5.07e-04	2.83e-04	7.16e-05
3.00e+00	1.48e-03	2.31e-04	2.56e-04	6.09e-05
4.00e+00	1.51e-03	3.68e-04	2.48e-04	4.56e-05
5.00e+00	1.16e-03	5.21e-04	1.81e-04	5.45e-05
6.00e+00	1.79e-03	6.16e-04	2.29e-04	7.65e-05
7.00e+00	1.08e-03	5.76e-04	1.41e-04	5.98e-05
8.00e+00	1.76e-03	6.26e-04	2.28e-04	7.76e-05
9.00e+00	2.19e-03	7.12e-04	2.73e-04	9.75e-05
1.00e+01	1.49e-03	2.93e-04	1.56e-04	4.55e-05
1.10e+01	1.83e-03	8.50e-05	2.23e-04	3.08e-05
1.20e+01	2.17e-03	5.56e-04	2.68e-04	7.15e-05
1.30e+01	1.68e-03	3.32e-04	2.16e-04	5.12e-05
1.40e+01	1.21e-03	2.12e-04	1.88e-04	1.67e-05
1.50e+01	1.60e-03	2.31e-04	2.00e-04	9.03e-06
1.60e+01	1.38e-03	4.23e-04	1.61e-04	7.64e-05
1.70e+01	1.31e-03	3.29e-04	1.50e-04	4.22e-05
1.80e+01	1.53e-03	6.67e-04	2.01e-04	8.18e-05
1.90e+01	1.78e-03	3.07e-04	2.07e-04	5.30e-05
2.00e+01	1.57e-03	5.71e-04	1.77e-04	7.22e-05
2.10e+01	3.33e-03	1.75e-03	5.10e-04	2.50e-04
2.80e+01	7.48e-03	3.01e-03	9.14e-04	2.78e-04
3.50e+01	7.71e-03	3.05e-03	9.83e-04	3.67e-04
4.20e+01	9.45e-03	1.39e-03	1.11e-03	1.10e-04
4.90e+01	9.50e-03	7.78e-03	1.15e-03	3.10e-04
5.60e+01	1.16e-02	2.61e-03	1.41e-03	3.43e-04
6.30e+01	1.01e-02	2.56e-03	1.25e-03	2.79e-04
7.00e+01	8.46e-03	1.07e-03	1.31e-03	3.56e-04
7.70e+01	7.89e-03	3.99e-03	1.08e-03	4.29e-04
8.40e+01	5.95e-03	2.29e-03	7.82e-04	2.06e-04

Table A.2. Fractional Releases from Irradiated Cement

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	2.09e-04	1.24e-04	1.43e-05	7.26e-06
8.30e-02	1.14e-03	8.04e-04	1.36e-04	6.07e-05
2.92e-01	2.04e-04	1.06e-04	8.05e-05	3.10e-05
1.00e+00	2.40e-03	1.19e-03	4.24e-04	2.50e-04
2.00e+00	2.51e-03	3.63e-04	5.61e-04	1.83e-04
3.00e+00	3.20e-03	2.98e-03	5.38e-04	3.54e-04
4.00e+00	1.69e-03	8.87e-04	2.55e-04	5.47e-05
5.00e+00	2.06e-03	8.77e-04	3.38e-04	3.32e-05
6.00e+00	1.69e-03	8.08e-04	2.79e-04	4.29e-05
7.00e+00	1.41e-03	5.96e-04	2.21e-04	1.90e-05
8.00e+00	1.47e-03	3.99e-04	2.09e-04	2.71e-05
9.00e+00	2.2[illegible]e-03	6.72e-04	3.50e-04	6.59e-05
1.00e+01	2.11e-03	7.15e-04	3.24e-04	9.67e-05
1.10e+01	2.14e-03	4.98e-04	3.71e-04	1.26e-04
1.20e+01	1.79e-03	2.02e-04	2.89e-04	2.09e-05
1.30e+01	1.06e-03	5.48e-04	1.70e-04	7.30e-05
1.40e+01	1.04e-03	5.48e-04	1.61e-04	8.04e-05
1.50e+01	1.65e-03	1.94e-04	2.07e-04	8.04e-05
1.60e+01	2.08e-03	6.04e-04	3.29e-04	1.10e-04
1.70e+01	1.63e-03	3.93e-05	2.62e-04	4.98e-05
1.80e+01	1.62e-03	4.58e-04	2.49e-04	9.04e-05
1.90e+01	1.96e-03	4.48e-04	2.57e-04	1.40e-04
2.00e+01	1.89e-03	3.64e-04	2.92e-04	2.35e-05
2.10e+01	4.64e-03	1.05e-04	7.66e-04	8.26e-05
2.80e+01	7.35e-03	2.86e-03	1.12e-03	4.30e-04
3.50e+01	7.75e-03	1.41e-03	1.21e-03	[illegible].07e-04
4.20e+01	1.10e-02	1.42e-03	1.30e-03	2.21e-04
4.90e+01	8.57e-03	2.68e-03	1.03e-03	4.47e-04
5.60e+01	1.11e-02	9.77e-04	1.40e-03	3.63e-04
6.30e+01	8.22e-03	1.83e-03	9.88e-04	2.40e-04
7.00e+01	6.46e-03	1.45e-02	8.34e-04	1.49e-04
7.70e+01	6.03e-03	5.1[illegible]e-04	6.65e-04	2.37e-04
8.40e+01	5.88e-03	2.24e-04	7.46e-04	1.41e-04
9.10e+01				

Table A.3. Fractional Releases from Pre-Compressive Strength Cement

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	5.17e-04	3.37e-04	7.10e-07	2.58e-07
8.30e-02	2.21e-02	8.21e-03	2.88e-05	9.42e-06
2.92e-01	2.11e-02	1.18e-02	4.73e-05	1.78e-05
1.00e+00	1.00e-01	5.66e-02	2.42e-04	1.43e-04
2.00e+00	1.19e-01	7.47e-02	2.05e-04	9.62e-05
3.00e+00	6.13e-02	2.36e-02	9.00e-05	1.87e-05
4.00e+00	7.89e-02	4.89e-02	1.11e-04	6.71e-05
5.00e+00	8.92e-02	3.59e-02	1.19e-04	4.08e-05
6.00e+00	5.81e-02	2.02e-02	6.71e-05	3.74e-05
7.00e+00	1.29e-01	1.23e-01	1.52e-04	1.18e-04
8.00e+00	1.03e-01	4.69e-02	1.17e-04	3.88e-05
9.00e+00	1.19e-01	8.96e-02	1.38e-04	9.94e-05
1.00e+01	6.54e-02	2.17e-02	7.83e-05	2.61e-05
1.10e+01	7.56e-02	4.05e-02	9.35e-05	5.33e-05
1.20e+01	5.20e-02	9.24e-03	5.46e-05	9.67e-06
1.30e+01	9.38e-02	6.17e-02	1.12e-04	8.34e-05
1.40e+01	6.25e-02	1.37e-02	6.72e-05	1.21e-05
1.50e+01	7.83e-02	4.30e-02	7.58e-05	4.59e-05
1.60e+01	7.83e-02	2.24e-02	9.03e-05	2.25e-05
1.70e+01	8.32e-02	4.66e-02	1.01e-04	5.61e-05
1.80e+01	5.89e-02	3.67e-02	8.21e-05	2.88e-05
1.90e+01	7.59e-02	2.04e-02	9.92e-05	1.86e-05
2.00e+01	8.67e-02	1.54e-02	1.01e-04	2.18e-05
2.10e+01	1.05e-01	3.83e-02	1.26e-04	3.86e-05
2.80e+01	6.89e-01	2.02e-01	7.51e-04	2.63e-04
3.50e+01	1.02e+00	4.38e-01	1.14e-03	4.84e-04
4.20e+01	8.74e-01	3.71e-01	1.11e-03	4.57e-04
4.90e+01	6.98e-01	1.14e-01	1.04e-03	1.50e-04
5.60e+01	5.80e-01	1.79e-01	9.24e-04	3.62e-04
6.30e+01	5.36e-01	1.59e-01	8.85e-04	2.34e-04
7.00e+01	5.69e-01	1.76e-01	8.19e-04	3.89e-04
7.70e+01	5.81e-01	2.04e-01	1.02e-03	4.20e-04
8.40e+01	4.00e-01	2.52e-01	6.89e-04	3.48e-04
9.10e+01	9.82e-01	2.62e-01	1.55e-03	3.55e-04

Table A.4. Fractional Releases from Cement in Barnwell Groundwater

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV
3.47e-04	1.86e-04	1.03e-04
8.30e-02	1.33e-03	6.43e-04
2.92e-01	1.35e-03	6.28e-04
1.00e+00	8.18e-03	2.05e-03
2.00e+00	2.97e-03	7.58e-04
3.00e+00	2.62e-03	9.14e-04
4.00e+00	4.37e-03	5.30e-04
5.00e+00	3.50e-03	8.69e-04
6.00e+00	2.31e-03	8.64e-05
7.00e+00	3.13e-03	9.29e-04
8.00e+00	1.01e-03	4.59e-05
9.00e+00	1.15e-03	4.42e-04
1.00e+01	1.48e-03	6.49e-04
1.10e+01	1.73e-03	9.28e-04
1.20e+01	1.70e-03	1.15e-04
1.30e+01	3.02e-03	5.65e-04
1.40e+01	9.69e-04	3.39e-04
1.50e+01	1.35e-03	7.70e-05
1.60e+01	1.09e-03	2.95e-04
1.70e+01	1.30e-03	7.52e-04
1.80e+01	1.25e-03	4.52e-04
1.90e+01	1.11e-03	5.63e-06
2.00e+01	1.96e-03	7.02e-04
2.10e+01	2.70e-03	1.30e-03
2.80e+01	5.09e-03	5.76e-04
3.50e+01	6.67e-03	2.27e-03
4.20e+01	4.16e-03	4.52e-03
4.90e+01	6.63e-03	1.71e-03
5.60e+01	5.30e-03	2.35e-03
6.30e+01	6.01e-03	1.44e-03
7.00e+01	6.17e-03	2.67e-03
7.70e+01	4.32e-03	1.24e-03
8.40e+01	8.73e-03	3.72e-03
9.10e+01	1.24e-03	3.95e-04

Table A.5. Fractional Releases from Cement in ANS 16.1 Test

CUMULATIVE TIME	ALUMINUM MEAN	ALUMINUM ST DEV	CALCIUM MEAN	CALCIUM ST DEV	CESIUM MEAN	CESIUM ST DEV
3.47e-04			3.48e-05	5.33e-06	1.84e-03	6.93e-04
8.30e-02	1.41e-05	3.82e-06	4.64e-04	9.06e-05	1.95e-02	5.45e-03
2.92e-01	1.93e-05	3.54e-06	5.06e-04	9.52e-05	1.53e-02	3.21e-03
1.00e+00	1.22e-04	1.05e-05	1.43e-03	2.58e-04	4.65e-02	5.31e-03
2.00e+00	8.40e-05	8.55e-06	1.19e-03	1.52e-04	2.67e-02	2.94e-03
3.00e+00	6.80e-05	1.22e-05	1.07e-03	1.76e-04	2.37e-02	1.40e-03
4.00e+00	5.47e-05	1.01e-05	8.54e-04	1.52e-04	1.63e-02	1.56e-03
5.00e+00			1.13e-03	1.16e-04	2.12e-02	1.78e-03
6.00e+00	1.72e-05	2.27e-06	5.86e-04	5.20e-05	9.07e-03	5.95e-04
7.00e+00	3.95e-05	4.74e-06	7.71e-04	9.56e-05	1.11e-02	1.34e-03
8.00e+00	3.76e-03	5.14e-06	6.09e-04	8.54e-05	8.64e-03	1.01e-03
9.00e+00	2.87e-05	5.90e-06	7.11e-04	6.68e-05	1.05e-02	1.11e-03
1.00e+01	4.46e-05	5.23e-06	6.97e-04	9.75e-05		
1.10e+01	5.09e-05	1.92e-06	7.44e-04	7.98e-05		
1.20e+01	4.58e-05	3.43e-06	6.69e-04	5.53e-05	8.82e-03	4.68e-04
1.30e+01	3.37e-05	2.77e-06	6.88e-04	6.57e-05		
1.40e+01	2.16e-05	3.14e-06	5.99e-04	4.47e-05	7.50e-03	5.97e-04
1.50e+01	4.33e-05	2.07e-06	5.72e-04	4.47e-05	4.98e-03	4.37e-04
1.60e+01	3.57e-05	4.16e-06	5.62e-04	4.12e-05		
1.70e+01	4.71e-05	3.56e-06	5.72e-04	4.47e-05	5.67e-03	3.12e-04
1.80e+01	4.01e-05	2.45e-06	5.44e-04	4.06e-05	5.04e-03	3.67e-04
1.90e+01	4.46e-05	3.83e-06	4.97e-04	3.78e-05	5.09e-03	4.11e-04
2.00e+01	3.44e-05	2.16e-06	5.16e-04	4.06e-05	5.44e-03	2.62e-04
2.10e+01	2.10e-05	2.11e-06	4.37e-04	2.96e-05	4.18e-03	2.82e-04
2.80e+01	1.74e-04	5.99e-06	1.49e-03	9.43e-05	2.97e-02	1.70e-03
3.50e+01	1.58e-04	7.22e-06	1.33e-03	6.49e-05	2.81e-02	1.25e-03
4.20e+01	1.59e-04	5.76e-06	1.28e-03	7.43e-05	2.68e-02	1.20e-03
4.90e+01	1.63e-04	5.28e-06	1.26e-03	7.10e-05	2.22e-02	7.35e-04
5.60e+01	1.60e-04	7.73e-06	1.20e-03	5.74e-05	1.95e-02	5.43e-04
6.30e+01	1.54e-04	9.00e-06	1.15e-03	6.64e-05	1.73e-02	8.41e-04
7.00e+01	1.75e-04	9.24e-06	1.12e-03	6.42e-05	1.67e-02	1.08e-03
7.70e+01	1.59e-04	9.62e-06	1.09e-03	5.20e-05	1.47e-02	3.82e-04
8.40e+01	1.46e-04	8.95e-06	1.01e-03	6.95e-05	1.22e-02	5.38e-04
9.10e+01	1.44e-04	6.01e-06	9.67e-04	5.68e-05	1.23e-02	4.37e-04
9.80e+01	1.62e-04	6.15e-06	9.58e-04	4.76e-05	1.25e-02	3.86e-04
1.05e+02	1.67e-04	3.64e-06	9.43e-04	4.36e-05	1.13e-02	2.85e-04
1.12e+02	1.53e-04	6.57e-06	9.25e-04	5.31e-05	8.38e-03	4.67e-04
1.19e+02	1.48e-04	4.92e-06	8.97e-04	5.51e-05	8.04e-03	3.45e-04
1.26e+02	1.48e-04	7.83e-06	8.70e-04	5.73e-05	9.27e-03	3.16e-04
1.33e+02	1.53e-04	6.62e-06	8.83e-04	5.67e-05	9.34e-03	2.98e-04
1.40e+02	1.43e-04	5.38e-06	8.23e-04	4.73e-05	7.18e-03	1.93e-04
1.47e+02	1.37e-04	7.23e-06	7.57e-04	4.51e-05	7.37e-03	5.44e-04
1.54e+02	1.07e-04	2.25e-05	7.37e-04	1.84e-04	6.31e-03	1.56e-03
1.61e+02	1.40e-04	5.09e-06	8.37e-04	3.77e-05	6.47e-03	3.16e-04
1.68e+02	1.36e-04	5.57e-06	7.88e-04	4.35e-05	6.37e-03	3.06e-04
1.96e+02	2.58e-04	1.86e-05	1.54e-03	1.30e-04	1.54e-02	7.55e-04
2.24e+02	5.03e-05	9.52e-06	3.14e-04	6.38e-05	3.11e-03	4.77e-04
2.52e+02	8.39e-05	2.69e-05	4.85e-04	1.77e-04	4.36e-03	1.44e-03
2.80e+02	8.69e-05	1.87e-05	5.33e-04	1.27e-04	4.13e-03	7.78e-04
3.08e+02	9.90e-05	2.65e-05	7.27e-04	2.54e-04	7.65e-03	2.82e-03
3.36e+02	6.89e-05	2.34e-05	4.28e-04	1.93e-04	2.05e-03	8.39e-04

Table A.5. (continued)

CUMULATIVE TIME	COBALT MEAN	COBALT ST DEV	COPPER MEAN	COPPER ST DEV	IRON MEAN	IRON ST DEV
3.47e-04					1.54e-06	3.51e-07
8.30e-02					2.96e-06	6.46e-07
2.92e-01					1.54e-06	
1.00e+00					1.07e-06	1.95e-07
2.00e+00						
3.00e+00					8.01e-06	5.61e-06
4.00e+00					3.07e-06	
5.00e+00						
6.00e+00						
7.00e+00						
8.00e+00						
9.00e+00						
1.00e+01						
1.10e+01						
1.20e+01						
1.30e+01						
1.40e+01						
1.50e+01						
1.60e+01						
1.70e+01						
1.80e+01						
1.90e+01						
2.00e+01						
2.10e+01						
2.80e+01			3.30e-06	6.01e-07	1.08e-06	3.77e-07
3.50e+01			3.30e-06	5.10e-07	2.74e-06	1.33e-06
4.20e+01			4.17e-06		9.00e-07	3.45e-07
4.90e+01					2.05e-06	1.29e-06
5.60e+01					2.35e-06	2.36e-06
6.30e+01					1.60e-06	1.33e-06
7.00e+01					2.10e-06	1.66e-06
7.70e+01					2.21e-06	1.47e-06
8.40e+01			3.58e-06		2.26e-06	1.27e-06
9.10e+01			8.36e-06	6.73e-06	9.07e-06	1.54e-05
9.80e+01			3.45e-06	8.80e-07	2.57e-06	1.75e-06
1.05e+02			5.00e-06	2.36e-06	3.77e-06	1.09e-06
1.12e+02			3.83e-06	9.75e-07	3.75e-06	2.42e-06
1.19e+02					7.69e-06	7.48e-06
1.26e+02			2.99e-06	8.42e-07	3.37e-06	1.26e-06
1.33e+02			2.98e-06		3.59e-06	1.95e-06
1.40e+02					3.86e-06	1.26e-05
1.47e+02			4.93e-06	1.07e-06	7.99e-06	3.22e-06
1.54e+02	2.79e-06	8.87e-07	2.74e-06	6.45e-07	4.85e-06	1.23e-06
1.61e+02			3.00e-06	8.88e-07	7.15e-06	2.45e-06
1.68e+02			3.24e-06	1.53e-06	5.72e-06	1.24e-06
1.96e+02			3.19e-06	8.73e-07	8.24e-06	2.31e-06
2.24e+02	2.60e-06	4.37e-07	1.23e-06	3.78e-07	2.74e-06	8.87e-07
2.52e+02	3.67e-06	1.53e-06	1.67e-06	5.87e-07	4.16e-06	1.37e-06
2.30e+02	4.66e-06	1.50e-06	1.89e-06	8.85e-07	4.52e-06	2.02e-06
3.08e+02			2.84e-06	1.54e-06	5.72e-06	3.13e-06
3.30e+02			2.22e-06	7.85e-07	4.13e-06	1.59e-06

Table A.5. (continued)

CUMULATIVE TIME	SILICON MEAN	SILICON ST DEV	SODIUM MEAN	SODIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	1.47e-05	5.09e-06	2.97e-04	1.13e-04	2.44e-05	3.33e-07
8.30e-02	4.51e-05	7.93e-06	5.19e-03	7.83e-04	4.42e-04	1.23e-04
2.92e-01	6.16e-05	1.18e-05	2.28e-03	4.65e-04	9.78e-04	2.53e-04
1.00e+00	3.21e-04	3.36e-05	6.81e-03	7.33e-04	4.55e-03	1.05e-03
2.00e+00	3.28e-04	3.73e-05	4.02e-03	3.46e-04	3.64e-03	7.04e-04
3.00e+00	3.41e-04	4.27e-05	3.63e-03	2.36e-04	3.41e-03	7.20e-04
4.00e+00	3.08e-04	3.95e-05	2.83e-03	3.67e-04	2.68e-03	5.38e-04
5.00e+00	4.26e-04	3.78e-05	3.60e-03	2.36e-04	3.58e-03	5.15e-04
6.00e+00	2.41e-04	2.38e-05	1.58e-03	1.01e-04	1.79e-03	2.22e-04
7.00e+00	3.41e-04	1.59e-05	2.06e-03	2.71e-04	2.11e-03	3.35e-04
8.00e+00	2.57e-04	3.46e-06	1.55e-03	1.76e-04	1.61e-03	2.82e-04
9.00e+00	3.41e-04	4.27e-05	1.90e-03	2.24e-04	1.91e-03	2.90e-04
1.00e+01	3.30e-04	3.22e-05	1.87e-03	2.63e-04	1.75e-03	3.27e-04
1.10e+01	3.68e-04	1.78e-05	2.08e-03	2.05e-04	1.77e-03	2.58e-04
1.20e+01	3.50e-04	2.33e-05	1.78e-03	1.62e-04	1.59e-03	2.21e-04
1.30e+01	3.73e-04	1.59e-05	1.66e-03	1.22e-04	1.60e-03	2.00e-04
1.40e+01	3.26e-04	1.35e-05	1.32e-03	1.27e-04	1.40e-03	1.63e-04
1.50e+01	3.17e-04	1.33e-05	1.26e-03	1.23e-04	1.19e-03	1.60e-04
1.60e+01	3.19e-04	8.56e-06	1.25e-03	1.07e-04	1.16e-03	1.45e-04
1.70e+01	3.33e-04	1.12e-05	1.30e-03	5.38e-05	1.17e-03	1.37e-04
1.80e+01	3.21e-04	1.34e-05	1.22e-03	2.96e-05	1.12e-03	1.18e-04
1.90e+01	2.94e-04	3.49e-06	1.14e-03	1.56e-04	1.00e-03	1.14e-04
2.00e+01	3.15e-04	1.02e-05	1.07e-03	5.91e-05	1.02e-03	1.22e-04
2.10e+01	2.65e-04	9.75e-06	7.77e-04	2.71e-05	8.58e-04	9.25e-05
2.80e+01	7.72e-04	4.44e-05	5.53e-03	2.52e-04	3.80e-03	4.99e-04
3.50e+01	7.00e-04	4.16e-05	4.10e-03	2.03e-04	3.25e-03	4.09e-04
4.20e+01	7.25e-04	3.71e-05	4.33e-03	2.05e-04	3.38e-03	3.97e-04
4.90e+01	7.38e-04	3.71e-05	3.90e-03	4.73e-04	3.11e-03	3.65e-04
5.60e+01	7.27e-04	3.65e-05	3.18e-03	9.14e-05	2.87e-03	3.65e-04
6.30e+01	7.20e-04	2.44e-05	2.83e-03	1.87e-04	2.62e-03	3.18e-04
7.00e+01	7.22e-04	2.86e-05	2.79e-03	9.99e-05	2.62e-03	3.14e-04
7.70e+01	7.13e-04	1.80e-05	2.52e-03	1.33e-04	2.54e-03	2.81e-04
8.40e+01	6.91e-04	1.77e-05	2.17e-03	1.23e-04	2.20e-03	2.65e-04
9.10e+01	6.69e-04	1.79e-05	2.04e-03	8.51e-05	2.16e-03	1.62e-04
9.80e+01	6.75e-04	1.59e-05	1.93e-03	5.47e-05	2.09e-03	2.30e-04
1.05e+02	6.69e-04	1.18e-05	1.84e-03	4.01e-05	2.01e-03	1.66e-04
1.12e+02	6.62e-04	1.15e-05	1.75e-03	5.40e-05	1.99e-03	1.83e-04
1.19e+02	6.31e-04	1.09e-05	1.61e-03	1.04e-04	1.87e-03	1.83e-04
1.26e+02	6.26e-04	1.30e-05	1.44e-03	6.74e-05	1.79e-03	1.25e-04
1.33e+02	6.35e-04	1.23e-05	1.50e-03	5.24e-05	1.77e-03	1.66e-04
1.40e+02	5.93e-04	1.60e-05	1.33e-03	5.37e-05	1.57e-03	1.48e-04
1.47e+02	5.75e-04	1.21e-05	1.42e-03	1.10e-04	1.51e-03	1.53e-04
1.54e+02	5.23e-04	1.17e-04	9.71e-04	1.49e-04	1.24e-03	2.47e-04
1.61e+02	6.22e-04	3.71e-05	1.31e-03	3.43e-05	1.46e-03	7.96e-05
1.68e+02	5.78e-04	2.21e-05	1.23e-03	5.87e-05	1.36e-03	1.29e-04
1.96e+02	9.87e-04	6.22e-05	4.90e-03	2.26e-04	3.17e-03	2.09e-04
2.24e+02	2.04e-04	4.67e-05	8.42e-04	1.58e-04	5.94e-04	2.37e-04
2.52e+02	2.94e-04	7.90e-05	1.09e-03	3.15e-04	1.01e-03	3.38e-04
2.80e+02	3.23e-04	5.57e-05	1.08e-03	6.15e-04	9.93e-04	2.36e-04
3.08e+02	4.03e-04	1.61e-04	1.67e-03	5.73e-04	1.41e-03	4.30e-04
3.36e+02	2.74e-04	1.27e-04	3.91e-04	1.14e-04	7.41e-04	3.23e-04

Table A.6. Fractional Releases from Cement in IAEA Test

CUMULATIVE TIME	ALUMINUM MEAN	ALUMINUM ST DEV	CALCIUM MEAN	CALCIUM ST DEV	CESIUM MEAN	CESIUM ST DEV
6.94e-03	1.32e-05	1.48e-07	2.27e-04	3.36e-05	8.02e-03	2.40e-03
6.94e-02	1.87e-05	2.67e-06	6.64e-04	6.10e-05	1.46e-02	8.43e-04
2.50e-01	2.93e-05	2.80e-06	9.33e-04	1.41e-04	1.86e-02	3.22e-03
1.00e+00	1.38e-04	3.28e-06	2.20e-03	3.03e-04	4.39e-02	4.41e-03
2.00e+00	1.44e-04	1.12e-05	2.11e-03	2.68e-04	4.18e-02	3.06e-03
3.00e+00	1.29e-04	7.39e-06	1.81e-03	1.65e-04	3.49e-02	1.43e-03
4.00e+00	1.16e-04	9.15e-06	1.51e-03	1.48e-04	1.75e-02	1.30e-03
7.00e+00	1.85e-04	1.17e-05	2.47e-03	2.12e-04	3.74e-02	2.13e-03
8.00e+00	6.39e-05	5.31e-06	1.06e-03	9.16e-05	1.14e-02	3.75e-04
9.00e+00	4.73e-05	2.84e-06	9.47e-04	8.01e-05	7.58e-03	4.05e-04
1.00e+01	6.13e-05	5.83e-06	9.12e-04	7.10e-05	9.51e-03	3.52e-04
1.10e+01	5.24e-05	5.54e-06	8.70e-04	5.76e-05	8.62e-03	3.81e-04
1.40e+01	1.39e-04	7.87e-06	1.68e-03	1.04e-04	2.45e-02	6.02e-04
1.50e+01	5.56e-05	1.89e-06	8.09e-04	5.46e-05	8.02e-03	3.56e-04
1.60e+01	4.54e-05	1.85e-06	7.10e-04	3.98e-05	5.28e-03	2.13e-04
1.70e+01	5.86e-05	6.69e-06	6.63e-04	4.34e-05	7.01e-03	2.80e-04
1.80e+01	4.88e-05	3.74e-06	6.28e-04	4.16e-05	7.76e-03	2.80e-04
2.10e+01	1.07e-04	2.49e-06	1.21e-03	4.60e-05	1.82e-02	5.60e-04
2.20e+01	5.17e-05	3.36e-06	5.75e-04	2.89e-05	7.67e-03	2.31e-04
2.30e+01	4.93e-05	3.05e-06	5.62e-04	2.54e-05	6.80e-03	2.28e-04
2.40e+01	4.36e-05	2.91e-06	5.39e-04	3.01e-05	6.45e-03	2.06e-04
2.50e+01	4.64e-05	1.59e-06	5.48e-04	3.15e-05	6.78e-03	2.81e-04
2.80e+01	1.04e-04	4.80e-06	1.09e-03	5.10e-05	1.46e-02	4.36e-04
3.50e+01	1.76e-04	8.47e-06	1.55e-03	5.00e-05	2.79e-02	7.47e-04
4.20e+01	1.55e-04	7.37e-06	1.41e-03	4.72e-05	2.22e-02	4.55e-04
4.90e+01	1.61e-04	1.21e-05	1.34e-03	4.71e-05	1.60e-02	3.38e-04
5.60e+01	1.66e-04	6.64e-06	1.27e-03	4.03e-05	1.78e-02	8.72e-05
6.30e+01	1.80e-04	9.02e-06	1.28e-03	4.22e-05	1.54e-02	5.49e-04
7.00e+01	1.71e-04	6.99e-06	1.20e-03	4.19e-05	1.49e-02	2.85e-04
7.70e+01	1.54e-04	1.06e-05	1.14e-03	4.40e-05	1.08e-02	3.40e-04
8.40e+01	1.68e-04	9.91e-06	1.12e-03	4.44e-05	1.20e-02	1.82e-04
9.10e+01	1.59e-04	6.10e-06	1.08e-03	2.98e-05	1.03e-02	1.14e-04

CUMULATIVE TIME	COBALT MEAN	COBALT ST DEV	COPPER MEAN	COPPER ST DEV	IRON MEAN	IRON ST DEV
6.94e-03			2.57e-05	3.58e-06		
6.94e-02			1.03e-05	1.56e-06	2.15e-06	1.77e-06
2.50e-01						
1.00e+00			6.08e-06	3.35e-07	5.12e-06	8.79e-06
2.00e+00					1.85e-06	3.75e-07
3.00e+00					1.41e-05	1.87e-05
4.00e+00			4.01e-06	9.47e-07	1.13e-06	2.56e-07
7.00e+00			4.25e-06	9.54e-07	1.96e-06	1.07e-06
8.00e+00			4.13e-06	1.62e-06	1.58e-06	3.86e-07
9.00e+00					9.44e-07	1.56e-07
1.00e+01			3.55e-06	1.20e-06	1.49e-06	6.59e-07
1.10e+01			2.40e-06		1.03e-06	3.31e-07
1.40e+01			3.16e-06	6.64e-07	1.23e-06	4.19e-07
1.50e+01			2.90e-06		6.97e-07	8.47e-08
1.60e+01			5.22e-06		1.11e-06	5.83e-07
1.70e+01			5.08e-06	1.24e-06	1.34e-06	2.46e-07
1.80e+01			3.42e-06	1.05e-06	1.06e-06	6.49e-07
2.10e+01			3.18e-06	6.49e-07	8.47e-07	1.93e-07
2.20e+01			4.13e-06	6.94e-07	1.13e-06	4.50e-07
2.30e+01			3.79e-06	9.40e-07	1.84e-06	2.19e-06
2.40e+01			2.36e-06		1.41e-06	1.07e-06
2.50e+01					7.76e-07	1.90e-07
2.80e+01					1.95e-06	1.57e-06
3.50e+01			2.90e-06		2.80e-06	2.11e-06
4.20e+01					2.86e-06	3.66e-06
4.90e+01					3.57e-06	2.94e-06
5.60e+01			3.11e-06	1.11e-06	1.54e-06	4.83e-07
6.30e+01	8.77e-05		7.67e-06	9.26e-07	3.50e-06	2.21e-06
7.00e+01			1.16e-05	4.14e-06	2.64e-06	1.63e-06
7.70e+01					2.27e-06	1.22e-06
8.40e+01			6.96e-06	1.66e-06	2.30e-06	1.58e-06
9.10e+01			7.33e-06	1.44e-06	2.26e-06	1.16e-06

Table A.6. (continued)

CUMULATIVE TIME	SILICON MEAN	SILICON ST DEV	SODIUM MEAN	SODIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
6.94e-03	2.04e-05	7.13e-06	1.39e-03	2.58e-04	1.76e-04	6.14e-05
6.94e-02	3.51e-05	3.15e-06	2.23e-03	1.69e-04	1.00e-03	2.15e-04
2.50e-01	4.78e-05	6.63e-06	2.35e-03	1.87e-04	2.11e-03	3.73e-04
1.00e+00	1.67e-04	2.29e-05	5.15e-03	4.33e-04	5.84e-03	8.21e-04
2.00e+00	2.27e-04	2.22e-05	4.88e-03	3.90e-04	5.88e-03	7.44e-04
3.00e+00	2.52e-04	2.67e-05	4.47e-03	1.21e-04	5.02e-03	4.80e-04
4.00e+00	2.59e-04	1.57e-05	3.73e-03	2.23e-04	4.00e-03	4.09e-04
7.00e+00	3.93e-04	2.45e-05	6.49e-03	4.52e-04	7.50e-03	7.36e-04
8.00e+00	2.70e-04	1.46e-05	2.26e-03	1.00e-04	2.62e-03	2.35e-04
9.00e+00	3.10e-04	2.23e-05	2.15e-03	1.45e-04	2.24e-03	2.09e-04
1.00e+01	3.19e-04	1.41e-05	2.05e-03	1.14e-04	2.11e-03	1.71e-04
1.10e+01	3.24e-04	1.44e-05	1.93e-03	1.05e-04	2.01e-03	1.39e-04
1.40e+01	5.76e-04	2.22e-05	5.38e-03	1.52e-04	4.47e-03	3.19e-04
1.50e+01	3.06e-04	1.64e-05	1.24e-03	1.19e-04	1.79e-03	1.46e-04
1.60e+01	3.10e-04	1.38e-05	1.36e-03	6.46e-05	1.42e-03	1.04e-04
1.70e+01	3.08e-04	1.32e-05	8.63e-04	1.16e-04	1.26e-03	9.46e-05
1.80e+01	2.98e-04	1.68e-05	1.20e-03	4.48e-05	1.20e-03	9.18e-05
2.10e+01	5.68e-04	1.81e-05	2.92e-03	2.68e-04	2.56e-03	1.70e-04
2.20e+01	2.53e-04	7.20e-06	1.10e-03	5.20e-05	1.19e-03	8.21e-05
2.30e+01	2.56e-04	5.70e-05	1.11e-03	5.10e-05	1.08e-03	7.20e-05
2.40e+01	2.99e-04	1.27e-05	1.12e-03	5.29e-05	1.04e-03	6.99e-05
2.50e+01	3.17e-04	1.48e-05	1.04e-03	5.04e-05	1.05e-03	7.44e-05
2.80e+01	5.99e-04	2.02e-05	2.67e-03	1.70e-04	2.38e-03	1.74e-04
3.50e+01	7.13e-04	2.70e-05	5.13e-03	1.59e-04	3.97e-03	2.47e-04
4.20e+01	6.69e-04	2.28e-05	4.60e-03	5.83e-04	3.60e-03	2.22e-04
4.90e+01	6.99e-04	2.50e-05	3.62e-03	1.60e-04	3.13e-03	1.77e-04
5.60e+01	6.72e-04	1.27e-05	3.25e-03	8.94e-05	3.10e-03	1.94e-04
6.30e+01	7.02e-04	2.52e-05	3.13e-03	1.82e-04	3.00e-03	1.68e-04
7.00e+01	6.88e-04	7.25e-06	2.72e-03	1.00e-04	2.73e-03	1.62e-04
7.70e+01	6.67e-04	8.98e-06	2.34e-03	1.57e-04	2.44e-03	1.47e-04
8.40e+01	6.91e-04	6.76e-06	2.49e-03	6.61e-05	2.40e-03	1.33e-04
9.10e+01	6.96e-04	8.47e-06	2.17e-03	9.42e-05	2.28e-03	9.87e-05

Table A.7. Fractional Releases from Cement in Equilibrium Test

CUMULATIVE TIME	ALUMINUM MEAN	ALUMINUM ST DEV	CALCIUM MEAN	CALCIUM ST DEV	CESIUM MEAN	CESIUM ST DEV
2.00e+00	9.83e-05	2.01e-05	1.11e-03	9.18e-04	7.82e-02	5.67e-03
3.00e+00	1.65e-04	1.83e-05	3.10e-03	6.34e-04	1.06e-01	4.77e-03
4.00e+00	2.20e-04	1.11e-05	4.24e-03	5.21e-04	1.30e-01	7.74e-03
7.00e+00	2.53e-04	2.04e-05	7.42e-03	1.12e-03	1.87e-01	5.52e-03
8.00e+00	2.41e-04	1.59e-05	4.49e-03	2.59e-03	1.97e-01	3.45e-02
9.00e+00	1.98e-04	4.33e-05	7.49e-03	1.08e-03	2.10e-01	1.35e-02
1.00e+01	2.43e-04	1.60e-05	7.83e-03	1.22e-03	2.14e-01	6.52e-03
1.10e+01	2.48e-04	1.87e-05	7.80e-03	1.11e-03	2.19e-01	1.07e-02
1.40e+01	2.77e-04	2.63e-05	9.79e-03	2.18e-03	2.80e-01	3.75e-02
1.50e+01	2.79e-04	1.68e-05	8.72e-03	1.21e-03	2.71e-01	1.29e-02
1.60e+01	2.84e-04	1.94e-05	8.82e-03	1.21e-03	2.90e-01	1.14e-02
1.70e+01	2.83e-04	1.96e-05	8.82e-03	1.23e-03	2.95e-01	1.45e-02
1.80e+01	2.69e-04	2.12e-05	9.25e-03	1.35e-03	2.95e-01	9.95e-03
2.10e+01	2.58e-04	2.82e-05	9.27e-03	1.23e-03	3.11e-01	8.44e-03
2.20e+01	2.47e-04	3.02e-05	9.30e-03	1.27e-03	3.18e-01	1.43e-02
2.30e+01	2.83e-04	3.49e-05	9.92e-03	1.28e-03	3.32e-01	1.10e-02
2.40e+01	2.77e-04	2.79e-05	9.81e-03	1.30e-03	3.35e-01	8.92e-03
2.50e+01	2.89e-04	6.93e-05	8.10e-03	4.67e-03	3.22e-01	1.53e-02
2.80e+01	2.78e-04	3.03e-05	9.75e-03	1.17e-03	3.48e-01	1.78e-02
3.50e+01	2.78e-04	3.74e-05	1.13e-02	1.86e-03	3.69e-01	1.33e-02
4.20e+01	2.95e-04	4.06e-05	1.13e-02	1.75e-03	3.95e-01	8.89e-03
4.90e+01	2.82e-04	4.65e-05	1.13e-02	1.27e-03	4.14e-01	1.28e-02
5.60e+01	2.91e-04	5.13e-05	9.99e-03	3.50e-03	1.67e-01	1.70e-02
6.30e+01	2.93e-04	4.87e-05	1.09e-02	1.34e-03	4.16e-01	1.40e-02
7.00e+01	3.25e-04	5.27e-05	1.10e-02	1.20e-03	4.07e-01	6.09e-03
7.70e+01	3.25e-04	6.65e-05	1.12e-02	1.34e-03	4.33e-01	2.05e-02
8.40e+01	4.37e-04	7.16e-05	1.15e-02	1.35e-03	1.74e-01	1.11e-02
9.10e+01	3.22e-04	7.39e-05	1.12e-02	1.38e-03	1.85e-01	7.51e-03
9.80e+01	3.15e-04	8.66e-05	1.11e-02	1.46e-03	4.29e-01	1.75e-02
1.05e+02	3.24e-04	9.54e-05	9.73e-03	3.58e-03	4.39e-01	2.02e-02
1.12e+02	3.01e-04	8.61e-05	1.12e-02	1.40e-03	4.36e-01	1.40e-02
1.19e+02	3.55e-04	1.33e-04	1.13e-02	1.46e-03	4.36e-01	2.01e-02
1.26e+02	3.06e-04	9.55e-05	1.12e-02	1.65e-03	4.61e-01	5.69e-03
1.33e+02	3.95e-04	9.48e-05	1.10e-02	1.40e-03	5.51e-01	1.82e-01
1.40e+02	2.88e-04	8.78e-05	1.12e-02	1.56e-03	4.86e-01	2.92e-02
1.47e+02	2.86e-04	9.00e-05	1.11e-02	1.59e-03	4.71e-01	1.85e-02
1.54e+02	2.68e-04	8.15e-05	1.06e-02	1.59e-03	4.95e-01	1.73e-02
1.61e+02	2.77e-04	9.72e-05	1.03e-02	1.47e-03	5.25e-01	1.60e-02
1.68e+02	2.70e-04	8.54e-05	1.05e-02	1.78e-03	4.94e-01	1.93e-02
1.96e+02	2.72e-04	8.37e-05	1.04e-02	2.08e-03	4.95e-01	1.05e-02
2.24e+02	3.02e-04	8.96e-05	9.72e-03	1.80e-03	5.48e-01	2.89e-02
2.52e+02	2.93e-04	9.33e-05	1.11e-02	2.25e-03	5.49e-01	1.76e-02
2.80e+02	2.95e-04	8.45e-05	1.18e-02	2.36e-03	5.04e-01	1.95e-02
3.08e+02	2.93e-04	1.02e-04	9.10e-03	1.91e-03		
3.36e+02	3.03e-04	1.16e-04	8.68e-03	2.51e-03	5.76e-01	2.14e-02

Table A.7. (continued)

CUMULATIVE TIME	COBALT MEAN	COBALT ST DEV	COPPER MEAN	COPPER ST DEV	IRON MEAN	IRON ST DEV
2.00e+00			6.53e-05	3.44e-06	3.29e-06	
3.00e+00						
4.00e+00						
7.00e+00					1.13e-06	1.18e-07
8.00e+00					6.59e-06	4.96e-06
9.00e+00			2.11e-05	1.28e-05	1.38e-05	8.79e-06
1.00e+01			1.52e-05	1.02e-05	4.61e-06	3.08e-06
1.10e+01			1.38e-05	4.36e-06	1.75e-06	8.09e-07
1.40e+01			3.85e-05	1.84e-05	4.68e-06	3.50e-06
1.50e+01			1.70e-05	3.81e-06	3.15e-06	3.24e-06
1.60e+01	4.08e-04		1.66e-05	3.93e-06	6.21e-06	4.93e-06
1.70e+01	4.13e-04		1.98e-05	5.02e-06	3.41e-06	9.69e-07
1.80e+01			2.22e-05	6.23e-06	5.85e-06	3.76e-06
2.10e+01			1.75e-05	3.05e-06	2.19e-06	1.40e-06
2.20e+01	8.16e-04		7.69e-05	1.39e-04	3.94e-06	2.28e-06
2.30e+01			2.06e-05	3.50e-06	2.91e-06	6.21e-07
2.40e+01			6.59e-05	7.78e-05	4.72e-06	3.56e-06
2.50e+01			2.99e-05	2.20e-05	2.00e-06	6.81e-07
2.80e+01			2.07e-05	3.30e-06	4.31e-06	5.40e-06
3.50e+01			6.85e-05	5.31e-05	9.11e-06	1.07e-05
4.20e+01			4.86e-05	2.72e-05	5.29e-06	3.75e-06
4.90e+01			6.80e-05	2.47e-05	1.72e-05	2.46e-05
5.60e+01			6.06e-05	3.57e-05	3.53e-06	2.34e-06
6.30e+01			5.76e-05	4.35e-05	9.37e-06	9.54e-06
7.00e+01			6.59e-05	7.29e-05	3.98e-06	4.26e-06
7.70e+01			8.11e-05	5.31e-05	3.81e-06	3.56e-06
8.40e+01			1.18e-04	1.49e-04	3.24e-06	1.86e-06
9.10e+01			3.46e-05	7.35e-06	5.61e-05	1.03e-04
9.80e+01			4.10e-05	1.49e-05	7.09e-06	1.14e-05
1.05e+02			5.32e-05	3.34e-05	4.42e-06	3.78e-06
1.12e+02			4.87e-05	1.39e-05	3.67e-06	5.99e-07
1.19e+02			9.02e-05	8.82e-05	2.78e-06	6.49e-07
1.26e+02			4.79e-05	1.97e-05	2.73e-06	5.13e-07
1.33e+02			3.87e-05	1.09e-05	3.41e-06	1.84e-06
1.40e+02			5.19e-05	4.08e-05	2.30e-06	8.40e-07
1.47e+02			5.90e-05	5.95e-05	2.36e-06	1.61e-06
1.54e+02			4.22e-05	2.22e-05	8.61e-06	1.45e-05
1.61e+02			9.19e-05	1.31e-04	3.20e-06	2.38e-06
1.68e+02			3.42e-05	1.37e-05	8.85e-07	9.84e-10
1.96e+02			4.03e-05	3.05e-05		
2.24e+02			2.80e-05	1.49e-05	1.56e-06	9.18e-07
2.52e+02			6.86e-05	6.00e-05	2.11e-06	1.26e-06
2.80e+02			1.24e-04	6.01e-05	3.68e-06	1.13e-06
3.08e+02			4.58e-05	2.94e-05	1.42e-06	6.34e-07
3.36e+02			1.41e-04	2.47e-04	1.64e-06	

Table A.7. (continued)

CUMULATIVE TIME	SILICON MEAN	SILICON ST DEV	SODIUM MEAN	SODIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
2.00e+00	1.34e-04	1.71e-05	9.53e-03	1.28e-03	3.79e-03	1.89e-03
3.00e+00	2.00e-04	4.84e-05	1.78e-02	9.42e-04	1.28e-02	2.29e-03
4.00e+00	1.98e-04	4.85e-05	2.31e-02	6.67e-04	1.71e-02	1.99e-03
7.00e+00	1.77e-04	4.78e-05	3.32e-02	1.89e-03	2.78e-02	2.96e-03
8.00e+00	1.40e-04	3.81e-05	3.45e-02	2.30e-03	2.72e-02	7.10e-03
9.00e+00	1.65e-04	3.57e-05	2.95e-02	4.47e-03	3.04e-02	3.92e-03
1.00e+01	1.55e-04	3.30e-05	3.69e-02	3.07e-03	3.31e-02	3.52e-03
1.10e+01	1.48e-04	3.53e-05	3.83e-02	2.21e-03	3.43e-02	3.66e-03
1.40e+01	1.55e-04	2.32e-05	4.18e-02	2.50e-03	4.07e-02	6.77e-03
1.50e+01	1.33e-04	3.28e-05	4.31e-02	3.89e-03	4.07e-02	4.16e-03
1.60e+01	1.90e-04	2.92e-05	4.45e-02	1.92e-03	4.16e-02	4.25e-03
1.70e+01	1.28e-04	3.00e-05	4.50e-02	1.47e-03	4.30e-02	4.32e-03
1.80e+01	1.35e-04	2.48e-05	4.64e-02	2.39e-03	4.30e-02	4.36e-03
2.10e+01	1.14e-04	2.83e-05	4.61e-02	2.67e-03	4.48e-02	4.49e-03
2.20e+01	1.11e-04	2.62e-05	4.97e-02	2.28e-03	4.73e-02	4.75e-03
2.30e+01	1.16e-04	2.99e-05	5.59e-02	3.61e-03	5.04e-02	5.14e-03
2.40e+01	1.13e-04	2.85e-05	6.47e-02	2.62e-03	5.01e-02	4.90e-03
2.50e+01	1.15e-04	2.58e-05	6.73e-02	4.47e-03	5.03e-02	4.69e-03
2.80e+01	1.02e-04	2.36e-05	6.96e-02	3.20e-03	5.24e-02	4.40e-03
3.50e+01	1.12e-04	1.47e-05	7.40e-02	5.13e-03	5.87e-02	5.41e-03
4.20e+01	1.07e-04	1.74e-05	7.97e-02	2.87e-03	6.36e-02	5.91e-03
4.90e+01	1.05e-04	2.22e-05	9.02e-02	3.89e-03	6.69e-02	4.74e-03
5.60e+01	9.33e-05	1.94e-05	8.32e-02	5.14e-03	7.02e-02	5.86e-03
6.30e+01	9.00e-05	1.30e-05	8.89e-02	1.73e-03	6.81e-02	5.61e-03
7.00e+01	8.87e-05	1.40e-05	9.20e-02	3.40e-03	7.04e-02	5.30e-03
7.70e+01	8.92e-05	1.38e-05	9.37e-02	4.52e-03	7.32e-02	4.81e-03
8.40e+01	9.74e-05	1.61e-05	9.64e-02	3.78e-03	7.41e-02	5.56e-03
9.10e+01	8.58e-05	8.65e-06	9.99e-02	2.72e-03	7.44e-02	6.34e-03
9.80e+01	8.92e-05	1.07e-05	9.99e-02	3.30e-03	7.72e-02	5.11e-03
1.05e+02	8.69e-05	1.36e-05	1.05e-01	3.02e-03	7.81e-02	5.31e-03
1.12e+02	9.15e-05	1.65e-05	1.04e-01	4.62e-03	7.93e-02	5.32e-03
1.19e+02	9.60e-05	1.40e-05	1.04e-01	4.12e-03	8.07e-02	5.59e-03
1.26e+02	9.00e-05	1.05e-05	1.09e-01	2.27e-03	8.16e-02	5.32e-03
1.33e+02	8.64e-05	1.37e-05	1.06e-01	4.24e-03	8.28e-02	5.33e-03
1.40e+02	8.95e-05	1.51e-05	1.10e-01	5.18e-03	8.35e-02	5.33e-03
1.47e+02	8.68e-05	1.60e-05	1.07e-01	6.18e-03	8.47e-02	5.30e-03
1.54e+02	7.80e-05	1.77e-05	7.97e-02	3.72e-03	8.32e-02	5.40e-03
1.61e+02	9.89e-05	6.51e-05	9.20e-02	2.34e-03	8.68e-02	5.40e-03
1.68e+02	7.51e-05	1.79e-05	9.33e-02	3.67e-03	8.77e-02	6.17e-03
1.96e+02	7.26e-05	3.44e-05	9.82e-02	3.50e-03	8.76e-02	5.98e-03
2.24e+02	7.69e-05	2.32e-05	1.06e-01	4.05e-03	9.54e-02	6.35e-03
2.52e+02	1.20e-04	4.69e-05	9.90e-02	2.89e-03	9.73e-02	6.37e-03
2.80e+02	1.58e-04	5.07e-05	1.07e-01	3.39e-03	9.64e-02	6.67e-03
3.08e+02	8.47e-05	5.01e-05	1.09e-01	3.01e-03	9.76e-02	7.69e-03
3.36e+02	1.23e-04	7.48e-05	1.11e-01	2.50e-03	9.92e-02	7.63e-03

Table A.8. Fractional Releases from Large Cement Cylinders

CUMULATIVE TIME DAYS	CESIUM 5 X 6 CM	CESIUM 15 X 17 CM	CESIUM 30 X 35 CM	STRONTIUM 5 X 6 CM	STRONTIUM 15 X 17 CM	STRONTIUM 30 X 35 CM
1.00e+00	3.40e-02	6.76e-03	2.35e-03	4.61e-03	5.69e-04	1.24e-04
2.00e+00	3.32e-02	8.52e-03	8.97e-04	6.73e-03	9.01e-04	1.55e-04
3.00e+00	4.01e-02	1.19e-02	4.36e-03	8.10e-03	1.14e-03	3.06e-04
4.00e+00	4.63e-02	1.29e-02	5.31e-03	9.10e-03	1.47e-03	2.86e-04
7.00e+00	5.10e-02	1.32e-02	8.21e-03	1.21e-02	2.13e-03	4.08e-04
8.00e+00	5.56e-02	1.53e-02	8.97e-03	1.25e-02	2.04e-03	5.30e-04
9.00e+00	5.71e-02	1.53e-02	8.97e-03	1.37e-02	1.09e-03	5.30e-04
1.00e+01	5.56e-02	1.50e-02	9.60e-03	1.50e-02	2.09e-03	6.12e-04
1.10e+01	5.56e-02	1.56e-02	9.85e-03	1.62e-02	2.18e-03	6.73e-04
1.40e+01	6.25e-02	1.70e-02	1.20e-02	1.87e-02	2.32e-03	8.36e-04
1.50e+01	6.49e-02	1.88e-02	1.31e-02	1.99e-02	2.32e-03	8.57e-04
1.60e+01	6.49e-02	1.79e-02	1.26e-02	1.99e-02	2.32e-03	9.18e-04
1.70e+01	7.33e-02	2.09e-02	1.49e-02	2.12e-02	2.99e-03	9.18e-04
1.80e+01	7.41e-02	2.03e-02	1.52e-02	2.12e-02	2.66e-03	9.38e-04
2.10e+01	7.72e-02	2.14e-02	1.77e-02	2.24e-02	2.32e-03	1.12e-03
2.20e+01	8.49e-02	2.26e-02	1.77e-02	2.24e-02	2.32e-03	9.99e-04
2.30e+01	8.49e-02	2.35e-02	1.77e-02	2.24e-02	2.32e-03	1.10e-03
2.40e+01	8.49e-02	2.44e-02	2.02e-02	2.37e-02	2.37e-03	1.16e-03
2.50e+01	9.26e-02	2.47e-02	2.02e-02	2.09e-02	2.61e-03	1.31e-03
2.80e+01	1.00e-01	2.53e-02	2.15e-02	2.62e-02	2.70e-03	1.69e-03
3.50e+01	1.00e-01	2.94e-02	2.53e-02	2.62e-02	3.13e-03	2.00e-03
4.20e+01	1.17e-01	3.64e-02	3.18e-02	2.74e-02	2.70e-03	2.45e-03
4.90e+01	1.31e-01	4.11e-02	3.03e-02	2.87e-02	2.70e-03	3.88e-03
5.60e+01	1.39e-01	4.58e-02	3.89e-02	2.99e-02	3.22e-03	4.28e-03
6.30e+01	1.70e-01	4.11e-02	3.79e-02	2.99e-02	2.51e-03	5.30e-03
7.00e+01	1.70e-01	5.29e-02	4.30e-02	3.12e-02	1.94e-03	5.51e-03
7.70e+01	1.78e-01	5.58e-02	4.67e-02	3.12e-02	1.94e-03	5.30e-03
8.40e+01	1.85e-01	5.87e-02	4.80e-02	3.24e-02	1.85e-03	5.10e-03
9.10e+01	1.78e-01	6.17e-02	4.80e-02	3.24e-02	1.75e-03	4.28e-03

Table A.9. Fractional Releases from Thermal Cycled Bitumen

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	3.78e-05	3.41e-05	1.24e-05	6.29e-06
8.30e-02	2.27e-05	3.57e-06	1.18e-05	5.21e-06
2.92e-01	8.33e-06	1.26e-06	3.39e-06	1.05e-06
1.00e+00	3.61e-05	1.66e-06	1.95e-05	1.65e-06
2.00e+00	1.65e-05	3.81e-06	1.17e-05	4.36e-06
3.00e+00	1.79e-05	1.01e-06	1.31e-05	3.50e-06
4.00e+00	1.53e-05	1.30e-06	9.41e-06	1.72e-06
5.00e+00	1.64e-05	7.98e-06	9.40e-06	3.21e-06
6.00e+00	1.28e-05	5.96e-05	9.91e-06	5.07e-06
7.00e+00	1.02e-05	2.69e-06	7.86e-06	6.14e-07
8.00e+00	3.48e-05	7.52e-06	2.01e-05	3.96e-06
9.00e+00	2.84e-05	2.36e-05	2.13e-05	2.04e-05
1.00e+01	1.38e-05	4.29e-06	1.14e-05	6.45e-06
1.10e+01	1.07e-05	3.62e-06	9.23e-06	5.84e-07
1.20e+01	9.35e-06	2.28e-06	6.22e-06	2.66e-07
1.30e+01	1.16e-05	1.29e-06	7.15e-06	5.14e-07
1.40e+01	9.72e-06	3.86e-06	6.45e-06	2.19e-06
1.50e+01	1.60e-05	3.67e-06	8.16e-06	1.59e-06
1.60e+01	9.70e-06	2.43e-06	5.83e-06	2.14e-06
1.70e+01	1.25e-05	4.37e-06	7.12e-06	2.21e-06
1.80e+01	1.84e-05	9.33e-06	1.04e-05	3.23e-06
1.90e+01	1.57e-05	7.24e-06	1.00e-05	3.86e-06
2.00e+01	1.06e-05	1.72e-06	6.18e-06	4.97e-07
2.10e+01	1.98e-05	1.12e-05	1.29e-05	7.33e-06
2.80e+01	4.69e-05	3.49e-05	3.03e-05	1.51e-05
3.50e+01	1.04e-04	5.57e-05	4.74e-05	2.17e-05
4.20e+01	7.78e-05	4.15e-05	5.11e-05	2.10e-05
4.90e+01	5.07e-05	5.26e-06	3.39e-05	4.53e-06
5.60e+01	7.18e-05	1.40e-05	4.14e-05	7.44e-06
6.30e+01	1.04e-04	3.84e-05	4.63e-05	1.40e-05
7.00e+01	1.59e-04	7.92e-05	5.75e-05	2.02e-05
7.70e+01	8.75e-05	2.12e-05	3.76e-05	9.12e-06
8.40e+01	9.73e-05	5.81e-05	4.36e-05	2.19e-05
9.10e+01				

Table A.10. Fractional Releases from Irradiated Bitumen

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	1.35e-05	5.63e-06	7.56e-06	7.19e-06
8.30e-02	3.81e-05	7.90e-06	1.21e-05	2.92e-06
2.92e-01	2.01e-05	8.27e-06	7.08e-06	3.94e-06
1.00e+00	2.92e-05	9.68e-06	1.29e-05	3.57e-06
2.00e+00	2.37e-05	8.24e-06	1.46e-05	3.22e-06
3.00e+00	1.93e-05	9.49e-06	1.16e-05	3.88e-06
4.00e+00	1.76e-05	2.36e-06	1.00e-05	1.14e-06
5.00e+00	8.19e-06	5.86e-06	6.53e-06	3.92e-06
6.00e+00	1.19e-05	1.76e-06	8.06e-06	2.42e-06
7.00e+00	7.98e-06	2.72e-06	6.17e-06	1.13e-06
8.00e+00	9.30e-06	1.26e-06	7.30e-06	1.87e-06
9.00e+00	7.76e-06	3.64e-06	5.78e-06	2.83e-06
1.00e+01	8.44e-06	1.85e-06	6.54e-06	1.51e-06
1.10e+01	8.74e-06	4.10e-06	5.54e-06	1.54e-06
1.20e+01	4.82e-06	8.37e-07	3.60e-06	1.17e-06
1.30e+01	6.68e-06	3.47e-06	5.31e-06	2.97e-06
1.40e+01	6.00e-06	3.36e-06	4.80e-06	2.49e-06
1.50e+01	6.45e-06	2.72e-06	3.57e-06	6.53e-07
1.60e+01	4.50e-06	2.38e-06	2.76e-06	1.87e-06
1.70e+01	8.18e-06	4.10e-06	4.57e-06	1.15e-06
1.80e+01	5.05e-06	5.62e-07	3.81e-06	1.29e-06
1.90e+01	3.79e-06	2.89e-06	2.38e-06	7.88e-07
2.00e+01	3.32e-06	1.11e-06	2.88e-06	1.07e-06
2.10e+01	2.02e-05	1.14e-05	1.31e-05	4.22e-06
2.80e+01	1.84e-05	3.07e-06	1.96e-05	7.15e-06
3.50e+01	1.01e-05	1.51e-06	1.01e-05	6.21e-07
4.20e+01	2.62e-05	6.46e-06	2.40e-05	1.00e-05
4.90e+01	3.52e-05	8.96e-06	2.13e-05	7.41e-06
5.60e+01	3.89e-05	1.51e-05	2.40e-05	1.12e-05
6.30e+01	4.72e-05	5.93e-06	2.49e-05	1.81e-06
7.00e+01	5.09e-05	1.71e-05	2.46e-05	3.68e-06
7.70e+01	2.61e-05	1.20e-05	1.40e-05	4.58e-06
8.40e+01	2.94e-05	9.50e-06	1.49e-05	2.96e-06
9.10e+01				

Table A.11. Fractional Releases from Pre-Compressive Strength Bitumen

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04	8.00e-06	3.70e-06	4.48e-06	3.46e-06
8.30e-02	1.75e-05	7.24e-06	6.36e-06	2.94e-06
2.92e-01	1.80e-05	1.04e-05	6.98e-06	3.75e-06
1.00e+00	3.29e-05	1.39e-05	1.45e-05	5.02e-06
2.00e+00	1.75e-05	1.22e-05	1.13e-05	5.91e-06
3.00e+00	7.57e-06	4.60e-06	6.17e-06	2.24e-06
4.00e+00	7.30e-06	1.97e-06	6.14e-06	2.52e-06
5.00e+00	4.50e-06	9.56e-07	3.75e-06	1.28e-06
6.00e+00	3.34e-06		4.27e-06	3.98e-06
7.00e+00	4.75e-06	2.48e-06	5.35e-06	2.42e-06
8.00e+00	2.87e-06	6.37e-07	3.14e-06	9.10e-07
9.00e+00	3.86e-06	1.17e-06	3.05e-06	7.41e-07
1.00e+01	1.77e-06	4.47e-07	1.72e-06	4.93e-07
1.10e+01	2.80e-06	1.25e-06	3.50e-06	9.85e-07
1.20e+01	1.67e-06		1.24e-06	6.02e-07
1.30e+01	2.26e-06	8.65e-07	2.33e-06	1.06e-06
1.40e+01	2.11e-06	1.02e-06	1.69e-06	1.02e-06
1.50e+01	3.06e-06	1.98e-06	1.38e-06	4.55e-07
1.60e+01	4.46e-06		1.17e-06	7.95e-07
1.70e+01	2.53e-06	1.10e-06	1.66e-06	5.77e-07
1.80e+01	3.08e-06	7.58e-07	1.39e-06	6.60e-07
1.90e+01	2.40e-06	9.90e-07	2.09e-06	1.20e-06
2.00e+01	3.65e-06	2.27e-06	3.06e-06	2.11e-06
2.10e+01	2.78e-06	1.19e-06	1.99e-06	2.59e-07
2.80e+01	1.54e-05	5.09e-06	1.63e-05	4.45e-06
3.50e+01	1.25e-05	4.82e-06	1.28e-05	2.71e-06
4.20e+01	1.98e-05	9.05e-06	1.49e-05	9.93e-06
4.90e+01	2.38e-05	1.13e-05	1.47e-05	6.56e-06
5.60e+01	2.26e-05	7.00e-06	1.57e-05	3.12e-06
6.30e+01	1.54e-05	6.11e-06	9.56e-06	2.25e-06
7.00e+01	2.03e-05	7.55e-06	9.87e-06	2.43e-06
7.70e+01	2.32e-05	4.41e-06	1.19e-05	2.81e-06
8.40e+01	9.68e-06	1.12e-06	6.35e-06	9.71e-07
9.10e+01	2.51e-05	3.70e-06	1.42e-05	3.12e-06

Table A.12. Fractional Releases from Bitumen in Barnwell Groundwater

CUMULATIVE TIME, DAYS	CESIUM MEAN	CESIUM ST DEV
3.47e-04	4.17e-05	2.78e-05
8.30e-02	2.88e-05	1.62e-05
2.92e-01	5.92e-06	1.42e-06
1.00e+00	1.16e-05	2.23e-06
2.00e+00	1.17e-05	6.90e-06
3.00e+00	7.04e-06	1.72e-06
4.00e+00	1.13e-05	3.58e-06
5.00e+00	4.39e-06	1.66e-06
6.00e+00	8.57e-06	1.99e-06
7.00e+00	7.23e-06	1.77e-06
8.00e+00	9.13e-06	2.40e-06
9.00e+00	4.76e-06	6.01e-07
1.00e+01	4.55e-06	2.21e-06
1.10e+01	3.97e-06	2.88e-06
1.20e+01	3.81e-06	2.82e-07
1.30e+01	5.89e-06	1.74e-06
1.40e+01	2.37e-06	1.36e-06
1.50e+01	1.16e-06	2.01e-06
1.60e+01	1.62e-06	1.65e-07
1.70e+01	2.00e-06	2.52e-07
1.80e+01	1.81e-06	4.04e-07
1.90e+01	5.32e-06	1.25e-06
2.00e+01	5.99e-06	1.22e-06
2.10e+01	1.02e-05	8.03e-06
2.80e+01	1.62e-05	9.16e-06
3.50e+01	6.57e-05	7.92e-06
4.20e+01	4.59e-05	3.14e-05
4.90e+01	1.18e-04	1.12e-04
5.60e+01	6.49e-05	9.26e-06
6.30e+01	4.28e-05	1.17e-05
7.00e+01	4.56e-05	1.66e-05
7.70e+01	2.22e-05	7.54e-06
8.40e+01	2.38e-05	2.63e-06
9.10e+01	1.08e-05	9.90e-07

Table A.13. Fractional Releases from Bitumen in ANS 16.1 Test

CUMULATIVE TIME, DAYS	ALUMINUM MEAN	ALUMINUM ST DEV	CALCIUM MEAN	CALCIUM ST DEV	CESIUM MEAN	CESIUM ST DEV
3.47e-04			8.55e-05	2.07e-05	1.50e-04	1.67e-05
8.30e-02			2.26e-04	1.66e-04		
2.92e-01			4.66e-05	1.13e-05		
1.00e+00			4.09e-05	7.92e-06		
2.00e+00			6.05e-05	6.53e-05		
3.00e+00			1.41e-05			
4.00e+00			2.81e-05	1.78e-05		
5.00e+00			2.48e-05	1.33e-05		
2.80e+01			3.90e-05	2.82e-05		
3.50e+01			1.39e-04			
4.20e+01			3.5[illegible]-04	4.62e-04		
4.90e+01			3.45e-05	1.28e-05		
5.60e+01						
6.30e+01			1.44e-04			
7.00e+01	2.12e-05	2.93e-06	3.53e-05	1.96e-05		
7.70e+01						
8.40e+01			6.05e-05			
9.10e+01			1.69e-05			
9.80e+01	1.97e-05		1.84e-05			
1.05e+02	2.07e-05	1.36e-06	3.56e-05	1.22e-05		
1.12e+02			2.84e-05	1.90e-05		
1.19e+02			3.45e-05	1.83e-05		
1.26e+02			7.99e-04			
1.33e+02			2.18e-05	9.02e-06		
1.40e+02			3.75e-05			
1.47e+02			3.20e-05			
1.54e+02	6.41e-07	2.46e-07	1.01e-05	3.67e-06	3.87e-05	7.16e-06
1.61e+02	7.81e-07	6.04e-07	1.31e-05	1.54e-05	2.63e-05	4.25e-06
1.68e+02	1.80e-06	1.25e-06	1.01e-05	3.70e-06	2.98e-05	4.97e-06
1.96e+02	1.79e-06	8.29e-07	2.59e-05	2.02e-06	1.32e-04	2.23e-05
2.24e+02	7.33e-07	2.62e-07	1.07e-05	4.21e-06	2.86e-05	4.75e-06
2.52e+02	2.54e-06	3.29e-06	2.20e-05	1.36e-05	8.07e-05	5.32e-05
2.80e+02	8.51e-07	2.99e-07	2.68e-05	1.83e-05	7.48e-05	3.27e-05
3.08e+02	2.44e-06	1.04e-06	4.32e-05	1.76e-05	1.57e-04	7.12e-05
3.36e+02	9.94e-07	1.21e-06	1.79e-05	1.52e-05	2.80e-05	1.07e-05

CUMULATIVE TIME, DAYS	COBALT MEAN	COBALT ST DEV	COPPER MEAN	COPPER ST DEV	IRON MEAN	IRON ST DEV
3.47e-04	9.67e-05	2.12e-05	3.25e-05	1.40e-05	3.06e-06	1.29e-06
8.30e-02	1.21e-04	2.05e-05	6.96e-05	1.18e-05	2.65e-06	6.57e-07
2.92e-01	4.09e-05	4.53e-06	3.30e-05	7.38e-06	1.54e-06	1.52e-07
1.00e+00	8.19e-05	1.41e-05	6.09e-05	9.00e-06	2.04e-06	4.65e-07
2.00e+00	5.44e-05	9.13e-07	2.19e-05	7.27e-06	3.00e-06	
3.00e+00			1.62e-05	1.53e-06		
4.00e+00			1.24e-05	1.91e-06	7.03e-06	8.96e-06
5.00e+00						
2.80e+01			1.62e-05	3.62e-06	1.61e-06	1.16e-06
3.50e+01			1.66e-05	7.69e-06	1.98e-05	3.28e-05
4.20e+01			1.61e-05	4.52e-06	8.18e-07	1.94e-07
4.90e+01			1.47e-05	2.52e-06	1.08e-06	
5.60e+01			1.48e-05	6.73e-06		
6.30e+01			1.22e-05	4.95e-06		
7.00e+01			1.33e-05	3.77e-06	4.14e-06	3.08e-06
7.70e+01			1.10e-05	1.52e-06	9.72e-07	
8.40e+01			9.78e-06	2.35e-06	1.01e-05	
9.10e+01			2.21e-05	1.59e-05	3.18e-05	4.22e-05
9.80e+01			1.18e-05	1.33e-06	5.92e-06	3.74e-06
1.05e+02			1.20e-05	2.77e-06	2.82e-06	1.31e-06
1.12e+02			1.26e-05	1.90e-06	1.44e-06	1.05e-06
1.19e+02			1.02e-05	1.91e-06	2.13e-06	1.26e-06
1.26e+02			1.33e-05	4.95e-06	7.62e-05	
1.33e+02			1.17e-05	1.54e-06	1.11e-06	
1.40e+02			1.10e-05	1.99e-06	4.16e-06	
1.47e+02			1.39e-05	2.59e-06	5.64e-05	7.88e-05
1.54e+02	2.93e-05	3.60e-06	1.42e-05	2.87e-06	7.75e-07	1.18e-07
1.61e+02	2.25e-05	4.19e-06	1.35e-05	4.69e-06	7.45e-07	2.42e-07
1.68e+02	2.09e-05	2.83e-06	1.19e-05	1.49e-06	1.05e-06	6.10e-07
1.96e+02	1.10e-04	1.48e-05	5.89e-05	1.16e-05	1.73e-06	8.90e-07
2.24e+02	2.49e-05	3.95e-06	1.32e-05	2.77e-06	6.35e-07	2.77e-07
2.52e+02	6.43e-05	4.47e-05	3.64e-05	2.53e-05	1.40e-06	9.93e-07
2.80e+02	6.39e-05	3.02e-05	3.38e-05	1.48e-05	1.56e-06	7.27e-07
3.08e+02	1.36e-04	5.55e-05	8.37e-05	3.59e-05	3.68e-06	1.55e-06
3.36e+02	2.30e-05	7.23e-06	1.44e-05	4.50e-06	6.45e-07	1.78e-07

Table A.13. (continued)

CUMULATIVE TIME, DAYS	SILICON MEAN	SILICON ST DEV	SODIUM MEAN	SODIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
3.47e-04			1.51e-04	2.58e-07	7.60e-05	4.30e-05
8.30e-02	6.34e-06	7.41e-07	5.13e-04	5.30e-04	7.58e-05	1.60e-05
2.92e-01					5.12e-05	9.03e-06
1.00e+00					1.23e-04	2.06e-05
2.00e+00			2.37e-03	3.87e-03	6.35e-05	4.57e-06
3.00e+00					5.12e-05	4.73e-06
4.00e+00			1.18e-04		3.69e-05	4.89e-07
5.00e+00			5.34e-04	4.51e-04	4.91e-05	7.30e-06
2.80e+01					6.78e-05	2.59e-05
3.50e+01					4.69e-05	1.64e-05
4.20e+01					5.13e-05	9.37e-06
4.90e+01	7.50e-06				6.22e-05	3.47e-05
5.60e+01					4.95e-05	
6.30e+01					3.73e-05	
7.00e+01						
7.70e+01						
8.40e+01						
9.10e+01						
9.80e+01						
1.05e+02	6.09e-06	4.23e-07				
1.12e+02						
1.19e+02	7.61e-06	1.33e-06	2.97e-04			
1.26e+02	1.45e-05	4.03e-06			3.76e-05	
1.33e+02	6.97e-06					
1.40e+02			3.63e-04			
1.47e+02						
1.54e+02	1.18e-06	2.62e-07	6.18e-05	4.30e-06	1.68e-05	3.27e-06
1.61e+02	9.54e-07	3.70e-07	5.57e-05	7.71e-05	1.45e-05	2.89e-06
1.68e+02	8.57e-07	9.79e-07	1.24e-04	5.95e-05	1.34e-05	1.38e-06
1.96e+02	6.03e-07	2.65e-07	2.04e-05	8.39e-06	5.88e-05	6.70e-06
2.24e+02	1.17e-06	1.67e-07	8.84e-06	1.77e-06	1.45e-05	2.73e-06
2.52e+02	2.42e-05	2.76e-05	1.49e-05	8.07e-06	4.32e-05	3.17e-05
2.80e+02	3.14e-06	2.40e-06	1.80e-05	1.16e-05	4.03e-05	1.83e-05
3.08e+02	3.58e-06	1.35e-06	2.99e-05	1.22e-05	9.46e-05	4.58e-05
3.36e+02	2.28e-06	2.09e-06	2.31e-05	2.03e-05	1.82e-05	5.30e-06

Table A.14. Fractional Releases from Bitumen in IAEA Test

CUMULATIVE TIME	ALUMINUM MEAN	ALUMINUM ST DEV	CALCIUM MEAN	CALCIUM ST DEV	CESIUM MEAN	CESIUM ST DEV
6.94e-03			5.50e-05	2.19e-05	1.45e-04	
6.94e-02			9.78e-05	3.51e-05		
2.50e-01			7.96e-05	3.39e-05		
1.00e+00			1.62e-04	4.15e-05		
2.00e+00			1.83e-04	2.15e-05		
3.00e+00			1.83e-04	1.50e-05		
4.00e+00	1.96e-05		5.34e-05	2.36e-05		
7.00e+00	6.59e-05		1.04e-04	7.55e-05		
8.00e+00			6.12e-05	6.92e-05		
9.00e+00			1.83e-04	3.13e-04		
1.00e+01	1.98e-05		3.34e-04	3.52e-04		
1.10e+01			4.88e-04	8.70e-04		
1.40e+01			4.17e-05	1.86e-05		
1.50e+01			3.28e-05	1.12e-05		
1.60e+01						
1.70e+01			1.95e-05	7.23e-06		
1.80e+01	1.99e-05		4.19e-04	7.58e-04		
2.10e+01			2.06e-05	4.15e-06		
2.20e+01			1.49e-05	8.59e-07		
2.30e+01	2.25e-05	2.81e-06	2.47e-05	7.74e-06		
2.40e+01						
2.50e+01			1.80e-05			
2.80e+01						
3.50e+01			2.97e-04	4.53e-04		
4.20e+01			6.44e-05	8.98e-05		
4.90e+01			2.34e-04	3.65e-04		
5.60e+01			3.23e-05	3.23e-05		
6.30e+01			1.04e-04	6.24e-05		
7.00e+01			2.45e-05	8.03e-06		
7.70e+01			2.27e-05	2.06e-05		
8.40e+01			1.81e-05	5.23e-06		
9.10e+01			1.28e-05			

CUMULATIVE TIME	COBALT MEAN	COBALT ST DEV	COPPER MEAN	COPPER ST DEV	IRON MEAN	IRON ST DEV
6.94e-03	6.35e-05	1.92e-05	5.54e-05	6.89e-06	2.17e-06	1.49e-06
6.94e-02	8.77e-05	1.95e-05	5.72e-05	1.11e-05	1.36e-06	3.86e-07
2.50e-01	6.15e-05	7.08e-06	5.65e-05	1.96e-05		
1.00e+00	8.54e-05	1.87e-05	6.14e-05	1.39e-05	1.82e-06	1.37e-06
2.00e+00	5.11e-05	8.34e-06	3.33e-05	5.00e-06	1.93e-06	1.31e-06
3.00e+00	4.89e-05	1.67e-05	3.15e-05	1.77e-05	6.79e-06	1.18e-05
4.00e+00	5.54e-05		2.42e-05	8.71e-06	2.32e-06	1.90e-06
7.00e+00	3.03e-04	2.89e-04	3.25e-05	2.29e-05	5.02e-06	5.58e-06
8.00e+00			8.51e-06	3.41e-06	1.12e-06	
9.00e+00			6.24e-06	3.02e-06	9.90e-07	2.33e-07
1.00e+01			1.75e-05	1.92e-05	4.04e-06	2.35e-06
1.10e+01			8.52e-06	3.78e-06	1.79e-06	
1.40e+01			2.10e-05	8.34e-06	2.46e-06	2.36e-06
1.50e+01	2.11e-04		7.41e-06	2.55e-06	1.53e-06	3.77e-07
1.60e+01			3.02e-06	1.55e-06	8.25e-07	
1.70e+01			4.30e-06	1.32e-06	9.81e-07	
1.80e+01			1.10e-05	1.26e-05	3.15e-06	3.67e-06
2.10e+01			1.10e-05	8.95e-06	2.22e-05	4.19e-05
2.20e+01			5.37e-06	1.57e-06	9.17e-07	3.56e-07
2.30e+01			6.16e-06	2.53e-06	1.28e-06	5.18e-07
2.40e+01			5.68e-06	2.94e-06		
2.50e+01			6.06e-06	3.58e-06	1.06e-06	2.77e-07
2.80e+01			1.07e-05	2.94e-06	6.98e-07	4.39e-09
3.50e+01			1.54e-05	4.97e-06	1.44e-06	9.29e-07
4.20e+01			1.50e-05	3.93e-06	7.51e-06	
4.90e+01			9.87e-06	2.07e-06	3.21e-06	3.36e-06
5.60e+01			1.69e-05	6.28e-06	1.81e-06	
6.30e+01	6.35e-05	1.15e-05	2.10e-05	4.57e-06	1.43e-06	2.76e-07
7.00e+01	6.87e-05		2.11e-05	5.31e-06	1.49e-06	6.35e-07
7.70e+01			1.10e-05	9.60e-07	3.00e-06	1.26e-06
8.40e+01			1.99e-05	7.01e-06	1.23e-06	7.02e-07
9.10e+01			2.21e-05	8.54e-06	9.82e-07	1.94e-07

Table A.14. (continued)

CUMULATIVE TIME	SILICON MEAN	SILICON ST DEV	SODIUM MEAN	SODIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
6.94e-03					2.51e-04	4.35e-04
6.94e-02	1.10e-05	6.38e-06	3.26e-04	2.31e-04	3.50e-05	1.02e-05
2.50e-01			4.09e-04		4.77e-05	1.11e-05
1.00e+00					1.00e-04	1.33e-05
2.00e+00			1.43e-04		7.78e-05	7.05e-06
3.00e+00					6.53e-05	1.49e-05
4.00e+00			1.04e-03	3.12e-04	4.92e-05	
7.00e+00	5.68e-05				1.19e-04	1.81e-05
8.00e+00			2.14e-04			
9.00e+00			1.57e-04		2.53e-05	6.82e-07
1.00e+01			5.71e-04	2.47e-04		
1.10e+01			1.51e-04	6.96e-05		
1.40e+01					8.47e-03	1.37e-05
1.50e+01					4.38e-05	8.74e-06
1.60e+01						
1.70e+01						
1.80e+01	2.98e-05		5.71e-04	7.12e-04	6.27e-05	
2.10e+01			2.45e-04	5.96e-05		
2.20e+01			3.25e-04	1.08e-04		
2.30e+01			3.89e-04	1.74e-04		
2.40e+01						
2.50e+01	1.85e-05	2.21e-06				
2.80e+01			2.00e-04			
3.50e+01	6.14e-06				6.01e-05	1.02e-05
4.20e+01	1.40e-05	7.58e-06			5.00e-05	1.72e-05
4.90e+01					4.14e-05	7.23e-06
5.60e+01	9.49e-06	8.74e-07			3.76e-05	7.90e-07
6.30e+01	9.77e-06	1.06e-06	1.73e-04		4.50e-05	6.37e-06
7.00e+01	9.37e-06				4.76e-05	1.35e-05
7.70e+01					4.70e-05	1.86e-05
8.40e+01					3.71e-05	2.65e-07
9.10e+01						

Table A.15. Fractional Releases from Bitumen in Equilibrium Test

CUMULATIVE TIME	ALUMINUM MEAN	ALUMINUM ST DEV	CALCIUM MEAN	CALCIUM ST DEV	CESIUM MEAN	CESIUM ST DEV
2.00e+00			3.16e-04	6.69e-05	4.10e-04	3.46e-05
3.00e+00			4.84e-04	5.59e-05	3.99e-04	4.60e-05
4.00e+00			5.18e-04	8.53e-05	4.34e-04	4.93e-05
7.00e+00			4.60e-04	7.42e-05	5.55e-04	4.98e-05
8.00e+00			5.41e-04	7.78e-05	5.90e-04	6.23e-05
9.00e+00	2.79e-05	9.81e-06	4.26e-04	8.96e-05	6.18e-04	6.10e-05
1.00e+01			3.34e-04	7.19e-05	6.07e-04	7.66e-05
1.10e+01			3.31e-04	6.64e-05	6.07e-04	7.04e-05
1.40e+01	4.58e-05		3.83e-04	6.31e-05	6.59e-04	8.04e-05
1.50e+01			4.14e-04	6.73e-05	6.53e-04	6.09e-05
1.60e+01	2.13e-05	2.03e-06	4.43e-04	6.14e-05	6.82e-04	1.51e-04
1.70e+01	3.75e-05	9.53e-06	4.77e-04	6.90e-05	6.65e-04	6.73e-05
1.80e+01	2.29e-05	4.60e-06	4.60e-04	7.35e-05	6.70e-04	7.42e-05
2.10e+01			4.57e-04	8.73e-05	7.40e-04	4.76e-05
2.20e+01			4.23e-04	7.09e-05	6.01e-04	6.32e-05
2.30e+01			3.69e-04	1.79e-04	6.82e-04	6.10e-05
2.40e+01			4.80e-04	6.85e-05	7.16e-04	4.20e-05
2.50e+01	2.31e-05	4.43e-06	6.40e-04	1.41e-04	7.92e-04	1.13e-04
2.80e+01			4.80e-04	8.21e-05	6.65e-04	8.14e-05
3.50e+01	3.94e-05		6.07e-04	7.88e-05	8.78e-04	8.87e-05
4.20e+01	3.29e-05	1.83e-05	6.10e-04	9.13e-05	9.02e-04	8.68e-05
4.90e+01			5.41e-04	1.27e-04	1.20e-03	1.11e-04
5.60e+01			6.27e-04	1.27e-04	9.65e-04	9.08e-05
6.30e+01			6.39e-04	1.05e-04	9.77e-04	6.38e-05
7.00e+01			4.92e-04	7.69e-05	9.48e-04	7.96e-05
7.70e+01	2.82e-05	5.99e-06	4.99e-04	7.33e-05	1.03e-03	9.68e-05
8.40e+01	1.75e-04	3.88e-05	5.26e-04	7.45e-05	1.38e-03	1.29e-04
9.10e+01	3.65e-05	3.74e-06	5.35e-04	6.81e-05	1.36e-03	1.32e-04
9.80e+01	2.68e-05	2.60e-06	5.58e-04	7.77e-05	1.35e-03	1.12e-04
1.05e+02	1.96e-05		5.15e-04	8.05e-05	1.33e-03	1.26e-04
1.12e+02			6.75e-04	2.74e-04	1.35e-03	1.32e-04
1.19e+02			5.55e-04	9.38e-05	1.32e-03	7.73e-05
1.26e+02			1.62e-03	2.34e-03	1.46e-03	1.11e-04
1.33e+02	1.24e-04	5.88e-05	5.90e-04	8.65e-05	1.64e-03	1.19e-04
1.40e+02			5.55e-04	8.60e-05	1.64e-03	1.14e-04
1.47e+02			5.50e-04	7.54e-05	1.68e-03	1.19e-04
1.54e+02			5.81e-04	7.34e-05	1.68e-03	1.50e-04
1.61e+02	1.99e-05		5.84e-04	7.88e-05	1.55e-03	1.19e-04
1.68e+02			5.84e-04	7.96e-05	1.54e-03	1.40e-04
1.96e+02			5.96e-04	7.71e-05	1.87e-03	1.62e-04
2.24e+02	2.38e-05	2.47e-06	6.39e-04	7.47e-05	2.03e-03	1.42e-04
2.52e+02			6.82e-04	9.00e-05	2.16e-03	2.26e-04
2.80e+02	2.45e-05	5.58e-06	7.48e-04	8.99e-05	2.28e-03	2.03e-04
3.08e+02	5.31e-05	1.96e-05	8.84e-04	9.81e-05	2.47e-03	2.38e-04
3.36e+02	4.46e-05	6.34e-06	9.38e-04	1.07e-04	3.13e-03	3.99e-04

Table A.15. (continued)

CUMULATIVE TIME	COBALT MEAN	COBALT ST DEV	COPPER MEAN	COPPER ST DEV	IRON MEAN	IRON ST DEV
2.00e+00	3.48e-04	3.72e-05	1.94e-04	2.85e-05	7.36e-06	1.82e-06
3.00e+00	3.23e-04	2.13e-05	1.88e-04	2.99e-05	3.97e-06	1.07e-06
4.00e+00	3.31e-04	3.18e-05	2.07e-04	3.30e-05	5.84e-06	3.43e-06
7.00e+00	4.65e-04	3.25e-05	2.50e-04	3.51e-05	6.30e-06	1.33e-06
8.00e+00	4.47e-04	3.67e-05	2.59e-04	3.41e-05	3.36e-06	7.08e-07
9.00e+00	4.58e-04	2.61e-05	2.56e-04	3.07e-05	1.38e-05	3.42e-06
1.00e+01	4.29e-04	2.55e-05	2.61e-04	3.41e-05	1.04e-05	6.36e-07
1.10e+01	4.29e-04	2.55e-05	2.67e-04	3.56e-05	9.49e-06	4.52e-07
1.40e+01	5.08e-04	5.08e-05	2.88e-04	3.44e-05	1.06e-05	1.06e-06
1.50e+01	5.64e-04	4.49e-05	3.02e-04	2.25e-05	1.14e-05	1.48e-06
1.60e+01	5.48e-04	4.50e-05	3.08e-04	2.18e-05	1.63e-05	1.07e-05
1.70e+01	6.27e-04	5.12e-05	3.10e-04	2.42e-05	1.22e-05	1.72e-06
1.80e+01	5.90e-04	3.57e-05	3.03e-04	2.04e-05	2.43e-05	2.63e-05
2.10e+01	5.49e-04	1.64e-05	2.58e-04	1.29e-04	9.41e-06	2.10e-06
2.20e+01	5.34e-04	3.24e-05	3.15e-04	2.05e-05	7.13e-06	7.02e-07
2.30e+01	5.86e-04	4.54e-05	3.34e-04	1.72e-05	8.97e-06	3.42e-07
2.40e+01	5.89e-04	3.81e-05	3.35e-04	1.84e-05	8.61e-06	9.92e-07
2.50e+01	5.90e-04	3.57e-05	3.44e-04	1.09e-05	1.28e-05	4.90e-06
2.80e+01	6.03e-04	4.63e-05	2.99e-04	1.42e-04	7.85e-06	3.06e-06
3.50e+01	6.38e-04	5.04e-05	3.58e-04	1.89e-05	1.03e-05	1.93e-06
4.20e+01	6.93e-04	5.05e-05	3.78e-04	2.55e-05	8.59e-06	2.41e-06
4.90e+01	6.65e-04	6.87e-05	3.92e-04	2.54e-05	6.56e-06	2.03e-06
5.60e+01	7.04e-04	2.64e-05	4.09e-04	2.99e-05	7.59e-06	3.50e-06
6.30e+01	7.16e-04	4.19e-05	4.02e-04	2.89e-05	7.04e-06	1.46e-06
7.00e+01	7.27e-04	5.12e-05	4.08e-04	3.11e-05	2.08e-06	4.74e-07
7.70e+01	7.73e-04	4.75e-05	4.32e-04	4.05e-05	2.03e-06	6.30e-07
8.40e+01	8.07e-04	5.03e-05	4.36e-04	3.58e-05	5.23e-06	3.78e-06
9.10e+01	8.42e-04	5.73e-05	4.46e-04	3.20e-05	3.02e-06	8.14e-07
9.80e+01	8.70e-04	6.32e-05	4.52e-04	3.33e-05	4.08e-06	2.91e-06
1.05e+02	8.70e-04	6.32e-05	4.68e-04	3.71e-05	2.50e-06	9.98e-07
1.12e+02	8.70e-04	6.32e-05	4.82e-04	3.58e-05	2.23e-06	1.08e-06
1.19e+02	9.25e-04	6.34e-05	4.99e-04	3.61e-05	2.47e-06	4.39e-07
1.26e+02	9.47e-04	8.31e-05	5.01e-04	3.87e-05	2.80e-06	5.71e-07
1.33e+02	9.80e-04	6.36e-05	5.16e-04	4.26e-05	3.38e-06	1.08e-06
1.40e+02	9.88e-04	7.29e-05	5.23e-04	4.23e-05	4.92e-06	4.86e-06
1.47e+02	1.00e-03	8.74e-05	5.51e-04	5.05e-05	2.15e-05	3.90e-05
1.54e+02	1.08e-03	1.04e-04	5.62e-04	6.64e-05	3.86e-06	1.10e-06
1.61e+02	1.11e-03	8.81e-05	5.86e-04	6.68e-05	8.24e-06	4.01e-06
1.68e+02	1.13e-03	1.05e-04	5.86e-04	7.62e-05	4.64e-06	1.03e-06
1.96e+02	1.20e-03	1.03e-04	6.34e-04	7.98e-05	6.61e-06	1.52e-06
2.24e+02	1.34e-03	8.85e-05	6.98e-04	5.63e-05	1.29e-05	5.20e-06
2.52e+02	1.52e-03	1.06e-04	7.92e-04	8.08e-05	1.54e-05	1.96e-06
2.80e+02	1.66e-03	1.28e-04	8.72e-04	9.29e-05	2.11e-05	4.13e-06
3.08e+02	2.08e-03	1.30e-04	1.16e-03	1.11e-04	3.11e-05	2.79e-06
3.36e+02	2.25e-03	1.70e-04	1.22e-03	1.45e-04	3.69e-05	3.86e-06

Table A.15. (continued)

CUMULATIVE TIME	SILICON MEAN	SILICON ST DEV	SODIUM MEAN	SODIUM ST DEV	STRONTIUM MEAN	STRONTIUM ST DEV
2.00e+00	3.70e-05	2.18e-06	6.24e-04	1.93e-04	2.66e-04	6.33e-05
3.00e+00	1.79e-05	6.88e-06	4.14e-04	1.09e-04	3.23e-04	7.65e-05
4.00e+00	1.68e-05	5.57e-06	4.85e-04	2.11e-04	3.70e-04	8.03e-05
7.00e+00	2.05e-05	6.22e-06	6.86e-04	8.26e-05	5.44e-04	1.02e-04
8.00e+00	1.71e-05	6.56e-06	4.40e-04	8.76e-05	5.59e-04	9.99e-05
9.00e+00	3.06e-05	1.32e-05	6.25e-04	1.65e-04	5.76e-04	9.37e-05
1.00e+01					5.78e-04	1.00e-04
1.10e+01					5.98e-04	1.06e-04
1.40e+01	2.05e-05	4.94e-06			6.68e-04	1.08e-04
1.50e+01	3.66e-05	6.45e-06			6.90e-04	1.00e-04
1.60e+01	5.84e-05	1.52e-05	4.44e-04	1.52e-04	7.00e-04	1.12e-04
1.70e+01	4.89e-05	6.12e-06			7.12e-04	1.09e-04
1.80e+01	9.19e-05	4.70e-05	1.99e-04		7.05e-04	1.06e-04
2.10e+01	2.15e-05	9.75e-06	9.41e-03	1.24e-02	7.30e-04	1.06e-04
2.20e+01	1.53e-05	8.30e-06			7.45e-04	1.12e-04
2.30e+01	2.47e-05	7.23e-06	5.62e-04	2.13e-04	6.32e-04	3.12e-04
2.40e+01	2.81e-05	6.15e-06	9.26e-04	5.37e-04	7.87e-04	1.15e-04
2.50e+01	8.87e-05	2.85e-05	2.74e-03	4.27e-03	7.94e-04	1.12e-04
2.80e+01	3.12e-05	1.18e-05	5.84e-04	1.75e-04	8.27e-04	1.21e-04
3.50e+01	4.19e-05	9.93e-06	7.86e-04	2.70e-04	8.81e-04	1.11e-04
4.20e+01	3.92e-05	6.57e-06	7.06e-04	1.89e-04	9.38e-04	1.30e-04
4.90e+01	3.34e-05	1.35e-05	5.44e-04	2.50e-04	9.83e-04	1.50e-04
5.60e+01	3.48e-05	1.35e-05	6.77e-04	2.06e-04	1.01e-03	1.38e-04
6.30e+01	3.29e-05	9.27e-06	5.02e-04	3.13e-04	1.01e-03	1.72e-04
7.00e+01	2.66e-05	6.15e-06	6.26e-04	3.56e-04	1.03e-03	1.50e-04
7.70e+01	3.14e-05	5.81e-06	5.24e-04	2.61e-04	1.06e-03	1.54e-04
8.40e+01	3.68e-05	5.39e-06	8.14e-04	2.53e-04	1.08e-03	1.60e-04
9.10e+01	3.83e-05	5.68e-06	7.87e-04	4.46e-04	1.10e-03	1.57e-04
9.80e+01	4.36e-05	6.65e-06	7.45e-04	3.33e-04	1.12e-03	1.55e-04
1.05e+02	2.53e-05	8.48e-06	9.38e-04	7.46e-04	1.14e-03	1.56e-04
1.12e+02	2.79e-05	5.78e-06	2.80e-03	4.94e-03	1.21e-03	2.11e-04
1.19e+02	2.54e-05	7.60e-06	3.23e-04	8.41e-05	1.26e-03	2.52e-04
1.26e+02	2.82e-05	6.79e-06	5.46e-04	4.11e-04	1.27e-03	2.61e-04
1.33e+02	2.43e-05	6.40e-06	5.04e-04	3.18e-04	1.30e-03	2.66e-04
1.40e+02	2.90e-05	5.90e-06	3.43e-04	2.10e-04	1.31e-03	2.70e-04
1.47e+02	4.96e-05	5.12e-05	5.45e-04	9.34e-05	1.31e-03	3.29e-04
1.54e+02	4.25e-05	5.00e-05	2.31e-04	1.55e-04	1.37e-03	2.69e-04
1.61e+02	6.13e-05	6.70e-06	3.37e-04	1.20e-04	1.39e-03	2.72e-04
1.68e+02	2.43e-05	8.55e-06	5.24e-04	3.79e-04	1.39e-03	2.72e-04
1.96e+02	4.37e-05	6.99e-06	8.68e-04	1.36e-04	1.40e-03	2.84e-04
2.24e+02	2.93e-05	5.17e-06	6.66e-04	1.35e-04	1.51e-03	2.77e-04
2.52e+02	4.66e-05	7.25e-06	6.46e-04	9.00e-05	1.58e-03	2.89e-04
2.80e+02	5.80e-05	4.72e-06	8.64e-04	1.23e-04	1.71e-03	3.60e-04
3.08e+02	5.61e-05	1.14e-05	7.54e-04	2.06e-04	2.09e-03	3.61e-04
3.36e+02	5.10e-05	8.49e-06	7.10e-04	7.97e-05	2.18e-03	3.72e-04

Table A.16. Fractional Releases from Large Bitumen Cylinders

CUMULATIVE TIME DAYS	CESIUM 5 X 6 CM	CESIUM 15 X 17 CM	CESIUM 30 X 35 CM	STRONTIUM 5 X 6 CM	STRONTIUM 15 X 17 CM	STRONTIUM 30 X 35 CM
1.00e+00	1.19e-03	1.85e-04	2.73e-04	4.02e-04	9.51e-05	7.24e-05
2.00e+00	1.34e-03	2.46e-04	1.80e-04	5.50e-04	1.16e-04	7.73e-05
3.00e+00	1.47e-03	2.46e-04	1.98e-04	6.43e-04	1.32e-04	9.23e-05
4.00e+00	1.69e-03	2.83e-04	2.32e-04	7.10e-04	1.43e-04	9.98e-05
7.00e+00	1.78e-03	3.08e-04	2.56e-04	8.98e-04	1.80e-04	1.37e-04
8.00e+00	1.90e-03	3.20e-04	2.67e-04	1.02e-03	1.90e-04	1.50e-04
9.00e+00	1.97e-03	3.20e-04	2.38e-04	3.35e-03	1.95e-04	1.57e-04
1.00e+01	1.97e-03	3.32e-04	2.50e-04	1.15e-03	2.06e-04	1.65e-04
1.10e+01	2.03e-03	3.44e-04	2.96e-04	1.14e-03	2.11e-04	1.72e-04
1.40e+01	2.12e-03	3.57e-04	2.90e-04	1.27e-03	2.32e-04	2.02e-04
1.50e+01	2.28e-03	4.06e-04	3.20e-04	1.29e-03	2.32e-04	2.12e-04
1.60e+01	2.22e-03	4.18e-04	3.20e-04	1.34e-03	2.54e-04	2.25e-04
1.70e+01	2.34e-03	4.06e-04	3.37e-04	1.34e-03	2.64e-04	2.30e-04
1.80e+01	2.47e-03	4.31e-04	3.95e-04	1.34e-03	2.64e-04	2.42e-04
2.10e+01	2.47e-03	4.67e-04	4.12e-04	1.47e-03	2.75e-04	2.49e-04
2.20e+01	2.56e-03	4.80e-04	3.89e-04	1.47e-03	2.85e-04	2.74e-04
2.30e+01	2.47e-03	4.67e-04	3.72e-04	1.47e-03	3.01e-04	2.74e-04
2.40e+01	2.59e-03	4.80e-04	3.83e-04	1.61e-03	3.01e-04	2.74e-04
2.50e+01	2.53e-03	4.80e-04	5.17e-04	1.61e-03	3.06e-04	2.74e-04
2.80e+01	2.72e-03	5.17e-04	4.24e-04	1.74e-03	3.22e-04	2.99e-04
3.50e+01	2.62e-03	5.54e-04	4.30e-04	1.61e-03	3.17e-04	3.24e-04
4.20e+01	2.43e-03	5.90e-04	4.88e-04	1.61e-03	3.86e-04	3.74e-04
4.90e+01	2.56e-03	5.54e-04	4.30e-04	1.88e-03	4.07e-04	3.99e-04
5.60e+01	2.68e-03	6.89e-04	5.58e-04	1.88e-03	4.44e-04	4.24e-04
6.30e+01	2.87e-03	6.64e-04	5.23e-04	1.88e-03	4.54e-04	4.49e-04
7.00e+01	3.00e-03	7.13e-04	5.58e-04	2.01e-03	4.75e-04	4.49e-04
7.70e+01	2.87e-03	7.13e-04	5.58e-04	2.01e-03	5.81e-04	4.74e-04
8.40e+01	2.62e-03	6.40e-04	4.88e-04	2.14e-03	5.23e-04	4.99e-04
9.10e+01	2.56e-03	6.64e-04	5.00e-04	2.28e-03	5.81e-04	5.24e-04

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12. SUPPLEMENTARY NOTES

13. ABSTRACT *(200 words or less)*

Incinerator ash from the combustion of general trash and ion exchange resins were immobilized in cement and bitumen. Tests were conducted on the resulting waste forms to provide a data base for the acceptability of actual low-level waste forms. The testing was done in accordance with the Technical Position on Waste Form. Bitumen had a measured compressive strength of 120 psi and a leachability index of 13 as measured with the ANS 16.1 leach test procedure. Cement demonstrated a compressive strength of 1400 psi and a leachability index of 7. Both waste forms easily exceed the minimum compressive strength of 50 psi and leachability index of 6 specified in the Technical Position. Irradiation to 10^8 RAD and exposure to thirty +60° to -30°C thermal cycles did not significantly impact these properties. Neither waste form supported bacterial or fungal growth as measured with ASTM G21 and G22 procedures. However, there is some indication of biodegradation due to co-metabolism processes. Neither bitumen nor cement containing incinerator ash caused any corrosion or degradation of potential container materials including steel, polyethlyene and fiberglass. However, moist ash did cause corrosion of the steel.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
Low-Level Wastes
Incinerator Ash
Cement
Bitumen
Leachability
Corrosion
Radiation Stability
Mechanical Strength
Biodegradation

b. IDENTIFIERS/OPEN-ENDED TERMS

15. AVAILABILITY STATEMENT
Unlimited

16. SECURITY CLASSIFICATION
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CHARACTERIZATION OF CEMENT AND BITUMEN WASTE FORMS CONTAINING
SIMULATED LOW-LEVEL WASTE INCINERATOR ASH

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