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WASTE FORM EVALUATION PROGRAM

FINAL REPORT

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ABSTRACT

This report presents data that can be used to assess the acceptability of polyethylene and modified sulfur cement waste forms to meet the requirements of 10 CFR 61. The waste streams selected for this study include dry evaporator concentrate salts and incinerator ash as representative wastes which result from advanced volume reduction technologies and ion exchange resins which remain problematic for solidification using commercially available matrix materials. Property evaluation tests such as compressive strength, water immersion, thermal cycling, irradiation, biodegradation and leachability were conducted for polyethylene and sulfur cement waste forms over a range of waste-to-binder ratios. Based on the results of the tests, optimal waste loadings of 70 wt% sodium sulfate, 50 wt% boric acid, 40 wt% incinerator ash and 30 wt% ion exchange resins were established for polyethylene, although maximum loadings were considerably higher. For modified sulfur cement, optimal loadings of 40 wt% sodium sulfate, 40 wt% boric acid and 40 wt% incinerator ash are reported. Ion exchange resins are not recommended for incorporation into modified sulfur cement because of poor waste form performance even at very low waste concentrations. The results indicate that all waste forms tested within the range of optimal waste concentrations satisfied the requirements of the NRC Technical Position Paper on Waste Form.

1. INTRODUCTION

The overall objective of the Waste Form Evaluation program, sponsored by the U.S. Department of Energy's Low-Level Waste Management Program (DOE-LLWMP), is to develop and test technology for the improved solidification of low-level radioactive wastes through the application of materials and processes which are not currently employed in the United States.

The initial phases of the program, which began in October 1983, included the selection of polyethylene and modified sulfur cement as potential solidification agents. The waste types which could be successfully incorporated into the matrices were also selected.

The matrix materials were selected based on such considerations as compatibility with waste, solidification efficiency, ease of processibility, availability of materials and economics. The waste streams selected for this study were those which result from advanced volume reduction technologies. The results of this study, which include process development and preliminary waste form property evaluation, have been previously reported[2,3].

During the latter part of Fiscal Year 1985, program emphasis was directed towards a more comprehensive waste form testing and evaluation study. To assess the acceptability of polyethylene and modified sulfur cement waste forms to meet the 10 CFR 61 waste form stability requirements, the test procedures in this study are those suggested in the NRC Branch Technical Position Paper on Waste Forms, issued May 1983.[6]

This report summarizes the results of this study. However, because of time constraints, the entire series of polyethylene and modified sulfur cement waste forms was not completely evaluated in accordance with the prescribed tests. Included are also those results which were obtained using tests other than those suggested by the NRC. For continuity, this report also provides a brief description of the processing equipment and parameters used to fabricate the test specimens.

2. POLYETHYLENE

Polyethylene is an organic polymer material of crystalline-amorphous structure, formed through the polymerization of ethylene gas. The technology of polyethylene is well established and a very wide variety of polyethylenes is available, ranging from soft waxes to very tough plastics. Many polyethylenes are tailored for specific applications by control and design of their molecular structure. Such structural variations are usually produced by the manipulation of process parameters.

The degree of crystallinity determines density, which in turn affects a range of material properties. Polyethylene is generally categorized as low- or high-density, although the American Society for Testing and Materials (ASTM) grades polyethylene into three types: low, medium and high, with respective density ranges of 0.910 to 0.925; 0.926 to 0.940; and 0.941 to 0.967. Some of the properties of polyethylene, by grade, are given in Table 2.1.

The higher density polyethylenes have relatively few side branches or chains, thus, they will solidify from the melt with the chains being closely packed together in an orderly fashion, giving it a hard crystalline character. Low-density polyethylenes are highly branched, and the solidified material has a disorderly arrangement of polymer chains; they cannot pack so tightly and thus, the material has a lower density.

A second basic control is that of molecular weight (MW). The higher the MW, the more energy (temperature, pressure) is required to process it. With an increase in MW, however, there is a corresponding increase in strength, toughness and chemical resistance.

A third basic control is molecular weight distribution. If most of the molecules fall within a very narrow range of MW, the product will have better mechanical properties compared to a mixture of molecules with a broader range of MW. But these materials are also more difficult to process.

Based primarily on ease of processibility, low-density polyethylene (LDPE) is preferred over high-density polyethylene (HDPE) for the solidification of low-level wastes. An experimental survey of a number of commercially available LDPEs established preferred materials based on processing parameters such as melt temperature, pressure, melt index (a measure of viscosity) and extrusion rate[2]. Low-melt temperatures are preferred for solidification of radioactive wastes to prevent volatilization and decomposition of the radionuclides and/or other waste components. Because of its chemical structure, polyethylene is very resistant to chemical attack and is unaffected by most acids, alkalis and aqueous solutions.

One of the most important chemical changes produced in polyethylene by irradiation is the formation of intermolecular cross-links. Since cross-linking of low-density polyethylene leads to beneficial changes in some of its properties, such as heat resistance, tensile strength, cold flow, etc. the use of this material in applications where exposure to radiation is imminent has received by far the greatest attention among vinyl type polymers.

Table 2.1

Properties of Polyethylenes[a]

Property	Low Density	Medium Density	High Density
Compression Molding Temp, °C	135 - 177	150 - 190	150 - 230
Density, g/cc	0.910 - 0.925	0.926 - 0.940	0.941 - 0.965
Tensile Strength, MPa	4.14 - 15.86	8.27 - 24.13	21.37 - 37.92
(psi)	600 - 2300	1200 - 3500	3100 - 5500
Compressive Strength, MPa	-	-	18.61 - 24.82
(psi)	-	-	2700 - 3600
Water Absorbance, (24 hr, 1/8" thick, %)	<0.01	<0.01	<0.01
Flammability (Burn Rate, in/min)	1.04	1.00 - 1.04	1.00 - 10.4
Average Extent of Burning, in.	0.8	0.6	-
Average Time of Burning, sec.	<5 - 25	10 - 60	-
Effect of Weak Acid	Resistant	Very Resistant	Very Resistant
Effect of Strong Acid	Attacked by Oxidizing Acids	Attacked Slowly	Attacked Slowly
Effect of Weak Alkalies	Resistant	Very Resistant	Very Resistant
Effect of Strong Alkalies	Resistant	Very Resistant	Very Resistant
Effect of Organic Solvents	Resistant Below 60°C Except to Chlorinated Solvents	Resistant Below 60°C Except to Chlorinated Solvents	Resistant Below 80°C

[a] Data drawn from [1].

2.1 Waste Streams

The wastes used in this study were simulated to closely resemble actual wastes in both physical and chemical composition. Two of the wastes which simulate dry evaporator concentrates are BWR sodium sulfate waste and PWR boric acid waste. For that purpose anhydrous sodium sulfate (Na_2SO_4) and ortho boric acid (H_3BO_3) were used. Both reagents were employed as a fine, dry powder with bulk densities of 1.46 and 1.44 g/cm^3, respectively.

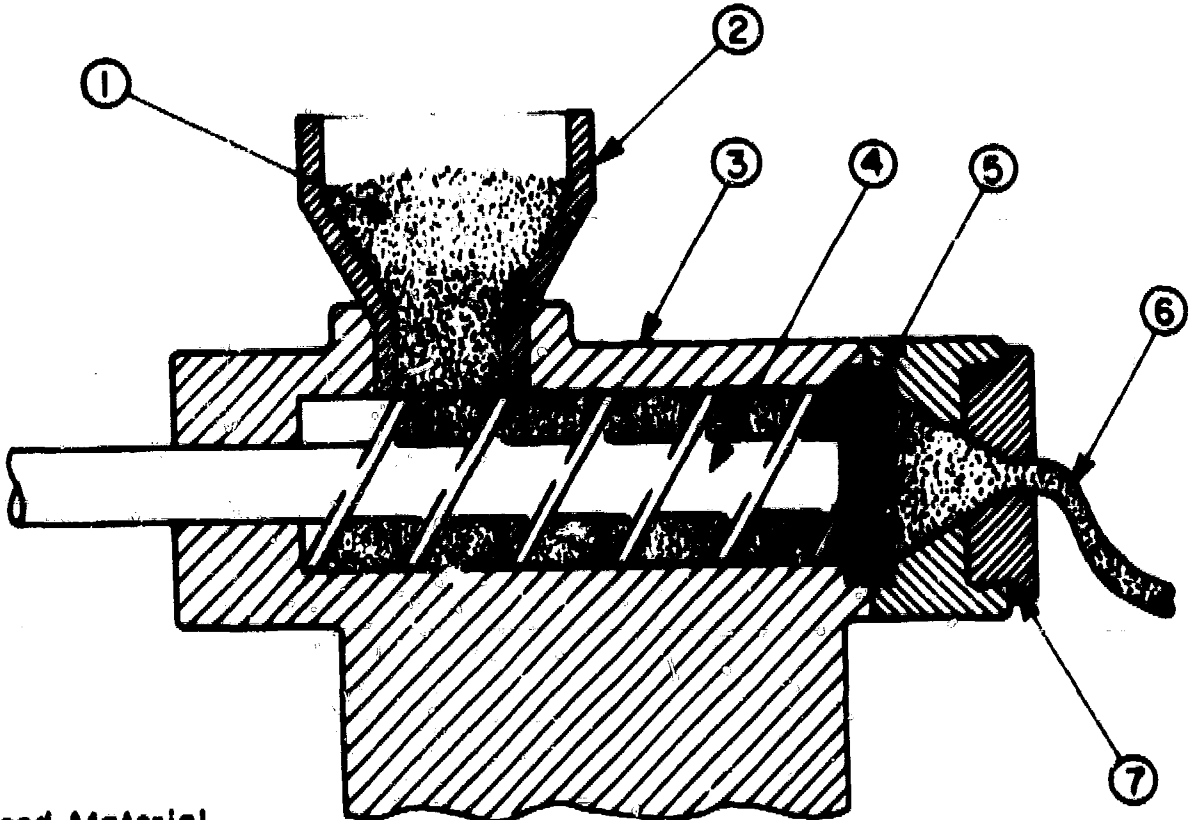
As a typical ash product, incinerator ash generated at the Rockwell International Rocky Flats Plant rotary kiln incinerator was employed[3]. This was produced by burning simulated waste with constituents equivalent to those present in actual combustible LLW as generated at Rocky Flats. To improve both, the processibility and the homogeneity of ash/polyethylene waste forms, the ash was put through a No. 8 sieve, resulting in a maximum particle size of 2.38 mm.

Unloaded mixed-bed resin beads manufactured by Rohm and Haas Corp., Philadelphia, PA, were used to simulate ion exchange resin waste. Although actual spent ion exchange waste is chemically loaded, the use of unloaded resins is not expected to alter results since the ions in spent resins are bonded to the resin and do not interact with the polyethylene. A ratio of two parts cation resin (IRN-77) to one part anion resin (IRN-78) was selected as representative of a typical demineralizer system. Resin bead particle sizes range between 0.5 and 1.0 mm in diameter. These resins (2:1 mixed-bed) have a density of approximately 1.21 g/cm^3 and contain approximately 58 percent moisture by weight. Prior to processing with polyethylene, the resins were oven dried at 110°C. This step was necessitated by design constraints of the bench scale extruder, which precludes the presence of moisture.

2.2 Process Development

A number of processing techniques were considered for incorporation of wastes into low-density polyethylene. These included batch heating vessels, wiped film evaporators and screw-type extruders. Based on such considerations as ease of processibility, quality control, and the use of a proven and available technology, the extrusion method was selected[2]. This process employs a simultaneous mixing and heating of the waste-binder mixture. A simplified schematic of the sectional view of a screw extruder is shown in Figure 2.1. Polyethylene is a thermoplastic material with properties which makes it well suited for processing via this technique as evidenced by numerous applications in the plastics industry.

For the production of laboratory-scale polyethylene waste forms, a commercially available 1 1/4 inch single-screw extruder, manufactured by Killion Extruders, Inc., Verona, NJ, was used. The extruder was modified to accommodate a dynamic feed system with two hoppers to eliminate static premixing and gravity feeding of waste and binder materials into the extruder. These feeders improved the homogeneity of the product by closely regulating the rate at which both waste and binder are introduced into the extruder. Since the laboratory scale extruder was not equipped with vents to allow water vapor to escape, all waste materials were dried to facilitate mixing with polyethylene, which is not miscible with water.



KEY

1. Feed Material
2. Feed Hopper
3. Heating Unit
4. Mechanical Screw
5. Strainer
6. Extruded Product
7. Die

Figure 2.1 Sectional view of a simplified screw extruder. The sketch depicts flow of material from the hopper to the output die, where it is extruded in a molten state. Redrawn from Reference 4.

To avoid contamination of the screw extruder, samples prepared with radioactive tracers for leach testing were produced by use of a dual-action heated mixing vessel, shown in Figure 2.2. The stainless steel mixer is heated by a series of external electrical resistance band heaters controlled by a digital time-proportioning temperature controller. Stirring of the waste-binder mixture is accomplished by the combined action of an impeller blade and Teflon wiper, powered by an air-driven motor. Use of this mixer required that formulations contain less waste than those processed by extrusion, and processing times be extended to compensate for less efficient mixing. Consequently, the highest sodium sulfate waste loadings that could be incorporated into the leaching samples by this method was 50 wt%.

Process development studies were conducted with a number of LDPEs varying principally according to their melt index, as shown in Table 2.2. The important process parameters investigated included temperatures, pressures, mixing pressures, mixing method, feed rates, waste pre-treatment, solidification kinetics and waste/binder ratios. In general, polyethylene with a higher melt index (those with a lower viscosity when molten) such as LDPE type Gulf-1409 and 1410 were able to incorporate greater quantities of waste. Lower viscosities also allowed for improved material flow, lower pressure buildup and enhanced homogeneity of the waste form product. Results of these studies are presented in Table 2.3, in terms of maximum waste loadings achievable. Maximum waste loadings for LDPE incorporating each of the waste types investigated are: 70 wt% sodium sulfate, 50 wt% boric acid, 40 wt% incinerator ash and 65% ion exchange resins. Waste loadings are presented in terms of dry weight percent and represent the maximum amount of waste which can be incorporated to form a monolithic solid, based solely on process constraints.

2.3 Sample Fabrication

Laboratory-scale samples of varying waste/binder ratios were prepared for both process development and waste form stability evaluation studies. The homogeneous extruded mixtures were solidified in cylindrical molds, yielding samples which measured approximately 4.8 cm (1.9 inches) in diameter and 9.0 cm (3.5 inches) in height. Those samples which were prepared for leach testing had radioactive tracers incorporated into the wastes. The radioisotopes used were Co-60, Sr-85 and Cs-137, since these are the radionuclides usually of greatest concern (in quantity and half-life) for low-level wastes. As mentioned earlier, these samples were prepared using a dual-action mixing vessel (Figure 2.2), to avoid contamination of the screw extruder. For convenience, waste loadings of 10, 30 and 50 wt% were used for polyethylene/sodium sulfate samples, 25 and 35 wt% for polyethylene/ incinerator ash samples and 10, 20 and 30 wt% for polyethylene/ion exchange resin samples.

Waste form activity source terms were calculated based upon the waste loading (wt%) and the final weight of each specimen.

2.4 Testing Procedures

Waste form stability is considered to be an important factor in the performance of shallow land burial sites. Thus, an evaluation of the structural stability of polyethylene waste forms was conducted to help predict their

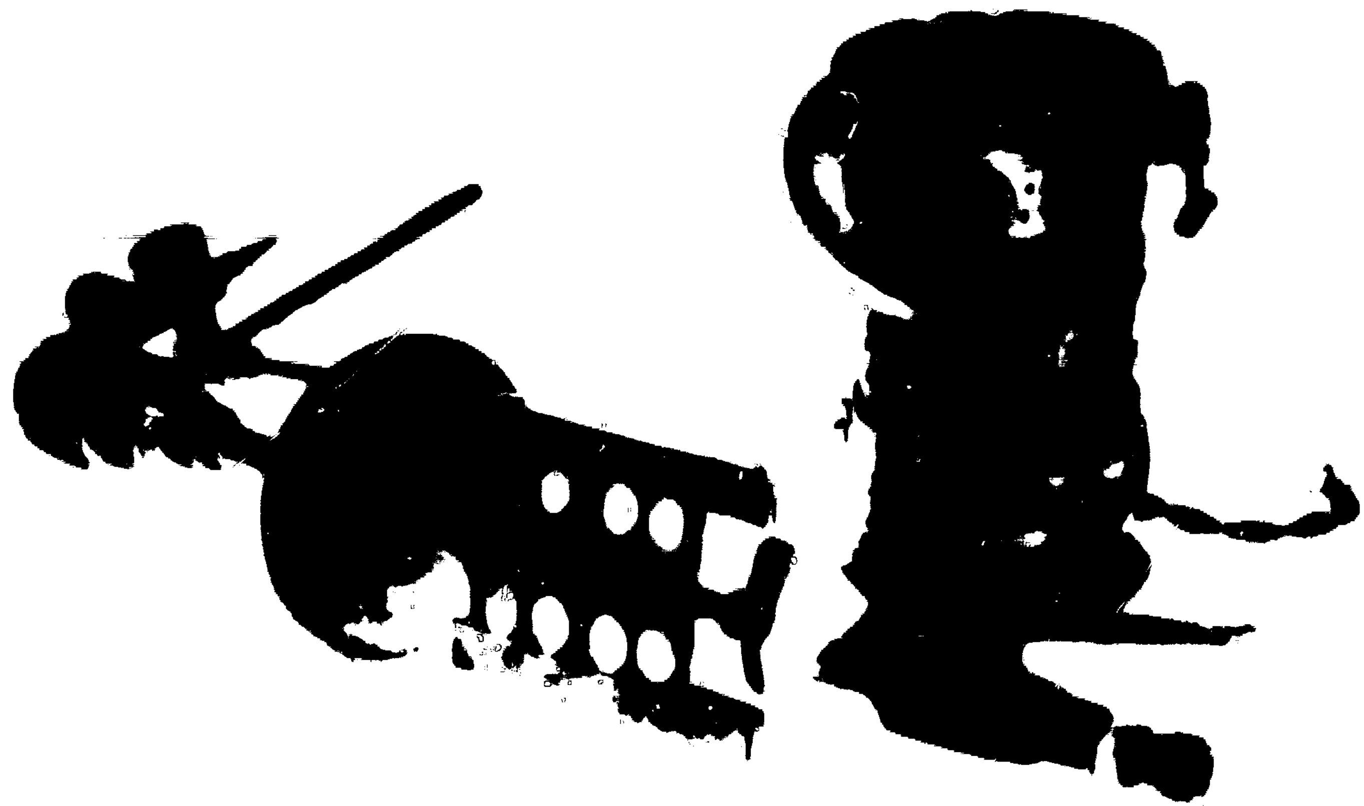


Figure 2.2 Dual-action heater mixing vessel shown with cover removed displaying mixing blade.

Table 2.2

Average Properties of Low-Density Polyethylene (LDPE) Materials Selected for Investigation[a]

LDPE Type[g]	End Use	Density[b] g/cm³	Melt Index[c] g/10 min	Molecular[d] Weight	Molecular Weight Distribution[e]
Gulf 1117-8	Extruded Film	0.924	2.0	NA[f]	NA
Gulf 1400	Injection Molding	0.924	8.0	70,000	3.0
Gulf 1408.5	Injection Molding	0.924	27.0	60,000	2.5
Gulf 1410	Injection Molding	0.924	35.0	55,000	2.5
Gulf 1409	Injection Molding	0.924	55.0	40,000	2.5
Eastman C-14	Non-Emulsifiable Wax	0.918	1.6	23,000	3.8
Eastman C-17	Non-Emulsifiable Wax	0.917	20.0	19,000	3.6

a) Data as supplied by manufacturers
b) Determined by ASTM Test Method D1505
c) Determined by ASTM Test Method D1238
d) Determined by Gel Permeation Chromatography (GPC)
e) Ratio of weight average molecular weight to number average molecular weight.
f) Not available
g) Manufactured by: Gulf Oil Chemicals, Houston, TX and Eastman Chemical Products, Kingsport, TN

Table 2.3

Maximum Waste Loadings for Polyethylene Waste Forms Achieved by the Extrusion Method

Waste Type	Wt%
Sodium Sulfate	70
Boric Acid	50
Incinerator Ash	40
Ion Exchange Resin	65

polyethylene waste forms measured the percent swelling after immersion in water for 90 days, deformation under compressive load, effects of thermal cycling and leaching of radionuclides. However, during the latter part of FY 85, further testing was conducted in accordance with guidance provided by the U.S. Department of Energy's Low-Level Waste Management Program (DOE-LLWMP).

The additional testing included compressive strength, biodegradation and radiation stability. However, due to time constraints some of the waste/binder combinations were not completely evaluated.

The tests which were used in this study are listed in Table 2.4. With the exception of the Plastic Deformation Test, which was used for testing some of the earlier polyethylene samples, all of the test methods used are those suggested in NRC's Branch Technical Position Paper on Waste Form[6]. The test methods and criteria by which waste form stability was determined are also included in Table 2.4. These tests were used to assess the acceptability of polyethylene and modified sulfur cement waste forms to meet the requirements of 10 CFR 61.

2.4.1 Compressive Strength. To ensure that a waste form remains stable under the compressive loads inherent in the disposal environment, solidified waste forms should have compressive strengths of at least 50 psi when tested in accordance with ASTM C-39 "Compressive strength of Cylindrical Concrete Specimens," or ASTM D-1074. Since polyethylene is a nonrigid plastic with no discrete brittle fracture yield point under compressive load, the standard compressive strength test according to ASTM C-39 is not applicable. Instead, the ASTM D-1074 "Standard Test Method for Compressive Strength of Bituminous Mixtures" was used as an alternative since the behavior of polyethylene under compressive load is similar to that of bitumen.

Prior to testing, the samples were capped according to ASTM C-617, "Capping Cylindrical Concrete Specimens," with sulfur mortar to assure appropriate plane surfaces. The compressive tests were performed using a Soiltest AP1000 Universal Testing Machine. The compressive strength in pounds per square inch was determined by dividing the maximum vertical load obtained during deformation by the original sectional area of the test specimen.

Table 2.4

Waste Form Test Methods

TEST	METHOD	TEST CRITERIA
Compressive strength		Compressive strength $\geq$ 50 psi
Polyethylene	ASTM D-1074	
Modified Sulfur Cement	ASTM C-39	
Plastic Deformation Test Polyethylene	ASTM D-621	Compressive Strength $\geq$ 50 psi
90-Day Immersion in Water		Compressive Strength $\geq$ 50 psi
Thermal Cycling	ASTM B-553	Compressive Strength $\geq$ 50 psi
Leach Testing (90 days)	ANS 16.1[7]	Leachability Index > 6.0 for each isotope
Irradiation - 10^8 Rad	Gamma Irradiator or Equivalent	Compressive Strength $\geq$ 50 psi
Biodegradation		
Fungus Attack	ASTM G21	No observed fungal growth Compressive Strength $\geq$ 50 psi
Bacteria Attack	ASTM G22	No observed bacterial growth Compressive Strength $\geq$ 50 psi

2.4.2 Deformation Under Compressive Load. Prior to adopting the ASTM D-1074 for determining the compressive strength of polyethylene waste forms, specimens were tested in accordance with ASTM D-621, "Standard Method of Test for Deformation of Plastics Under Load" during the early part of this program.

ASTM D-621 specifies a constant compressive load of 100 psi for a period of three hours. This compares with a minimum compressive strength of 50 psi, as required in the NRC Branch Technical Position Paper on Waste Form.

2.4.3 Water Immersion Test. Waste forms disposed by shallow land burial may potentially encounter periods of exposure to aqueous conditions in the form of percolate and/or ground water. Depending upon the composition of the contained waste, these conditions may cause swelling, cracking, dissolution or exfoliation of the waste form structure and subsequent deterioration of the disposal trench.

Water immersion tests were performed on representative, simulated waste forms for a period of 90 days. Test specimens were immersed in deionized water in a sealed polypropylene container. Deionized water was generated by passing distilled water through a Barnstaed Sybron/Nanopure deionization water system to obtain water with a conductance of less than 5 μ mhos/cm at 25°C.

In the tests performed in the early part of the program, dimensional changes, as well as gross failures in structural integrity were recorded at the end of 90 days. In the later tests, the compressive strength of some of the samples was measured after the 90 day immersion test, according to ASTM D-1074.

2.4.4 Thermal Cycle Test. To determine the effects of extreme temperature environments which waste forms may experience during storage, transportation or burial, thermal cycle testing was performed. Testing was conducted in accordance with the procedures of ASTM B-553, "Thermal Cycling of Electroplated Plastics".

Cycling of waste form specimens was performed using a Model T6C environmental chamber, manufactured by Tenney Engineering, Inc., Union, NJ. The chamber has a capacity of 6 cubic feet. Temperature settings and duration are microprocessor controlled. Heating and cooling functions are maintained by conditioned air flow.

Specimens for each waste-binder combination were placed in the chamber and cycled between +60°C and -40°C for a total of 30 cycles in accordance with NRC recommendations. Temperatures were held at each extreme for a period of one hour, separated by one hour at 20°C. Temperature ramp times varied between 8 minutes (20°C to 60°C) and 15 minutes (20°C to -40°C). The total time required to complete one cycle was approximatley 5 hours, as shown in Figure 2.3, which presents a graphical representation of cycling conditions. Chamber temperatures were recorded by a 24 hour circular chart recorder. In addition, representative specimens were monitored by thermocouples to verify uniform temperatures throughout the chamber and to track their response to changes in chamber temperatures.

Upon completion of thermal cycling, specimens were removed from the chamber for compressive strength and deformation testing.

2.4.5 Co-60 Gamma Irradiation. To determine resistance of waste forms to radiation degradation, the waste forms were exposed to a total accumulated dose of 10^8 Rads. Specimens were irradiated at ambient conditions using a Co-60 gamma source with a measured gamma dose rate of 3.6×10^6 Rads/hour. The dose rate was calibrated using a radiochromatography technique (Far West Technologies, Inc., Goleta, CA). Compressive strengths were measured after irradiation in accordance with ASTM D-1074 procedures.

2.4.6 Biodegradation. The ability of a waste form to resist bacterial degradation during its expectd life time in a land disposal environment is important in maintaining the integrity and stability of the burial trench. Solidified waste forms were tested for resistance to biodegradation in accordance with ASTM G21 and ASTM G22.

The bacteria used for ASTM G22 was:

Psuedomonas aeruginosa ATCC 13388.

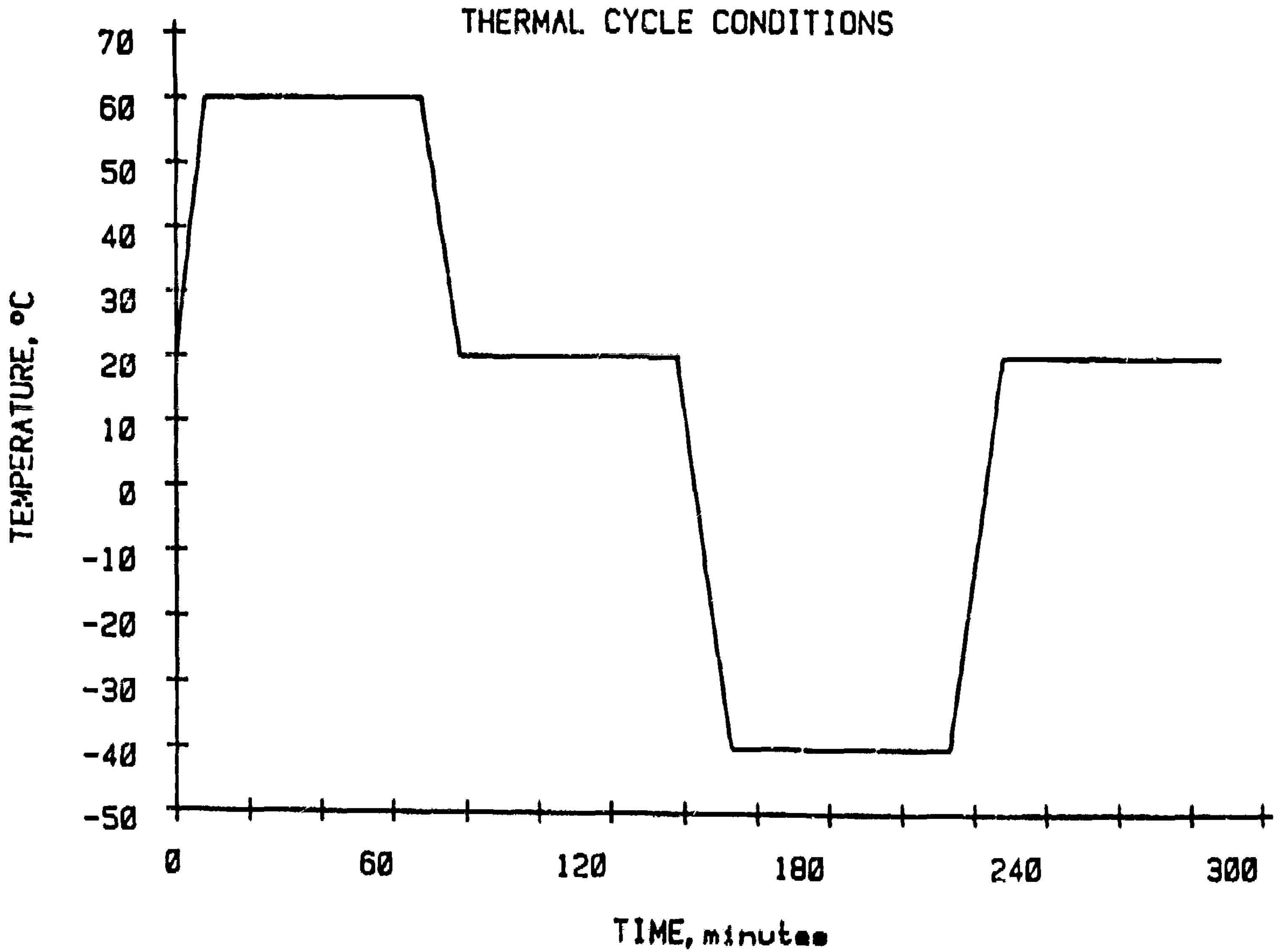


Figure 2.3 Graphical Representation of Temperature Conditions and Duration for One Thermal Cycle.

The fungi used for ASTM G21 consisted of a mixture of:

Aspergillus niger	ATCC 9642
Penicillium jenseni	ATCC 10456
Chaetomium globosum	ATCC 6205
Gliocladium virens	ATCC 9645
Aureobasidium pullans	ATCC 9348

One of the fungi in ASTM G22, Penicillium funicalosum, is a plant pathogen. A similar common fungus, Penicillium jenseni, was substituted for the pathogen with approval of the NRC.

The biodegradation tests were followed by compression testing in accordance with ASTM D1074.

2.4.7 Leaching Test. Leach testing was performed for a minimum of 90 days in accordance with the procedures in ANS 16.1 Standard, "Measurement of the Leachability of Solidified Low-Level Radioactive Wastes"[7]. This test was designed to provide a standardized laboratory method for characterizing the leaching behavior of low-level waste forms. Although the test procedures do not necessarily simulate waste form leaching under actual burial conditions, it allows a comparison of the relative leachability of various waste/binder combinations. The NRC has recommended its use for demonstration of waste form stability although leachability of waste forms is not addressed in 10 CFR 61.

Specimens were leached in demineralized water. The volume of leachant employed ranged between 1470 and 1720 ml as specified by the ratio of 10 ± 0.2 cm of leachant volume to external geometric surface area of the waste form. The temperature was maintained at 20 ± 2°C. After an initial 30 second rinse of the specimens, leachant was replenished at the following time intervals: 2 hour, 5 hour, 17 hour, 24 hour intervals for the next four days, 13 day, 28 day and 45 day, for a total of ten leachate samples.

Leachate aliquots were taken for analysis and acidified with nitric acid. The gamma activity of the radionuclides was determined with an intrinsic germanium detector and computerized multichannel analyzer system or a Searle Model 1185 NaI detector with three single channel analyzers and an automatic sample changer.

2.5 Waste Form Stability Testing Results

The results of the waste form stability tests performed on polyethylene waste forms, except for the leaching tests, are listed in Tables 2.5, 2.6 and 2.7.

The results indicate that the stability of polyethylene waste forms containing sodium sulfate, boric acid or incinerator ash was little affected by increased waste loadings during such tests as water immersion, thermal cycling, irradiation and biodegradation, whether followed by measurements of percent deformation or compressive strength. In all cases the compressive strength values, as shown in Table 2.5, are many times higher than the 50 psi limit recommended by the NRC. As shown in Table 2.6, the polyethylene waste form deformation values were less than 0.5%. All samples tested for deformation returned to at least 99% of their original shape within 15 hours.

Table 2.5

Compressive Strengths of Polyethylene Waste Forms[a]

Waste Type	Waste Loading (wt %)	Compressive Strengths (psi)[b]					
		Initial	After Immersion Test	After Thermal Cycling Test	After Irradiation[c]	After Biodegradation Test: Bacteria	After Biodegradation Test: Fungi
Na_2SO_4	30	1700 ± 100	d	d	2000 ± 170	d	d
	40	d	1397	d	d	d	d
	50	2000 ± 100	1680	2200 ± 100	2040 ± 60	1400 ± 10	2310 ± 20
	70	1600 ± 200	d	1900 ± 300	1780 ± 50	910 ± 60	1200 ± 400
H_3BO_3	20	2100 ± 250	d	d	d	d	d
	25	d	660	d	d	d	d
	35	1800 ± 100	d	1870 ± 40	1720 ± 120	2300 ± 100	1690 ± 40
	50	1600 ± 40	d	1800 ± 100	1670 ± 50	1300 ± 200	1300 ± 200
Incinerator Ash	20	1750 ± 140	d	d	d	d	d
	25	d	1137	d	d	d	d
	30	1600 ± 400	d	1800 ± 300	1700 ± 400	1700 ± 300	1500 ± 800
	40	2000 ± 200	d	2200 ± 90	1500 ± 180	2200 ± 400	2800 ± 150
Ion Exchange Resin[e]	10	2100 ± 170	d	d	d	d	d
	20	1800 ± 300	d	2300 ± 300	2100 ± 300	1390 ± 50	2230 ± 250
	30	2000 ± 200	1580	2000 ± 200	1600 ± 400	1700 ± 100	2000 ± 130

a. Performed in accordance with ASTM D1074. 1 psi = 6.98 kPa.
b. Results are reported as average ± one standard deviation.
c. Results for 0.5" length x 1.13" diameter cylinder samples were normalized and are reported as equivalent compressive strengths to 4" length x 2" diameter cylindrical samples.
d. Not available.
e. Two parts cation resin (Rohm a Haas IRN-77) plus one part anion resin (Rohm and Haas IRN-78).

Table 2.6

Polyethylene Waste Form Deformation Testing Under 100 psi Compressive Load[a]

Waste Type	Waste Loading (wt %)	LDPE Type	Deformation (%): Initial[b]	Deformation (%): After Thermal Cycling Test[c]	Deformation (%): After Irradiation[b]
Na_2SO_4	30	1409	d	d	0.27 ± 0.07
	50	1409	d	d	0.43 ± 0.17
	54	1409	0.21 ± 0.10	0.17 ± 0.13	d
	60	1409	0.15 ± 0.08	0.25 ± 0.07	d
	70	1409	0.14 ± 0.11	0.18 ± 0.14	0.18 ± 0.02
H_3BO_3	30	1410	0.16 ± 0.06	0.13 ± 0.07	d
	35	1410	d	d	0.18 ± 0.07
	40	1410	0.16 ± 0.06	0.16 ± 0.09	d
	50	1410	d	d	0.10 ± 0.03
Ion Exchange Resin[e]	20	1410	d	d	0.38 ± 0.04
	28	1410	0.24 ± 0.02	0.24 ± 0.17	d
	30	1410	d	d	0.49 ± 0.11
	50	1410	0.26 ± 0.06	0.33 ± 0.01	d
	60	1410	0.16 ± 0.04	0.29 ± 0.13	d
	65	1410	0.31 ± 0.10	0.16 ± 0.05	d
	60	1409	0.20 ± 0.09	0.10 ± 0.03	d
	50	1117-B	0.12	0.29 ± 0.16	d
Incinerator Ash	20	1409	0.18 ± 0.14	0.41 ± 0.16	d
	30	1409	d	d	0.30 ± 0.08
	40	1409	0.08 ± 0.08	0.06 ± 0.06	0.20 ± 0.12
	40	C-17	0.18 ± 0.17	0.20 ± 0.11	d

a. Performed in accordance with ASTM D-621.
b. Results reflect average for 3 replicates. Errors reported on one standard deviation of results.
c. Results reflect average for 2 replicates.
d. Test not performed.
e. Two parts cation resin (Rohm and Haas IRN-77) plus one part anion resin (IRN-78).

Table 2.7

Effect of Water Immersion Testing on Various Types of Low-Density Polyethylene (LDPE)

Waste Type	Waste Loading, wt%	LDPE Type	Swelling,[a] %
Sodium Sulfate	54	1409	0.0
	60	1409	0.2
	70	1409	1.7
	70	1410	0.7
Boric Acid	35	1410	0.2
	40	1410	0.0
	40	1409	0.0
	45	1409	0.0
	50	1409	0.0
Incinerator Ash	25	1409	0.5
	35	1409	2.0
Ion Exchange Resin	20	1409	0.0
	28	1410	0.7
	30	1409	1.3
	50	1127-B	8.7
	50	1410	S.C.[b]
	60	1410	S.C.
	60	1409	S.C.
	65	1409	S.C.

a. Measured as Δ length/original length
b. S.C.: severe cracking

Only those samples which contained ion exchange resins showed a correlation between waste loadings and waste form failure; and that was during the water immersion test, as shown in Table 2.7. For the samples containing up to 30 wt% dry ion exchange resins, overall swelling was $\leq$ 1.3%. For higher waste loadings results varied with the type of polyethylene employed. Specimens formulated from Gulf 1117-B containing 50 wt% resins, experienced a moderate degree of swelling (8.7%), but no deterioration in structural integrity was observed. Those formulated from Gulf 1410 which contained 50 wt% resin swelled severely with cracking. Waste forms containing 60 and 65 wt% ion exchange resins formulated from Gulf 1410 and Gulf 1409 also failed catastrophically due to swelling of the resin beads.

It can be concluded, therefore, that the behavior of ion exchange resin waste forms in an aqueous environment is dependent upon the quantity of waste incorporated and to some extent on the type of polyethylene binder used. Waste forms containing as much as 30 wt% resin loading were able to retain a compressive strength > 50 psi.

The leaching data for polyethylene waste forms are presented in terms of the incremental fraction leached (IFL), the cumulative fraction leached (CFL), and the leaching indices for the three radionuclides, Co-60, Sr-85 and Cs-137. These data are tabulated in Appendix A. The CFL is also presented graphically as a function of leaching time (in days) and will be discussed below. These leaching curves represent the average CFL of two sets of leaching data from the leaching of replicate specimens.

In contrast to the other test results, wherein insignificant changes were observed as a function of waste loading, a clear dependence of leachability upon increased waste loadings of 10, 30 and 50 wt% for all three isotopes was established for polyethylene/sodium sulfate specimens. This is shown in Figures 2.4, 2.5, and 2.6 where the CFL of Co-60, Sr-85 and Cs-137, respectively, is plotted as a function of time. Since sodium sulfate waste is a highly soluble salt, mobilization of contained radionuclides is controlled in part by leachate dissolution of the waste. This in turn is dependent upon the physical encapsulation of the waste. At the higher loadings the amount of binder available to encapsulate the waste material is minimal. In addition, as more sodium sulfate comes into contact with leachate and dissolves, porosity increases (as a result of the voids left behind) creating more pathways for migration.

A comparison of the leachability of the three isotopes at each waste loading, in Figures 2.7, 2.8 and 2.9, shows that they leach at similar rates from sodium sulfate waste forms, indicating a lack of chemical interaction between the waste and polyethylene binder. For example, at the highest loading (50 wt%), the CFL of Co-60 and Sr-85 is 2.3×10^{-3} while for Cs-137 it is 3×10^{-3}.

A similar trend in dependence of leachability upon increased waste loadings was also demonstrated for all isotopes in the leaching of polyethylene specimens containing incinerator ash at waste loadings of 25 wt% and 35 wt%. These results are shown in Figures 2.10, 2.11 and 2.12. For the less soluble ash this trend may be attributed to the reduced amount of binder available for waste encapsulation as the amount of waste loading is increased. In contrast to the relatively uniform leaching of all three isotopes evident in the sodium sulfate specimens, Cs-137 is more mobile than Sr-85 and Co-60 from solidified

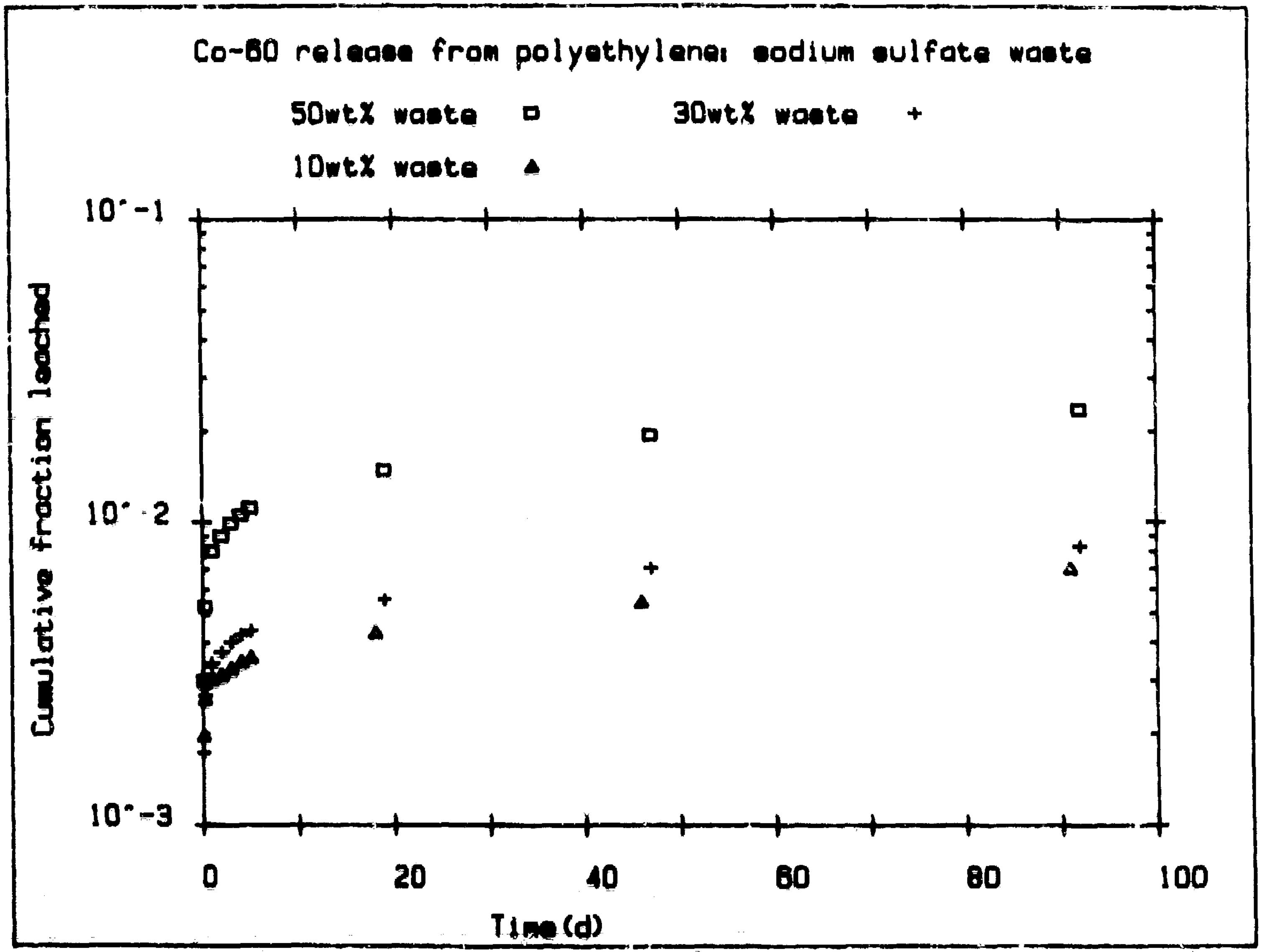


Figure 2.4 Cumulative fraction leached of Co-60 as a function of time from polyethylene waste forms containing 10, 30 and 50 wt% of sodium sulfate waste.

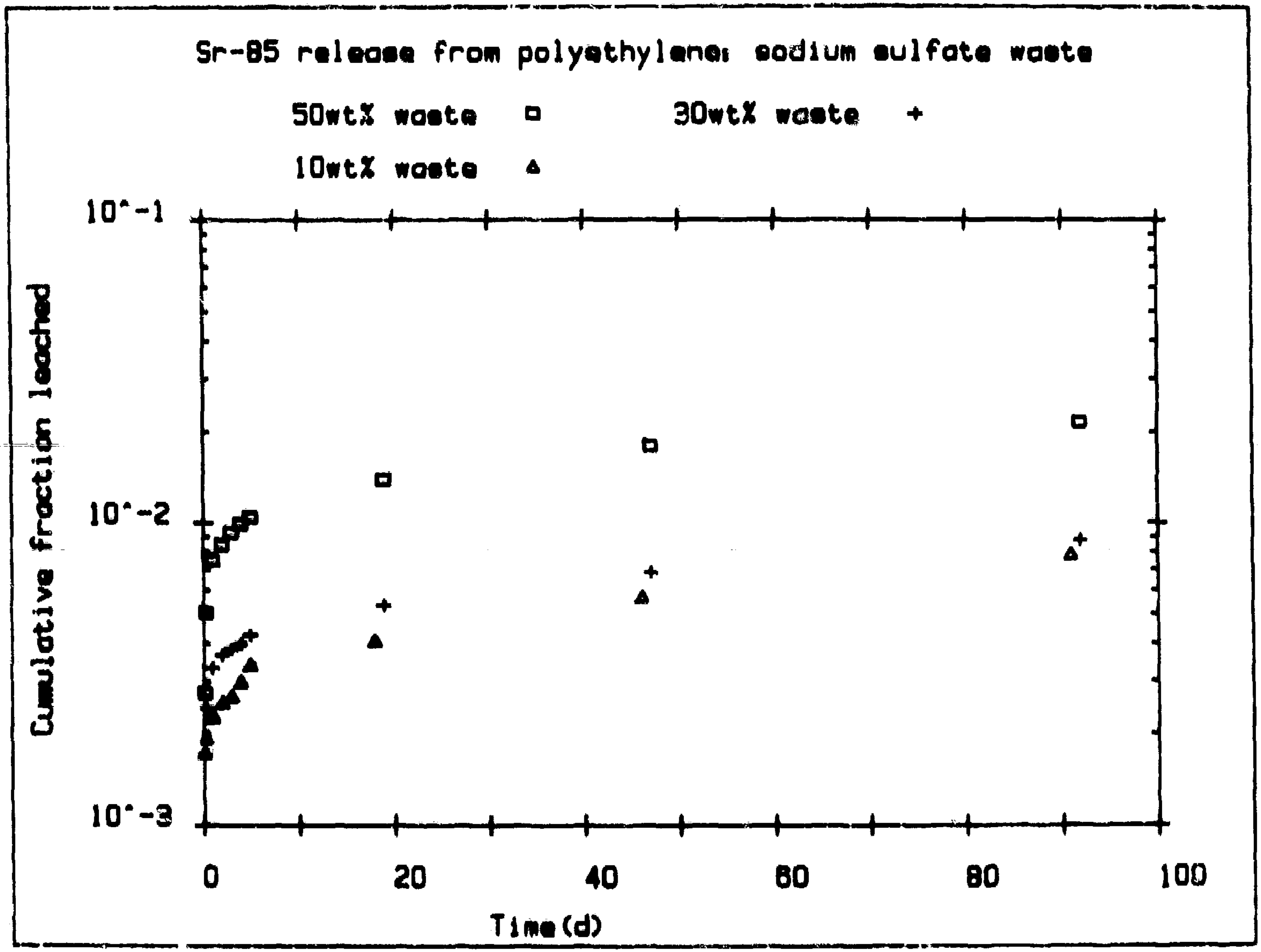


Figure 2.5 Cumulative fraction leached of Sr-85 as a function of time from polyethylene waste forms containing 10, 30 and 50 wt% of sodium sulfate waste.

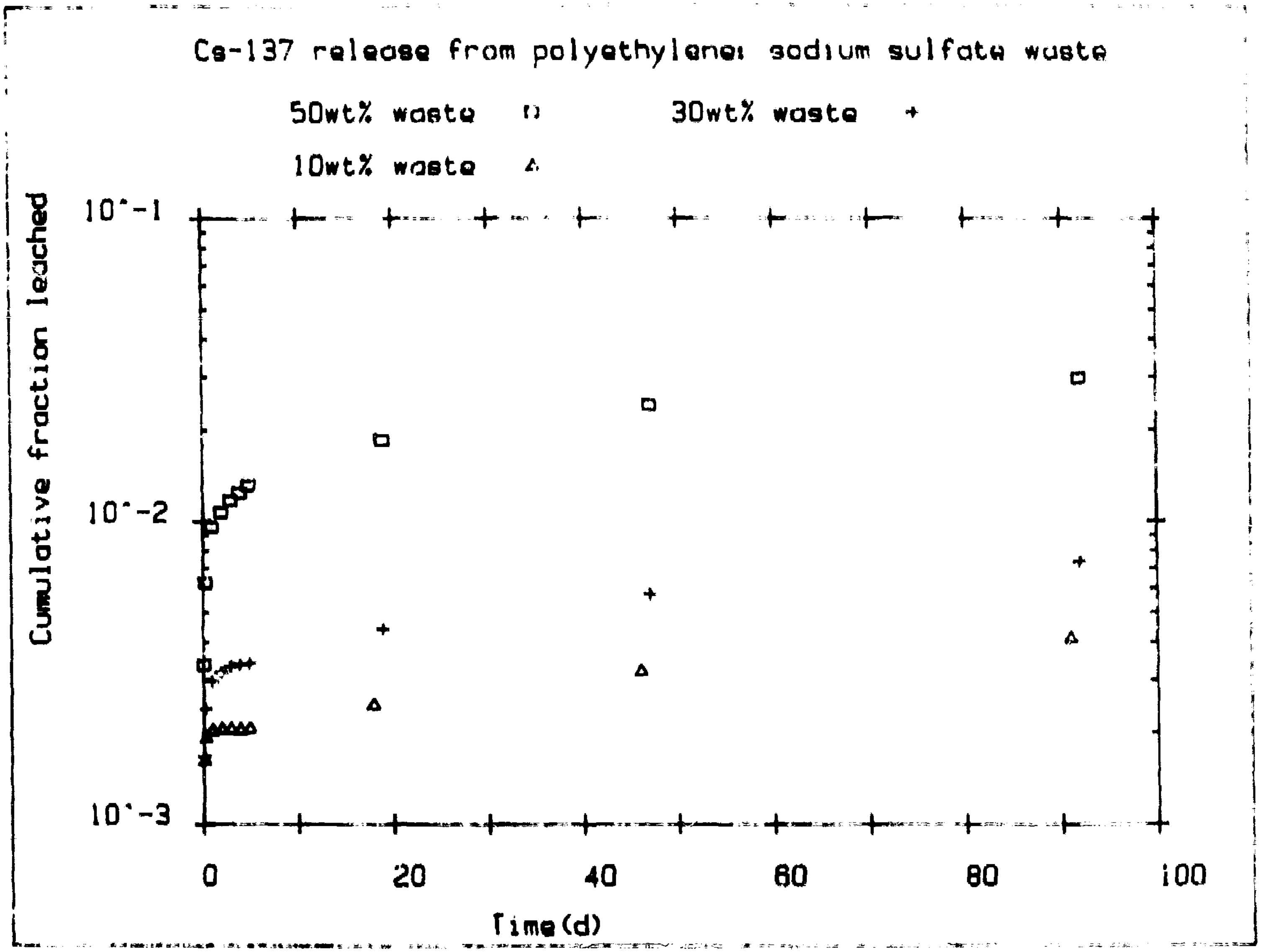


Figure 2.6 Cumulative fraction leached of Cs-137 as a function of time from polyethylene waste forms containing 10, 30 and 50 wt% of sodium sulfate waste.

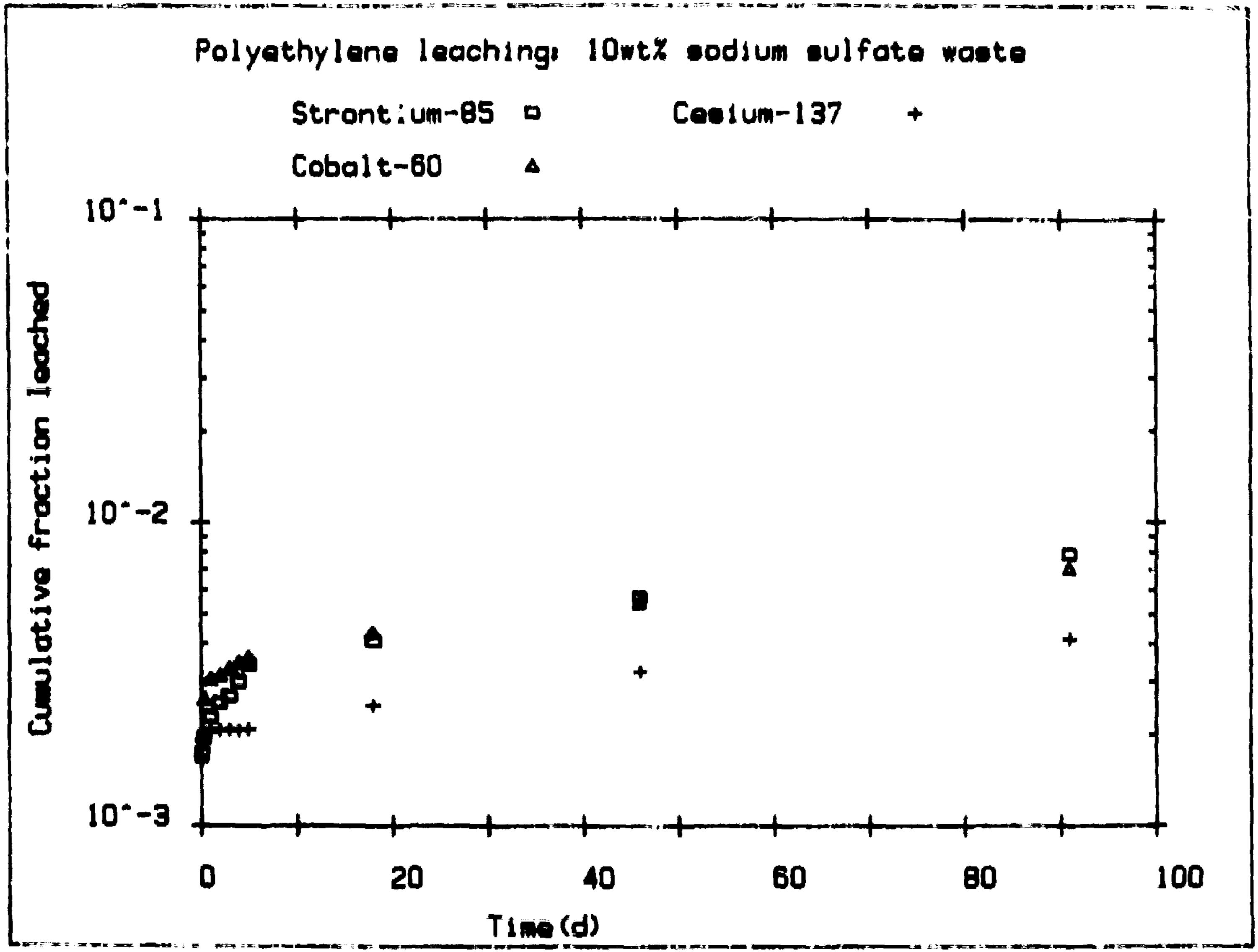


Figure 2.7 Cumulative fraction leached of Co-60, Sr-85 and Cs-137 as a function of time from polyethylene waste forms containing 10 wt% of sodium sulfate waste.

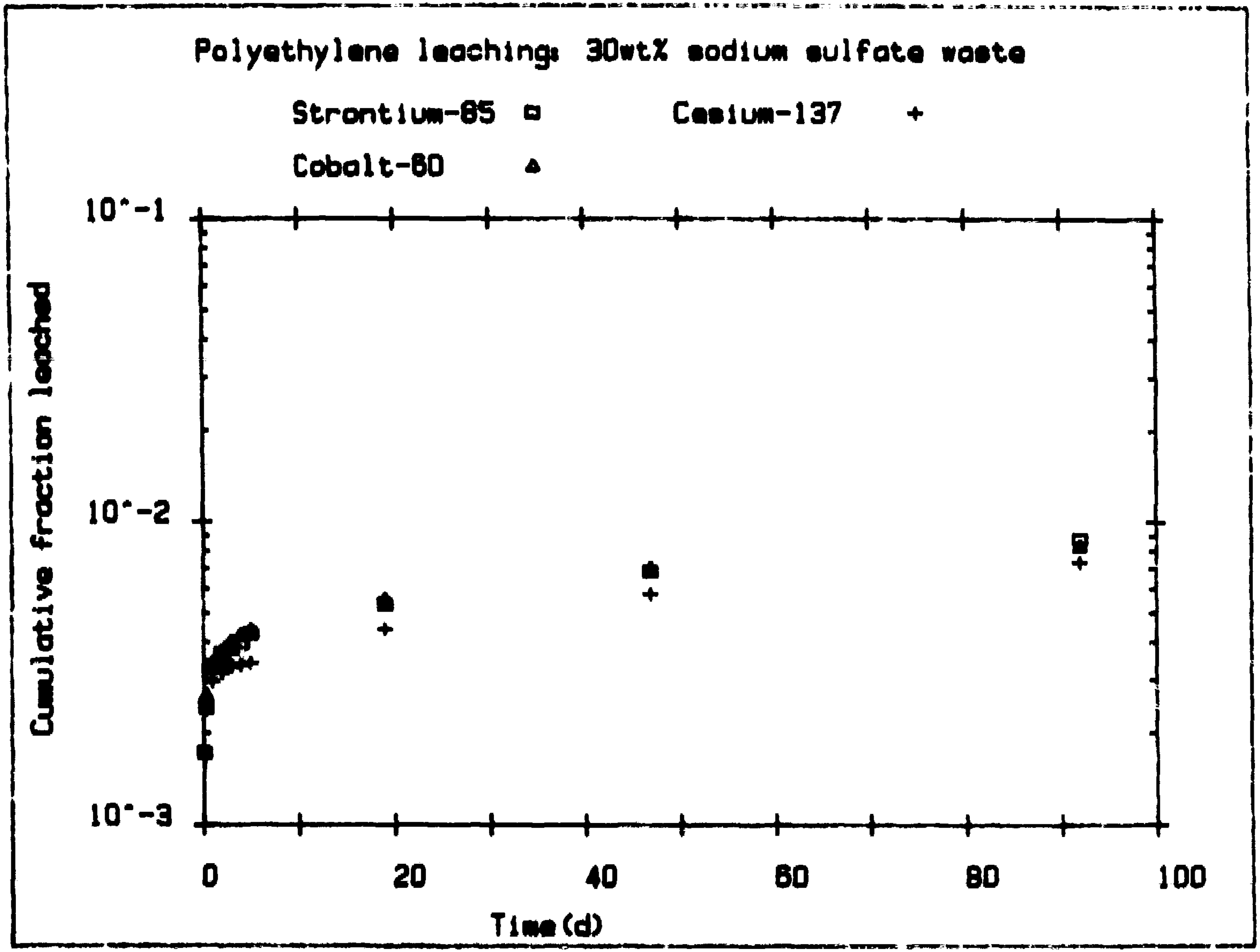


Figure 2.8 Cumulative fraction leached of Co-60, Sr-85, Cs-137 as a function of time from polyethylene waste forms containing 30 wt% of sodium sulfate waste.

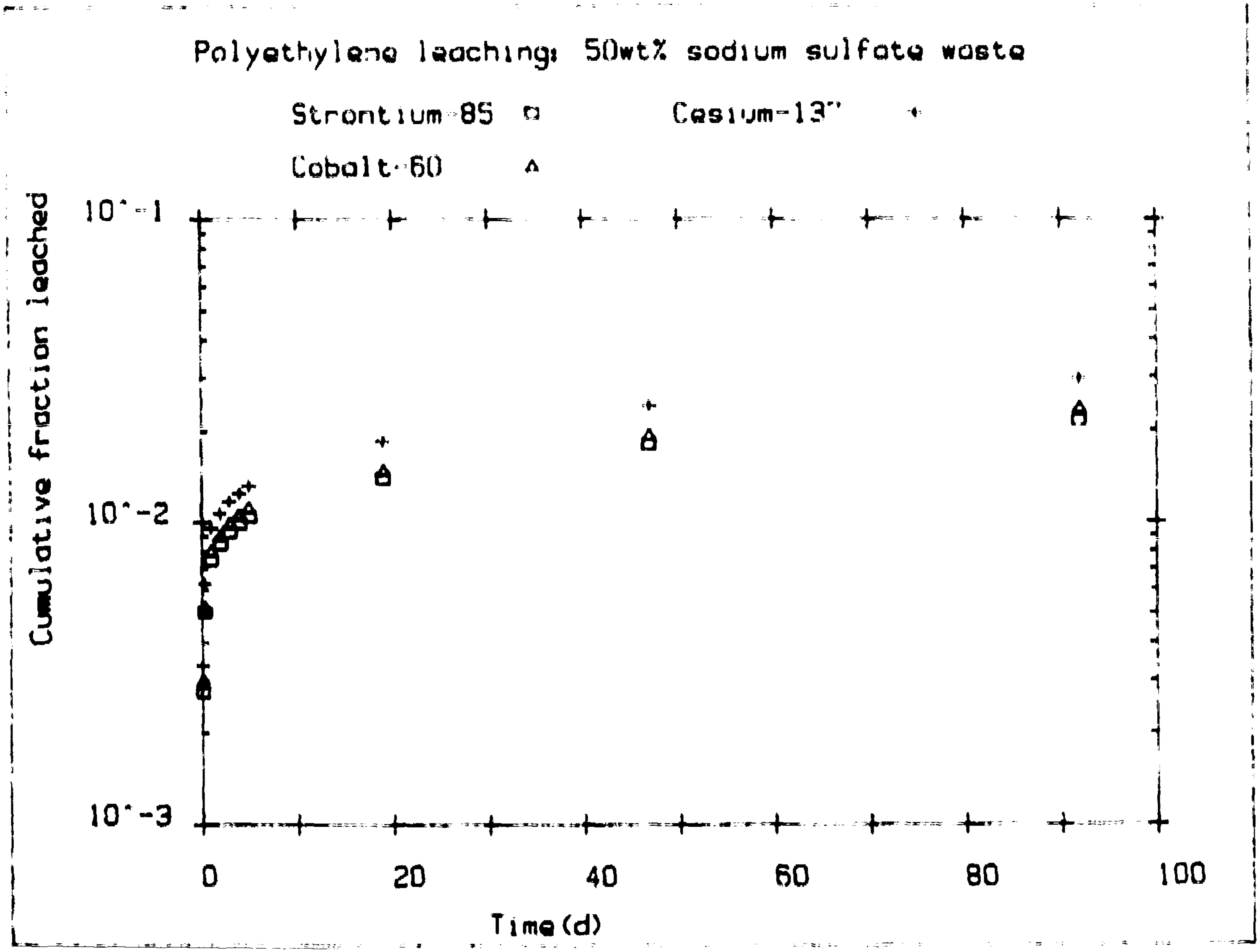


Figure 2.9 Cumulative fraction leached of Co-60, Sr-85, Cs-137 as a function of time from polyethylene waste forms containing 50 wt% of sodium sulfate waste.

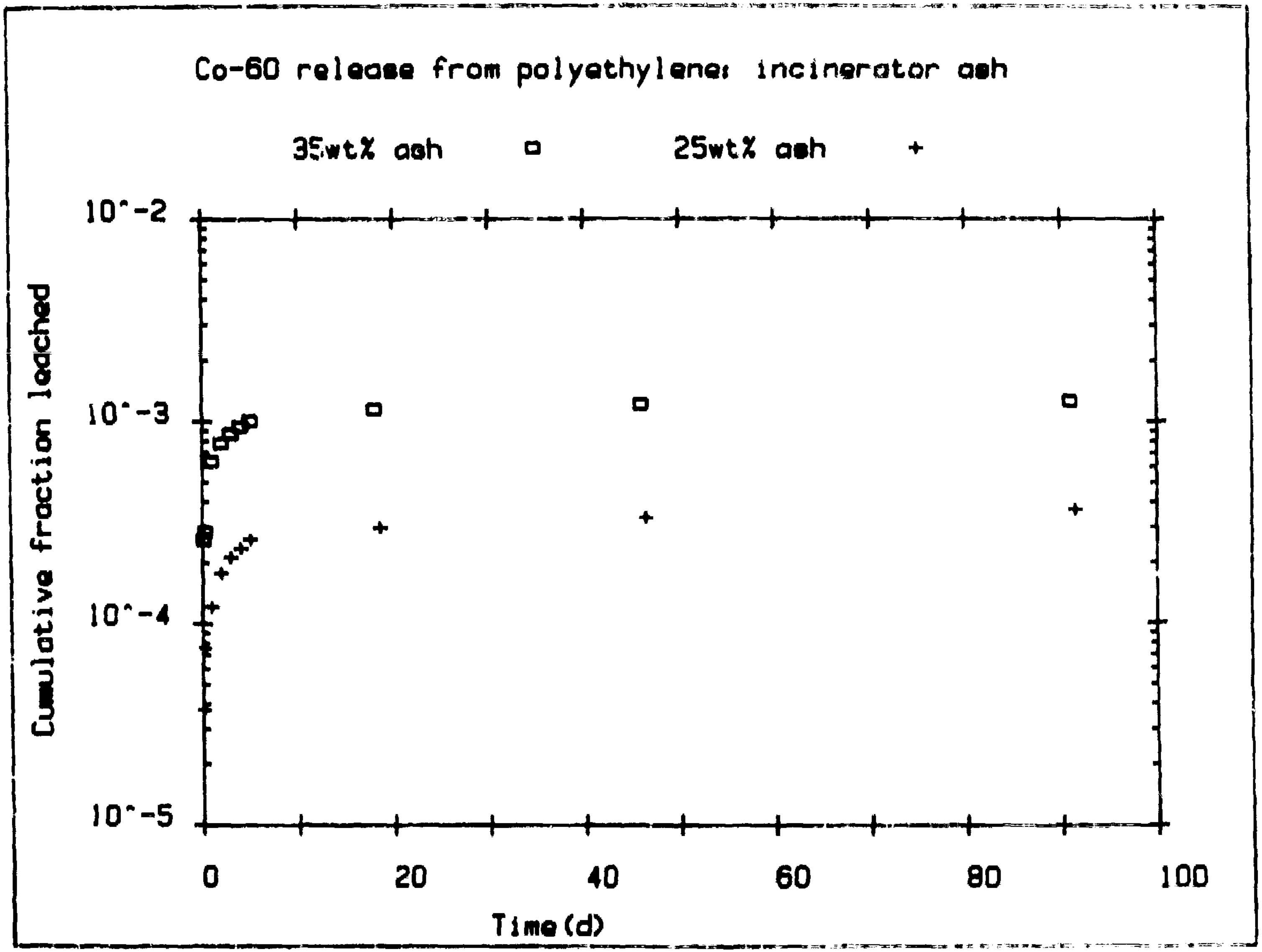


Figure 2.10 Cumulative fraction leached of Co-60 as a function of time from polyethylene waste forms containing 25 and 35 wt% of incinerator ash.

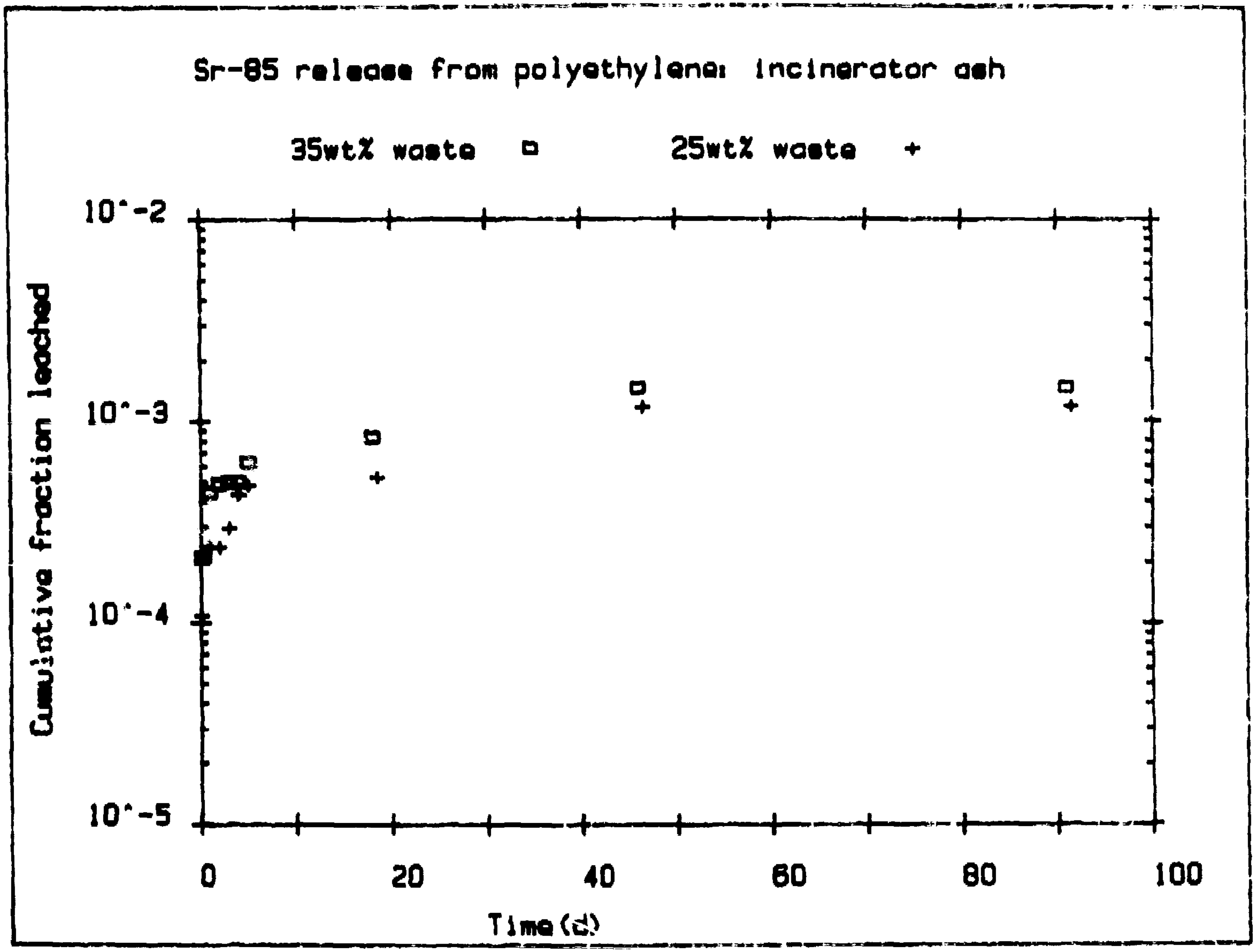


Figure 2.11 Cumulative fraction leached of Sr-85 as a function of time from polyethylene waste forms containing 25 and 35 wt% of incinerator ash.

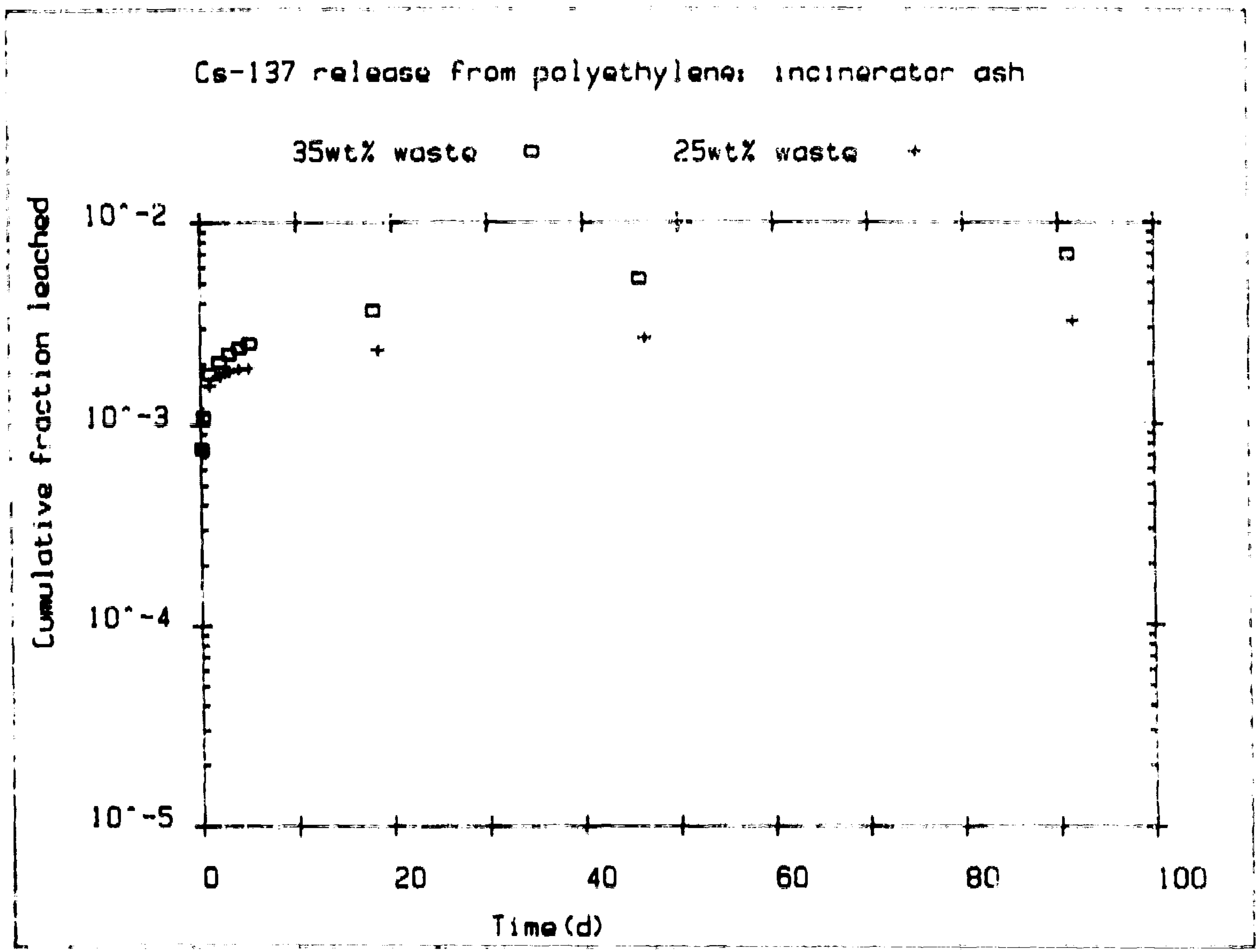


Figure 2.12 Cumulative fraction leached of Cs-137 as a function of time from polyethylene waste forms containing 25 and 35 wt% of incinerator ash.

ash waste forms. In Figures 2.13 and 2.14, which show the CFL for the three isotopes relative to each other at two different waste loadings (25 and 35 wt%), it can be seen that at both loadings Cs-137 release is the greatest and that of Co-60 the lowest. At 35 wt% loading the CFL of Cs-137 is 7×10^{-3} while the value for Sr-85 is 1.5×10^{-3} and Co-60 is 1.3×10^{-3}. Since polyethylene does not chemically interact with the waste, this disparity in leachability between isotopes suggests that the incinerator ash itself exhibits preferential sorption.

An opposite trend was observed in the dependence of leachability upon increased waste loadings of 10, 20 and 30 wt% of ion exchange resins in polyethylene. The higher the waste loading the lower the leachability for Co-60 and Sr-85. The data for Cs-137 were less conclusive. These results can be seen in Figures 2.15, 2.16 and 2.17 where the CFL of each isotope at different waste loadings has been plotted as a function of leaching time. A comparison of the three isotopes at the three waste loadings is shown in Figures 2.18, 2.19 and 2.20. It is obvious from the data that Sr-85 is retained less effectively by the waste form than Co-60, but it is difficult to make a definitive statement about Cs-137 since in the early leachate samplings Cs-137 levels were below the detection limit of 10^{-4}. At the highest waste loading of 30 wt% the CFL for Sr-85 is 5.5×10^{-4} and for Co-60 it is 2.4×10^{-4}.

The leaching indices were calculated as recommended in the ANS 16.1 method. This index is a dimensionless figure of merit which quantifies the relative leachability for a given waste type-solidification agent. It can thus be used as a basis for comparison of the radionuclide retention capabilities of various solidification matrix-waste type combinations. The NRC has issued a recommended minimum leachability index of > 6 for compliance with waste form stability requirements.

The leachability index for a given radionuclide, i, is given by[7]:

$$L_i = 1/10 \sum_{n=1}^{10} [\log (\beta/D_i)]_n \qquad \text{(Eq. 2.1)}$$

where:

β = 1 cm^2/sec (defined constant)

D_i = effective diffusivity (cm^2/sec)

The effective diffusivity is calculated from the leach test data by application of the following expression:

$$D_i = \pi \left[\frac{a_n/A_0}{(\Delta t)_n}\right]^2 (V/S)^2 T \qquad \text{(Eq. 2.2)}$$

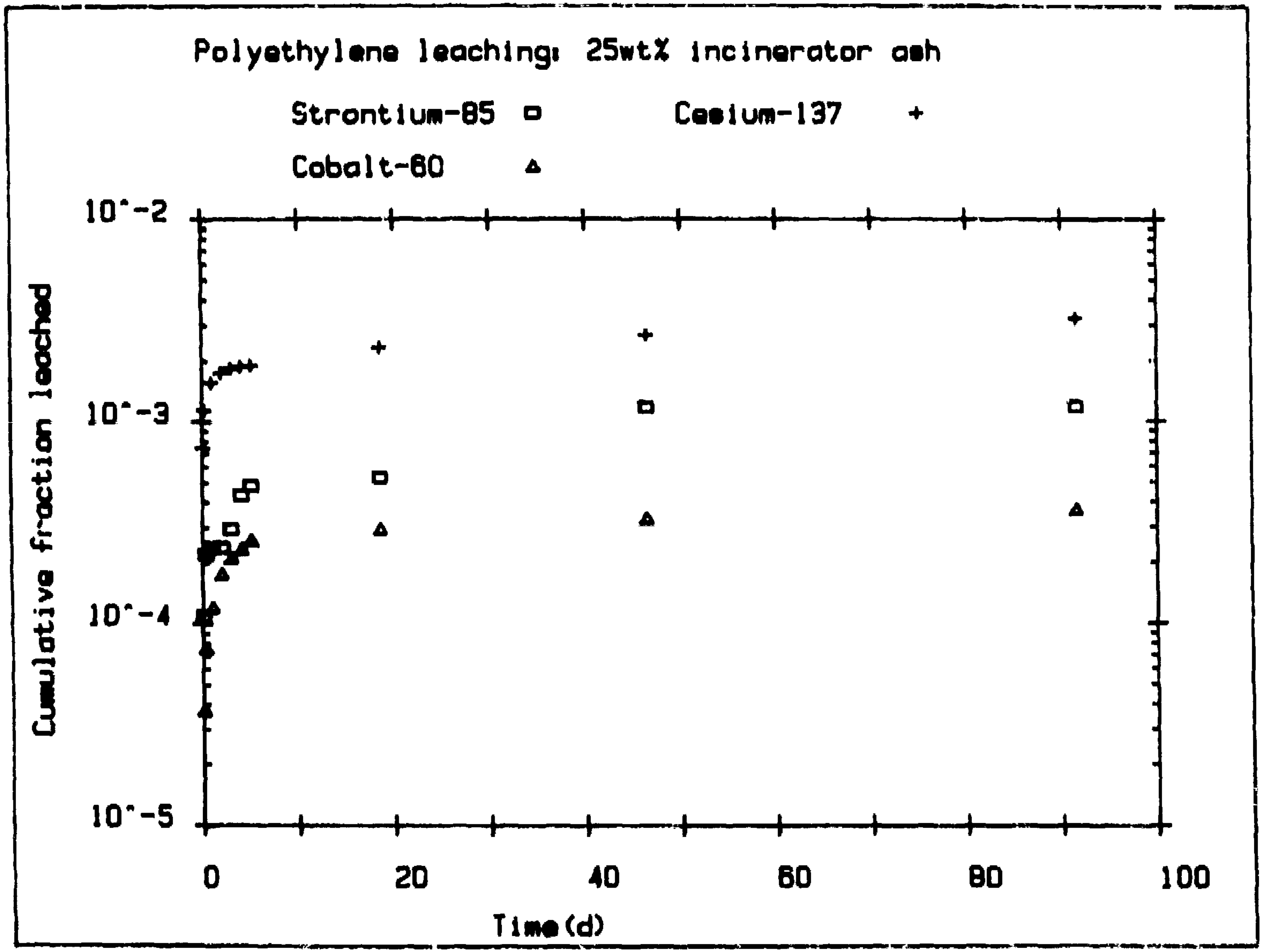


Figure 2.13 Cumulative fraction leached of Co-60, Sr-85 and Cs-137 as a function of time from polyethylene waste forms containing 25 wt% incinerator ash.

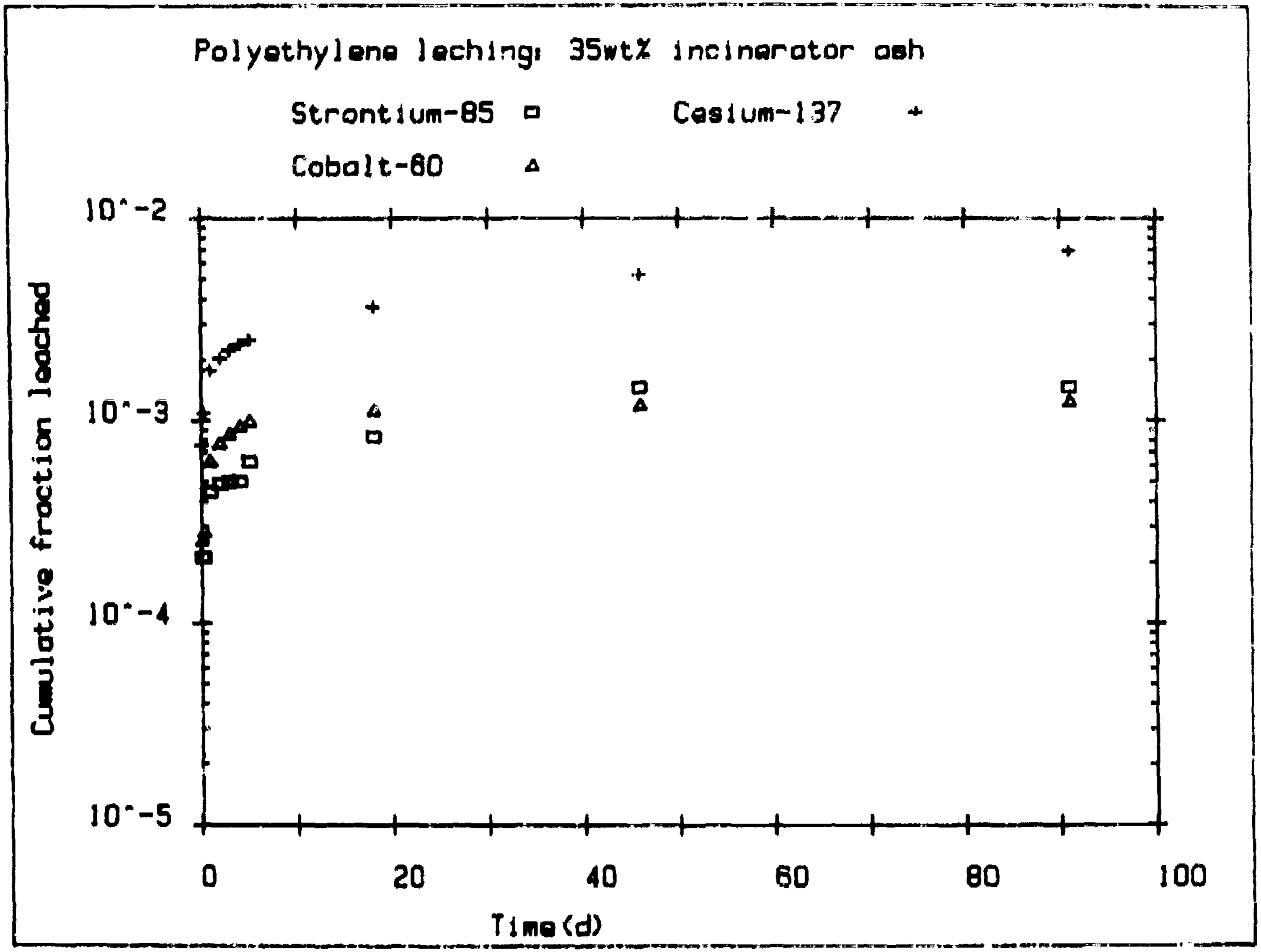


Figure 2.14 Cumulative fraction leached of Co-60, Sr-85 and Cs-137 as a function of time from polyethylene waste forms containing 35 wt% of incinerator ash.

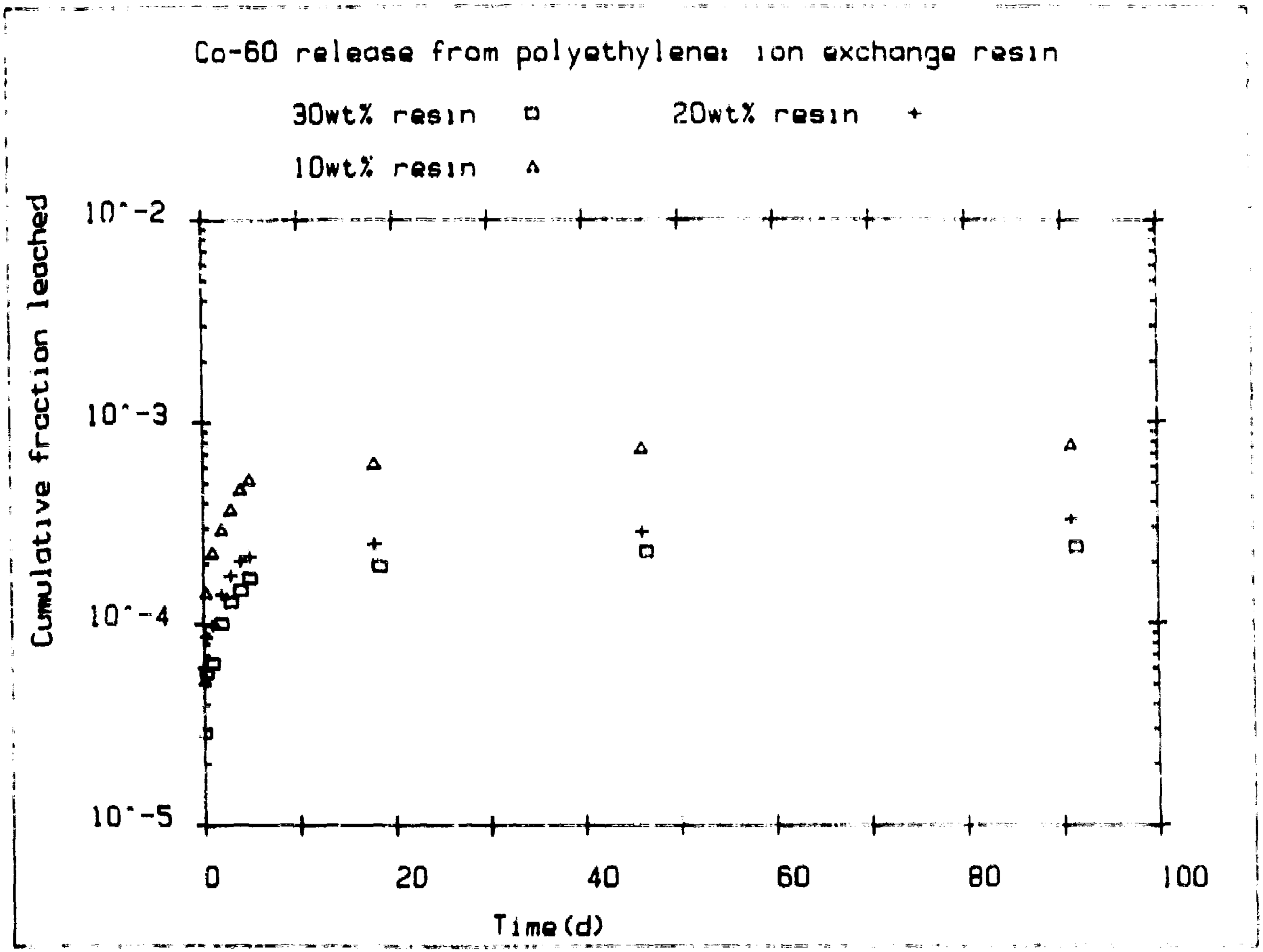


Figure 2.15 Cumulative fraction leached of Co-60 as a function of time from polyethylene waste forms containing 10, 20 and 30 wt% of ion exchange resin.

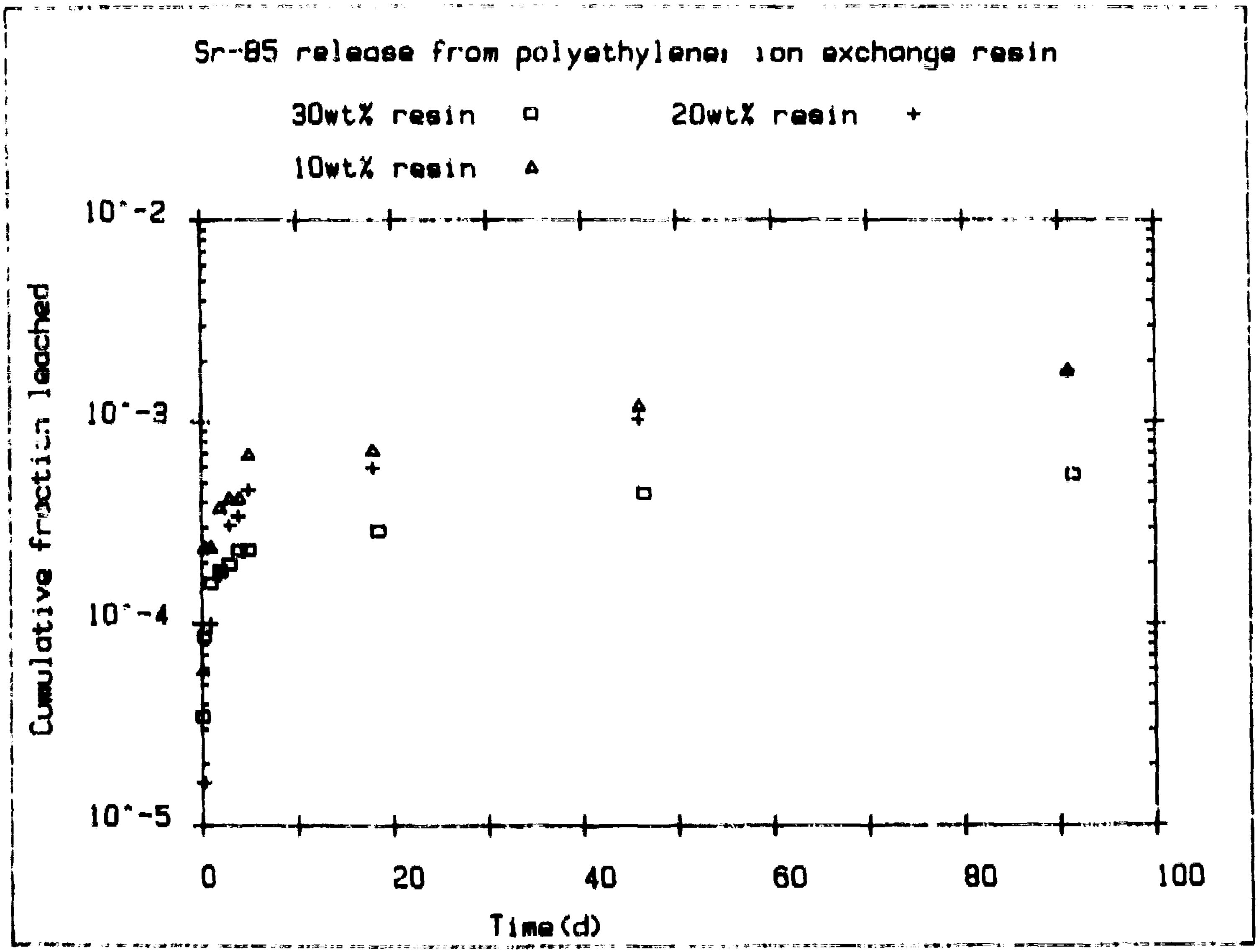


Figure 2.16 Cumulative fraction leached of Sr-85 as a function of time from polyethylene waste forms containing 10, 20 and 30 wt% of ion exchange resin.

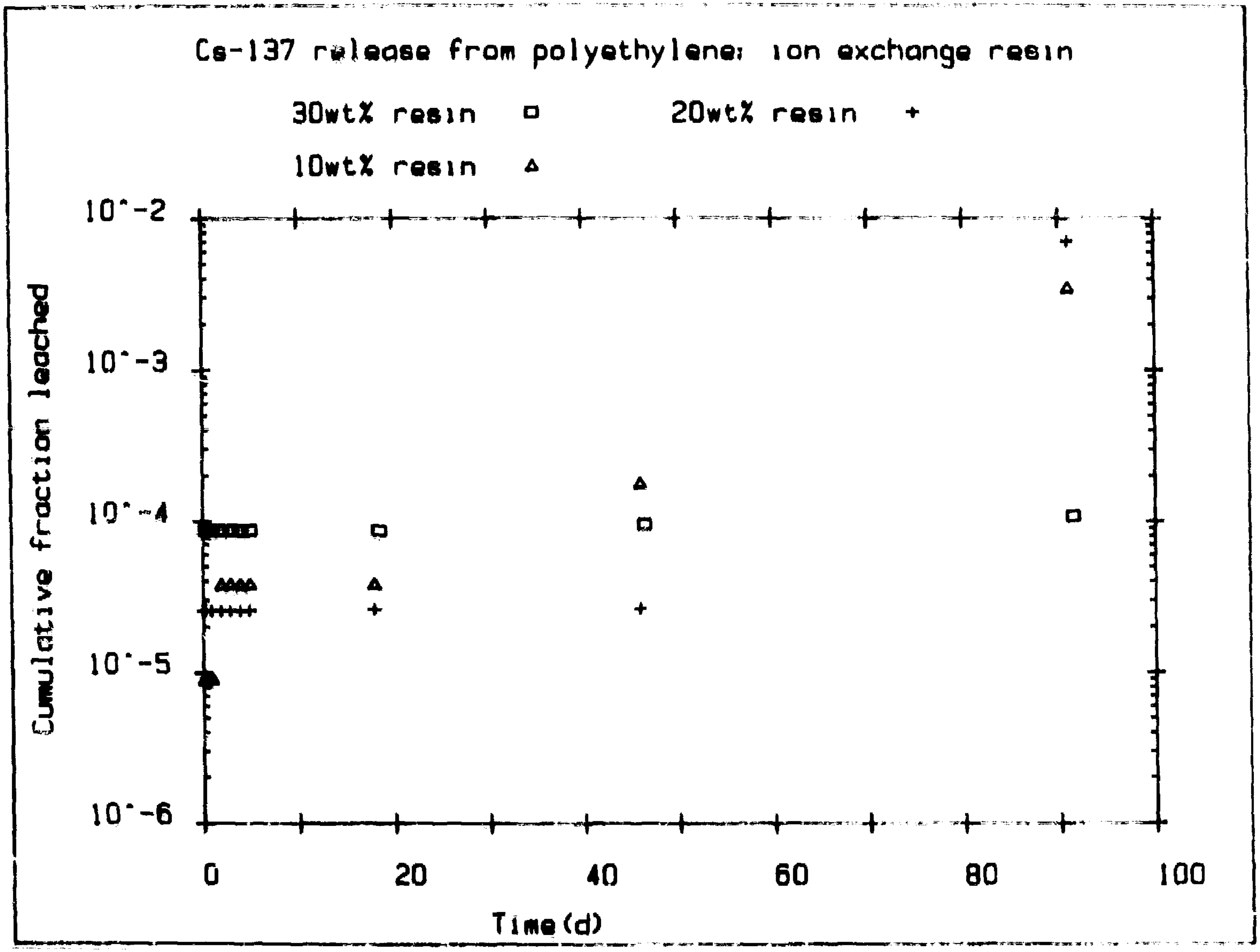


Figure 2.17 Cumulative fraction leached of Cs-137 as a function of time from polyethylene waste forms containing 10, 20 and 30 wt% of ion exchange resin.

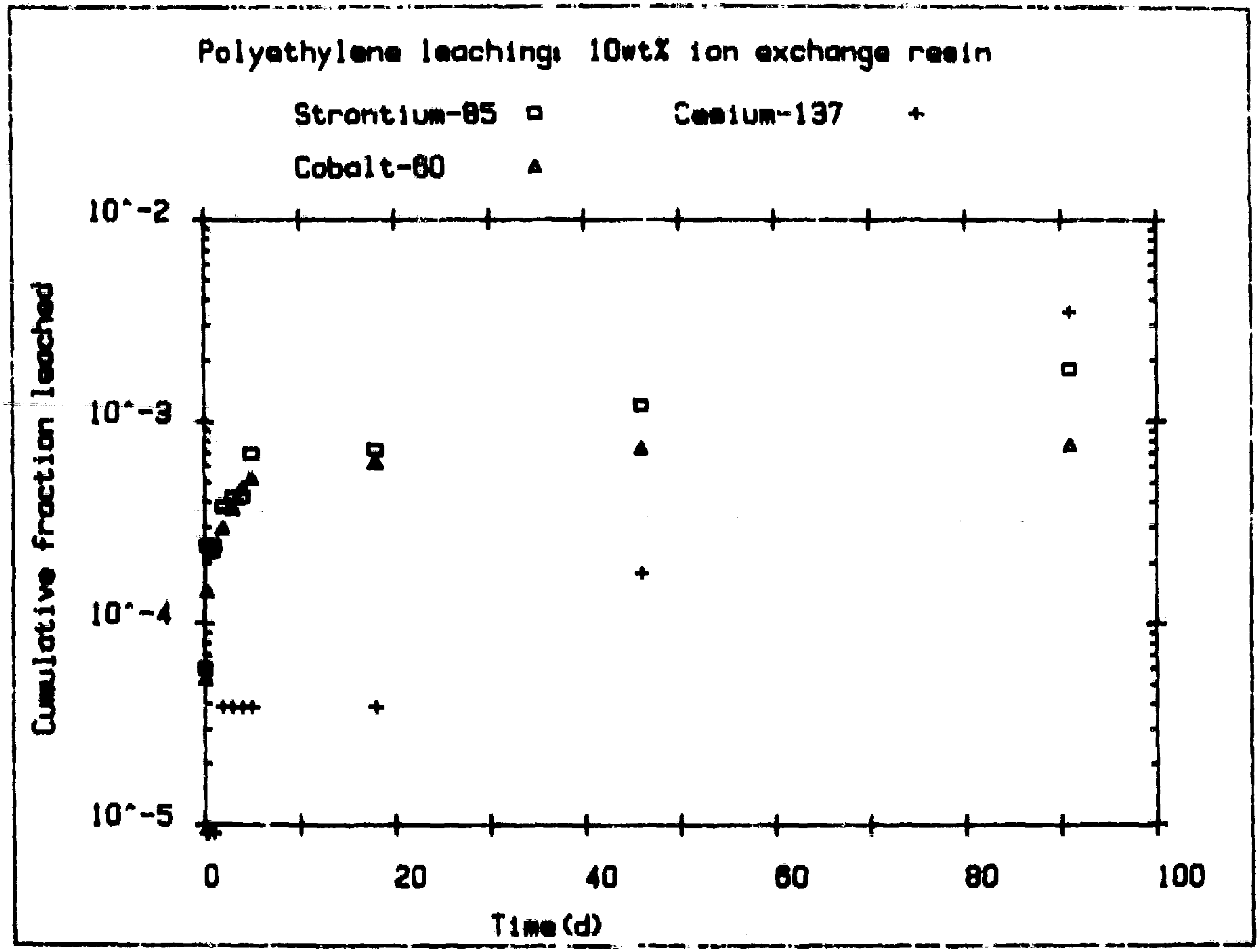


Figure 2.18 Cumulative fraction leached of Co-60, Sr-85 and Cs-137 as a function of time from polyethylene waste forms containing 10 wt% of ion exchange resin.

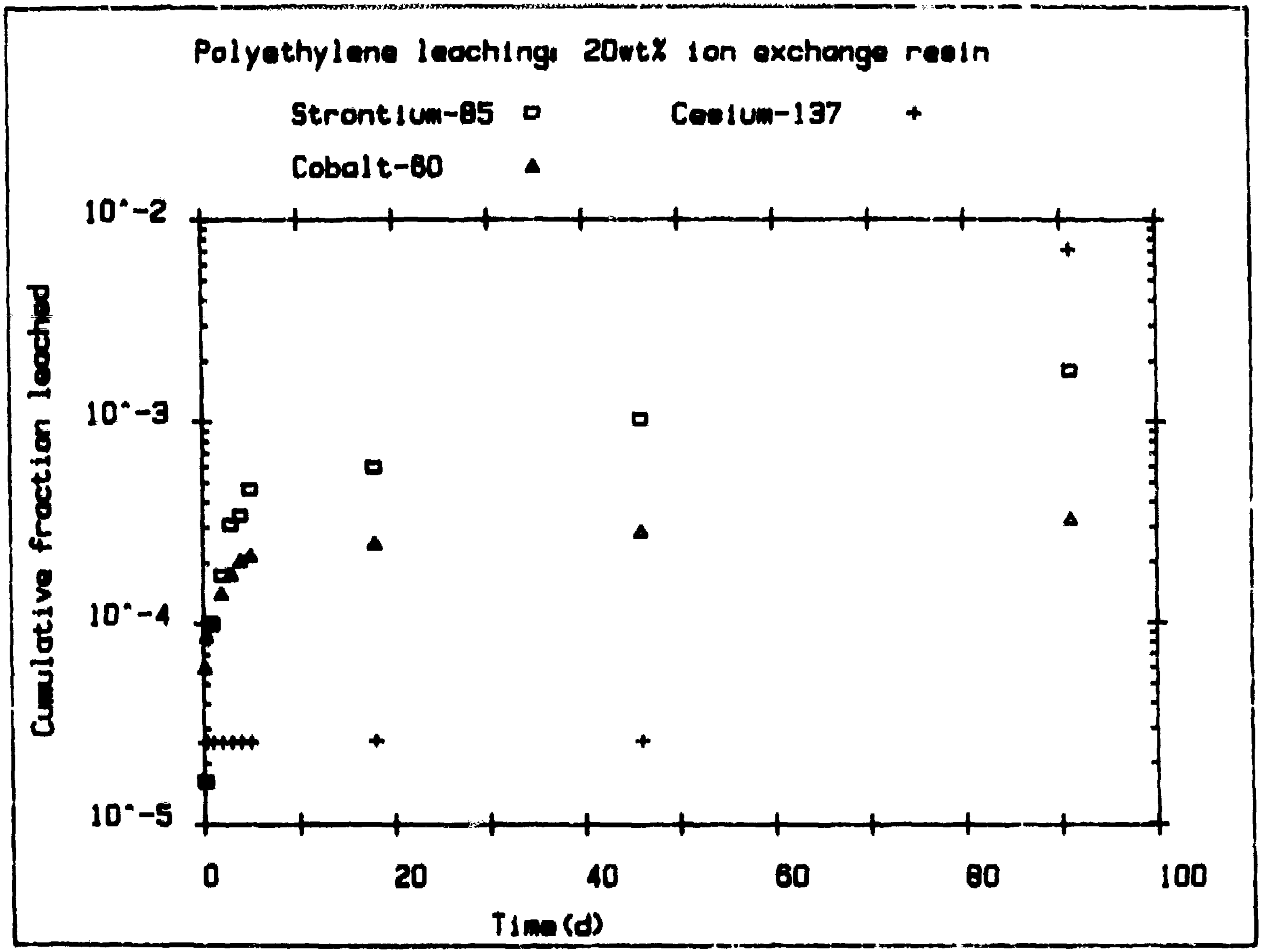


Figure 2.19 Cumulative fraction leached of Co-60, Sr-85 and Cs-137 as a function of time from polyethylene waste forms containing 20 wt% of ion exchange resin.

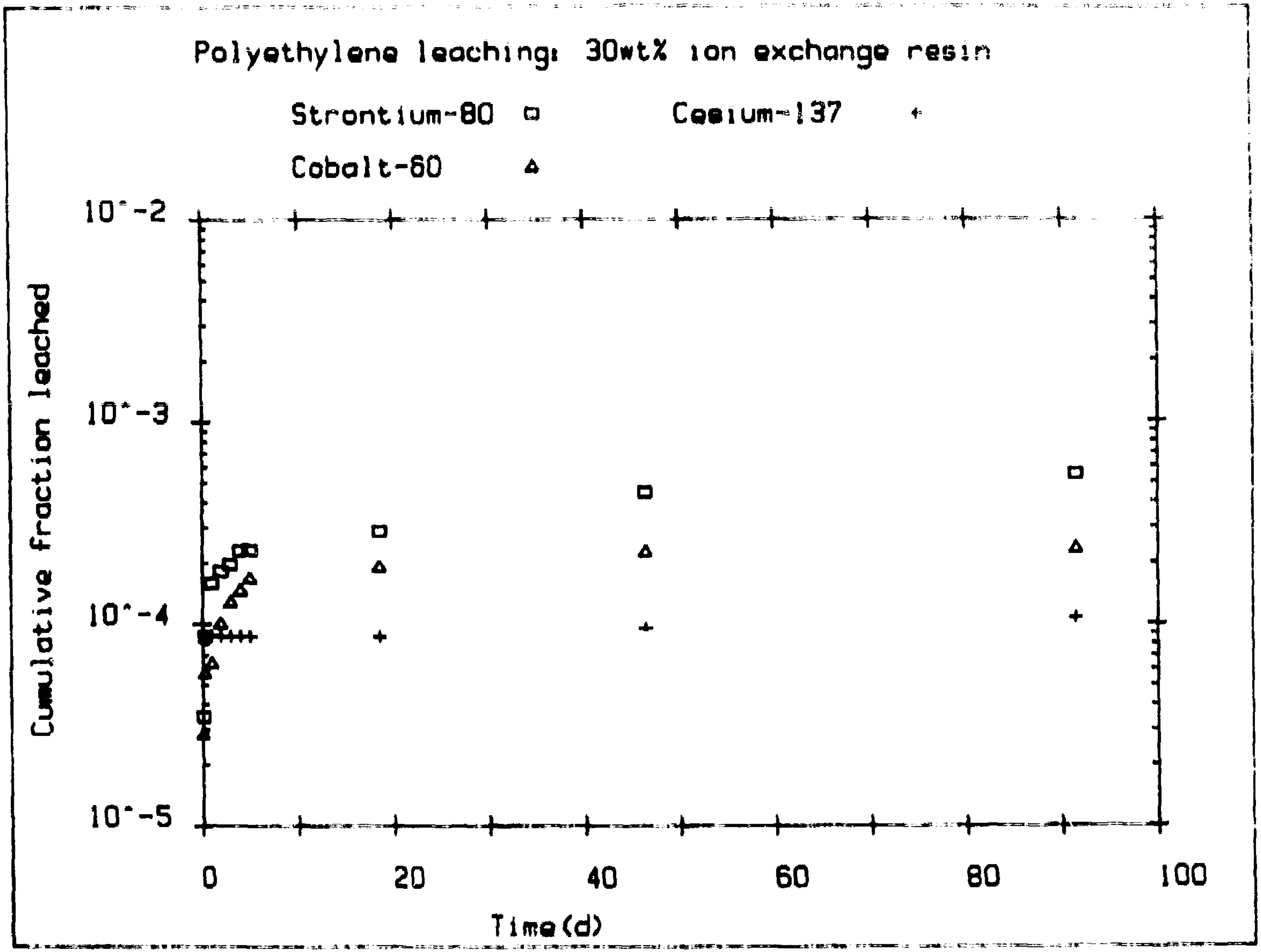


Figure 2.20 Cumulative fraction leached of Co-60, Sr-85 and Cs-137 as a function of time from polyethylene waste forms containing 30 wt% of ion exchange resin.

where:

a_n = activity released from the specimen during the leaching period n

A_0 = initial activity in the test specimen

V = volume of specimen (cm^3)

S = geometric surface area of specimen (cm^2)

$(\Delta t)_n$ = incremental leaching time (sec)

T = $[1/2\ (t_n^{1/2} + t_{n-1}^{1/2})]^2$, the leaching time (secs), representing the "mean time" of the leaching interval

where:

t_n = leaching time at the end of leaching interval n.

Average leaching indices were calculated for each of the two replicate sets of polyethylene waste forms which had been leach tested. These values are included in Appendix A. An average of these two sets of leaching indices is listed in Table 2.8. Since the leachability index is inversely proportional to effective diffusivity, higher index values represent reduced leachability. All of the polyethylene waste forms had a leaching index for each isotope greater than the minimum value recommended by the NRC.

Table 2.8

Average Radionuclide Leachability Indices for Polyethylene Waste Forms[a]

Waste Type	Waste Loading (Wt%)	Average Leachability Index, Co-60	Average Leachability Index, Sr-85	Average Leachability Index, Cs-137
Na_2SO_4	10	11.5	13.9	14.7
	30	11.1	11.1	11.4
	50	10.1	10.2	9.9
Incinerator Ash	25	13.9	15.5	12.5
	35	12.7	14.9	11.3
Ion Exchange Resin	10	13.6	16.2	18.2
	20	14.3	14.7	18.9
	30	14.6	16.1	19.5

a. Calculated in accordance with ANS 16.1 Leach Test.

3. MODIFIED SULFUR CEMENT

The modified sulfur cement used in this study was developed by the U.S. Bureau of Mines (USBM) by reacting elemental sulfur with a 5 wt% modifier consisting of equal parts of dicylopentadiene (DCPD) and oligomers of cyclopentadiene. Solid sulfur transforms on cooling below 96°C from the monoclinic (S_β) to the orthorhombic (S_α) crystalline form that is more dense and occupies less volume than the S_β form, resulting in a highly stressed product. The modifier prevents the phase transformation of the sulfur from S_β to S_α thus resulting in a more stable and durable product. Modified sulfur cement is a thermoplastic material which melts at 119°C to form a low-viscosity liquid which can be mixed with waste to form a homogeneous, solid monolithic product upon cooling. A chemically induced curing reaction is not required for solidification of modified sulfur cement as it is in the case of thermosetting materials. Therefore, the technology for solidification of LLW in modified sulfur cement should be similar to that developed for bitumen and polyethylene.

Modified sulfur cement is commercially available and is being used as a strong, highly corrosion resistant material for the preparation of high structural strength concretes that are extremely resistant to acidic and saline environments. Previous work[8] on processibility, solidification efficiencies and waste form characteristics has established the feasibility of modified sulfur cement as a potential solidification agent for several types of low-level waste streams.

3.1 Wastes Streams

The same waste streams which were used in the work on solidification of LLW in polyethylene were also used to study the solidification of LLW in modified sulfur cement. These include sodium sulfate, boric acid, incinerator ash and mixed-bed ion exchange resins.

3.2 Process Development

Process development studies were performed using a screw extruder method and a dual-action heated mixer. The low viscosity of the molten modified sulfur cement impeded conveyance through the extruder barrel and also hampered the screw's ability to mix the waste and binder constituents effectively at higher waste loadings. More suitable processing results were achieved by using the heated batch mixer, shown in Figure 2.2. The details of this process have been previously described[8].

Processing temperatures were kept as low as practical to prevent additional polymerization of the sulfur at 160°C and to prevent the conversion of ortho boric acid (H_3BO_3) to meta boric acid (HBO_2) which occurs at temperatures > 169°C. Additional polymerization would cause a sharp increase in viscosity while the formation of HBO_2 would result in the generation of water vapor and a change in density from 1.435 g/cm^3 to 2.486 g/cm^3. Since meta borate is extremely hygroscopic, rehydration to the original ortho boric acid form would occur, resulting in the deterioration of the solidified waste forms due to expansion.

Unlike the bench-scale extruder, the design of the dual-action mixer included ventilation so that wastes which release water vapor during mixing could be accommodated. But in order to expedite processing time, the wastes were dried prior to mixing with the molten sulfur cement.

Maximum waste loadings for modified sulfur cement waste forms as achieved during process development studies using the dual-action mixer are: 30 wt% sodium sulfate, 57 wt% boric acid and 43 wt% incinerator ash. These results are presented in Table 3.1. For comparison, the maximum waste loadings achieved when a screw extruder was employed are also included. In all cases, the use of the dual-action mixer clearly shows an increase in waste loading as compared to that obtained by use of the extruder.

Table 3.1

Summary of Maximum Waste Loadings for Modified Sulfur Cement Waste Forms Achieved During Process Development Studies

Waste Type	Max. Loading by Extrusion, wt%	Max. Loading by Dual Action Mixer, wt%
Sodium Sulfate	65	80
Boric Acid	40	57
Incinerator Ash	20	43
Ion Exchange Resin	40	NA[a]

a)Not applicable; see Section 3.5.

3.3 Sample Fabrication

Laboratory-scale samples of varying waste/binder ratios were prepared for waste form stability studies using the dual-action heated mixer described in Section 2.2. The mixtures were solidified in molds of 4.8 cm (1.9 inches) diameter yielding samples approximately 9.0 cm (3.5 inches) high.

Those samples which were prepared for leach testing had Co-60 and Cs-137 incorporated into the wastes. Simulated radioactive samples were prepared in duplicate containing 25 and 40 wt% sodium sulfate and 20 and 40 wt% incinerator ash. The maximum loading of 40 wt% for sodium sulfate samples was based on the results obtained in the immersion test during which samples containing $\geq$ 50 wt% sodium sulfate failed. The 40 wt% loading for incinerator ash was essentially the same as the maximum loading achieved during processing studies. Samples containing ion exchange resins were not prepared for leach testing since they failed the immersion test as discussed in Section 3.5.

As in the case of polyethylene samples, the activity source term calculations were based upon the waste loading (wt%) and the final weight of each sample.

3.4 Testing Procedures

Waste form stability testing was performed according to the tests listed in Table 2.4. Modified sulfur cement waste forms containing a range of waste loadings for each waste type were investigated to determine suitable waste/binder ratios for solidification of low-level waste.

The test descriptions, as presented in Sections 2.4.2 through 2.4.7, apply also to the testing of modified sulfur cement waste forms.

3.5 Test Results

Except for the leaching data, the results of the stability evaluation tests performed on modified sulfur cement waste forms containing various amounts of sodium sulfate, boric acid or incinerator ash are summarized in Table 3.2.

Samples containing ion exchange resins are not included because it became apparent during the testing program that ion exchange resins could not be satisfactorly solidified in modified sulfur cement. Spalling and flaking of these waste forms at low waste loadings occurred upon exposure to ambient air conditions within the laboratory. In water immersion, specimens containing 10 wt% resin deteriorated rapidly within 5 minutes as shown in Figure 3.1. Consequently, no further testing was performed on modified sulfur cement waste forms containing ion exchange resins. The encapsulation of ion exchange resins in modified sulfur cement is not recommended.

The compressive strength of modified sulfur cement samples, without waste, averaged about 1800 psi. The incorporation of sodium sulfate and incinerator ash, even at the highest loadings, essentially doubled the compressive strength of the waste forms, while the addition of boric acid had minimal effect.

The initial compressive strength of the waste forms did not change significantly after being subjected to the various stability tests, except in the case of water immersion tests, as shown in Table 3.2. Most of the detrimental effects on the waste forms were observed during the water immersion test. As previously discussed, specimens containing ion exchange resins failed almost immediately when immersed in water. Specimens containing 80 wt% sodium sulfate and 57 wt% boric acid suffered severe cracking within several days, while specimens containing 50 wt% sodium sulfate developed visible cracks after 48 days of immersion and failed within the 90 day test period.

No bacterial or fungal growth was observed on any of the waste forms as a result of the biodegradation test.

The results of leach testing two replicate sets of modified sulfur cement waste forms containing Co-60 and Cs-137 are presented in terms of the

Table 3.2

Modified Sulfur Cement Waste Form Testing Results[a]

Waste Type	Waste Loading (wt %)	Compressive Strengths (psi): Initial	After Immersion Test[c]	After Thermal Cycling Test	After Irradiation[b]	After Biodegradation Test: Bacteria	After Biodegradation Test: Fungi
Control	0	1800 ± 200	d	d	3000 ± 400	4400 ± 50	4300 ± 200
Sodium Sulfate	20	d	d	d	3000 ± 400	d	d
	30	3700 ± 500	2500 ± 900	2800 ± 1000	4110 ± 40	4500 ± 400	5100 ± 400
	40	4360 ± 60	3000 ± 900	3600 ± 600	3300 ± 1100	3800 ± 400	4500 ± 800
	50	4600 ± 200	Failed	3700 ± 1200	d	d	d
Boric Acid	20	2200 ± 100	3100 ± 600	2200 ± 1200	2600 ± 300	d	d
	30	2000 ± 200	2600 ± 200	3400 ± 400	3040 ± 80	2300 ± 17	1400 ± 600
	40	2000 ± 100	1400 ± 200	2200 ± 200	2100 ± 700	1630 ± 11	2300 ± 70
Incinerator Ash	10	5400 ± 300	2900 ± 800	4100 ± 1000	d	d	d
	20	4300 ± 300	4000 ± 600	4400 ± 900	4400 ± 400	d	d
	30	4200 ± 2100	3900 ± 1600	3800 ± 1700	4600 ± 1000	7100 ± 60	4800 ± 1700
	40	6400 ± 100	4100 ± 200	4700 ± 950	7200 ± 1300	5700 ± 1500	5700 ± 1100
	43	4400 ± 300	5400 ± 1100	5400 ± 2900	d	d	d

a. Performed in accordance with ASTM C-39. 1 psi = 6.98 kPa.
b. Results reflect average of 3 replicate samples ± one standard deviation.
c. Results reflect average of 2 replicate samples ± one standard deviation.
d. Test not performed.

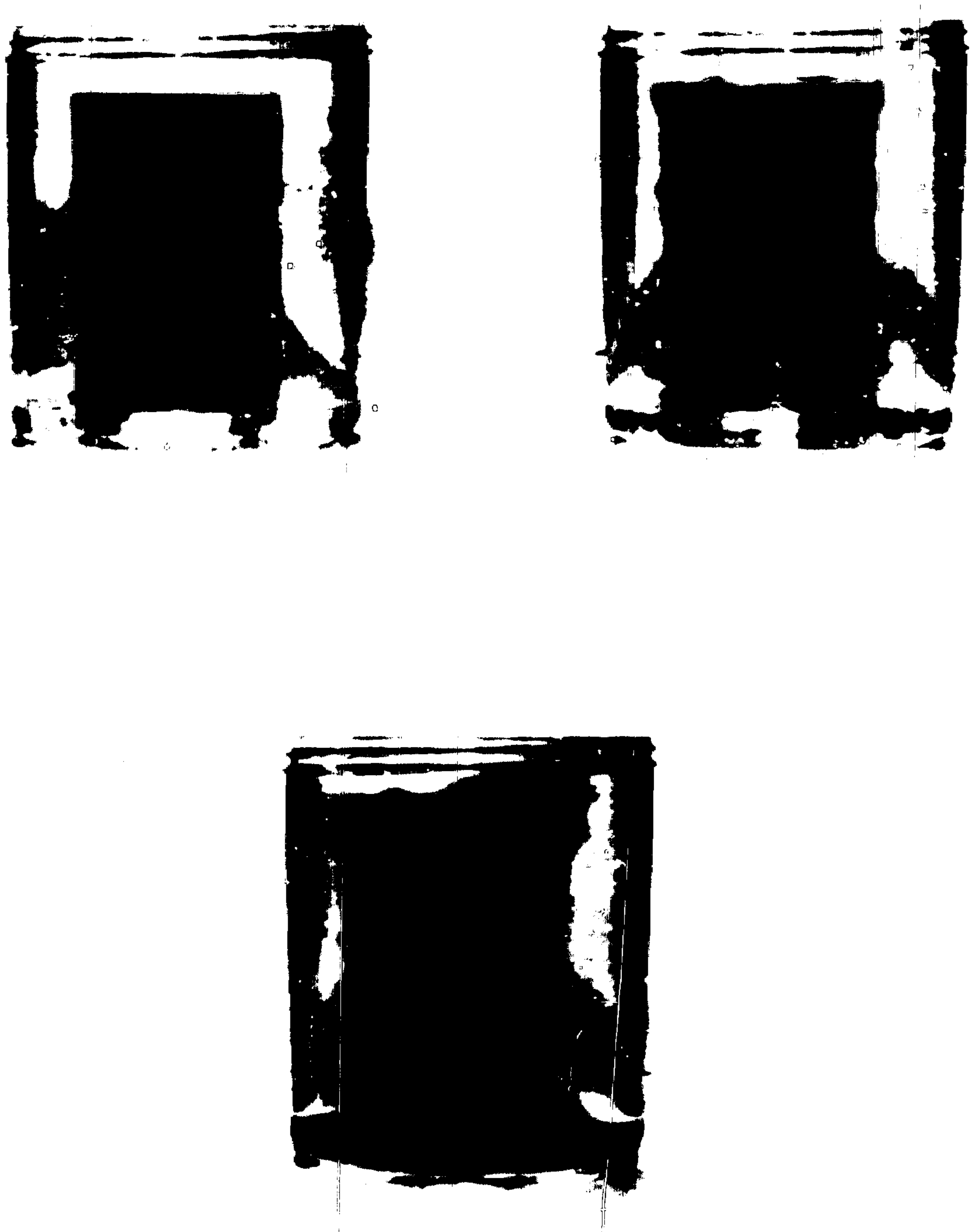


Figure 3.1 Modified sulfur cement 10 wt% dry ion exchange resin waste form undergoing a water immersion test. All three photographs are of the same sample, taken within five minutes of the initiation of the test. Complete structural failure of the sample was observed in less than one day.

cumulative fraction leached (CFL), the incremental fraction leached (IFL) and the average leaching indices for both radionuclides. These data are tabulated in Appendix B. The CFL has also been plotted as a function of leaching time (in days) and the results will be discussed below. These leaching curves represent the average C[illegible] of the two sets of leaching data.

A dependence of leachability upon increased waste loadings was observed for modified sulfur cement/sodium sulfate specimens. This is shown in Figures 3.2 and 3.3 where the CFL of both isotopes is higher at 40 wt% waste loading than at 25 wt% loading. At both waste loadings, the release rates for Cs-137 are greater than that for Co-60, as shown in Figures 3.4 and 3.[illegible]. At the 40 wt% loading the CFL of Cs-137 and Co-60 are 1.1×10^{-1} and 4.[illegible]$\times 10^{-2}$, respectively.

However, increased waste loadings from 20 wt% to 40 wt% had little effect on the leaching of waste forms containing incinerator ash, as shown in Figures 3.6 and 3.7. As in the case of sodium sulfate waste forms, Cs-137 was leached at a higher rate than Co-60 at both waste loadings. These data are shown in Figures 3.8 and 3.9. At a loading of 40 wt% the CFL of Cs-137 is 6.7×10^{-3} while that of Co-60 is only 1.6×10^{-4}.

The leaching indices for both radioisotopes of the two replicate sets of leaching data were calculated according to the method described in ANS 16.1[7] An average was taken of these two sets of data and the results are shown in Table 3.3. All of the values are > 6, the minimum required by the NRC.

Table 3.3

Average Radionuclide Leachability Indices for Modified Sulfur Cement Waste Forms

Waste Type	Waste Loading (Wt%)	Average Leachability Index, Co-60	Average Leachability Index, Cs-137
Na_2SO_4	25	12.5	10.6
	40	10.7	9.7
Incinerator Ash	20	14.0	11.2
	40	14.6	11.1

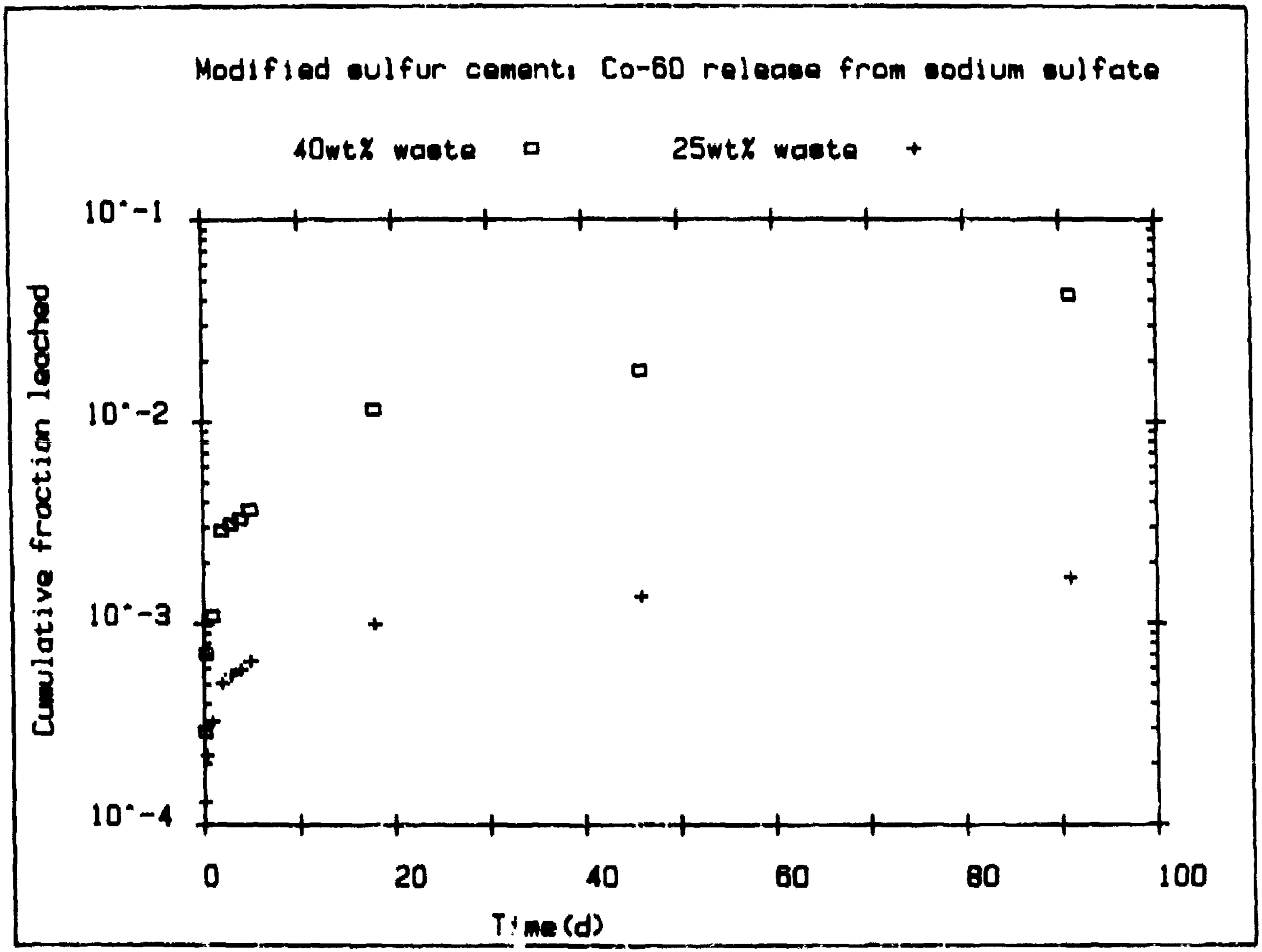


Figure 3.2 Cumulative fraction leached of Co-60 as a function of time from modified sulfur cement waste forms containing 25 and 40 wt% of sodium sulfate waste.

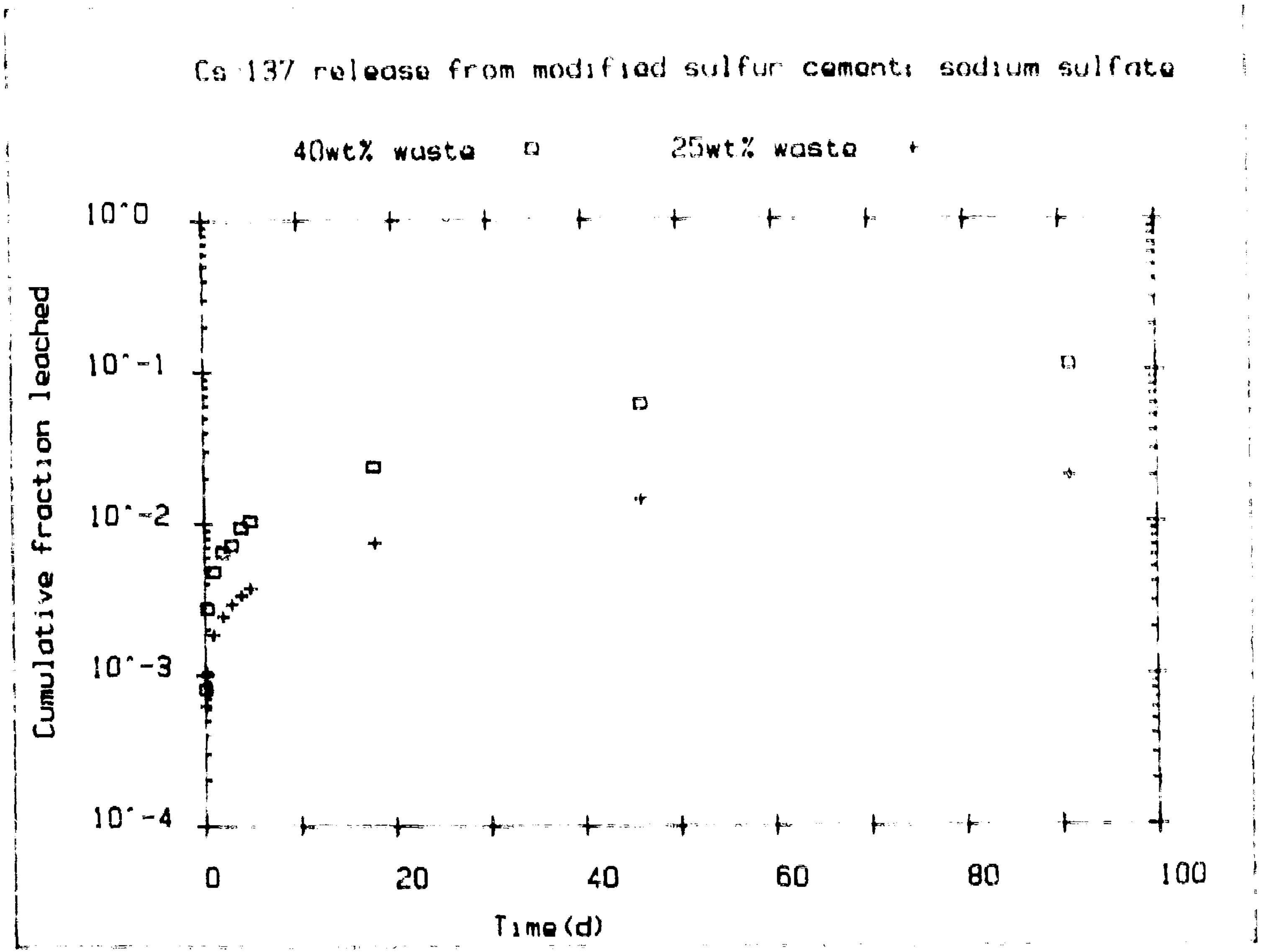


Figure 3.3 Cumulative fraction leached of Cs-137 as a function of time from modified sulfur cement waste forms containing 25 and 40 wt% of sodium sulfate waste.

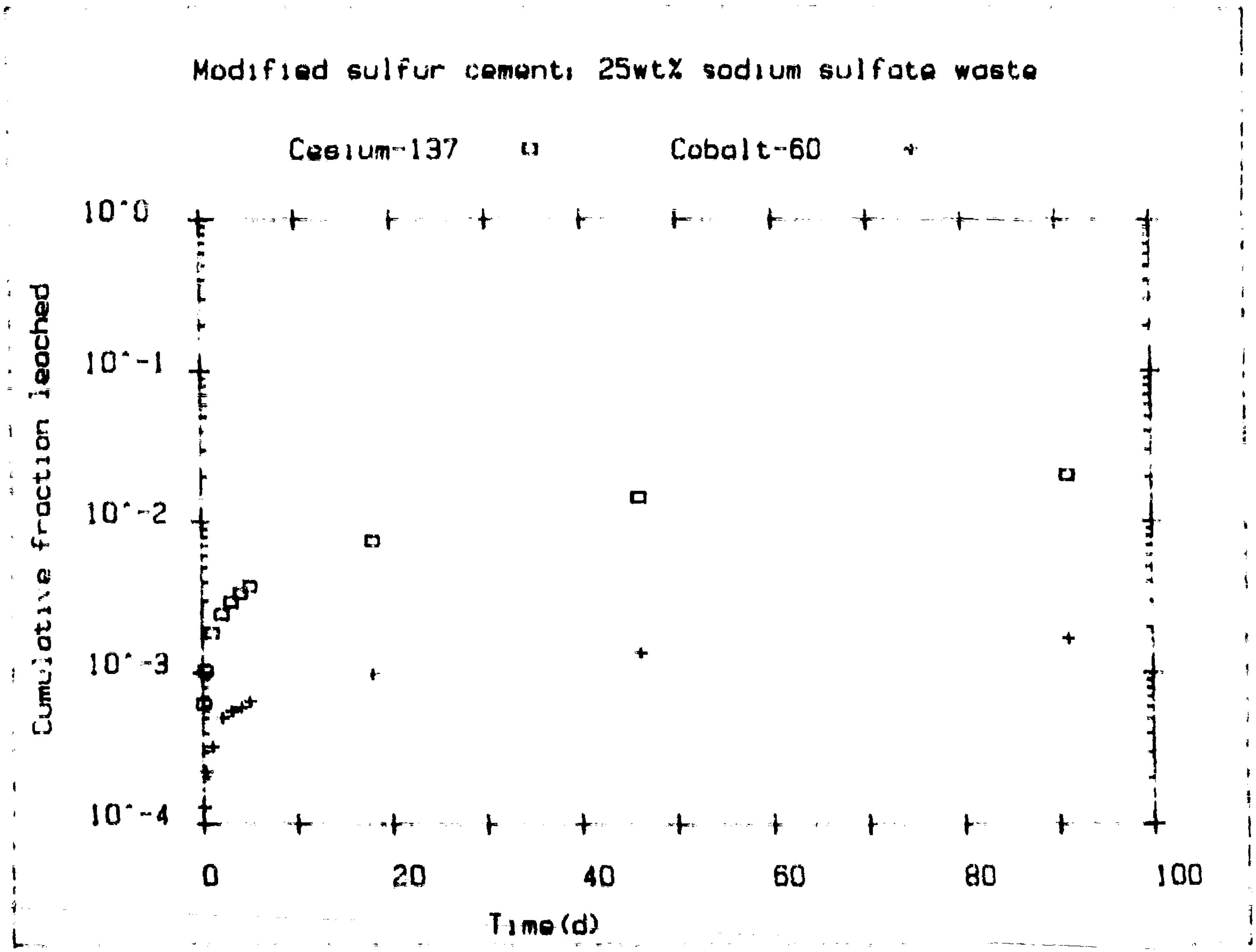


Figure 3.4 Cumulative fraction leached of Co-60 and Cs-137 as a function of time from modified sulfur cement waste forms containing 25 wt% of sodium sulfate waste.

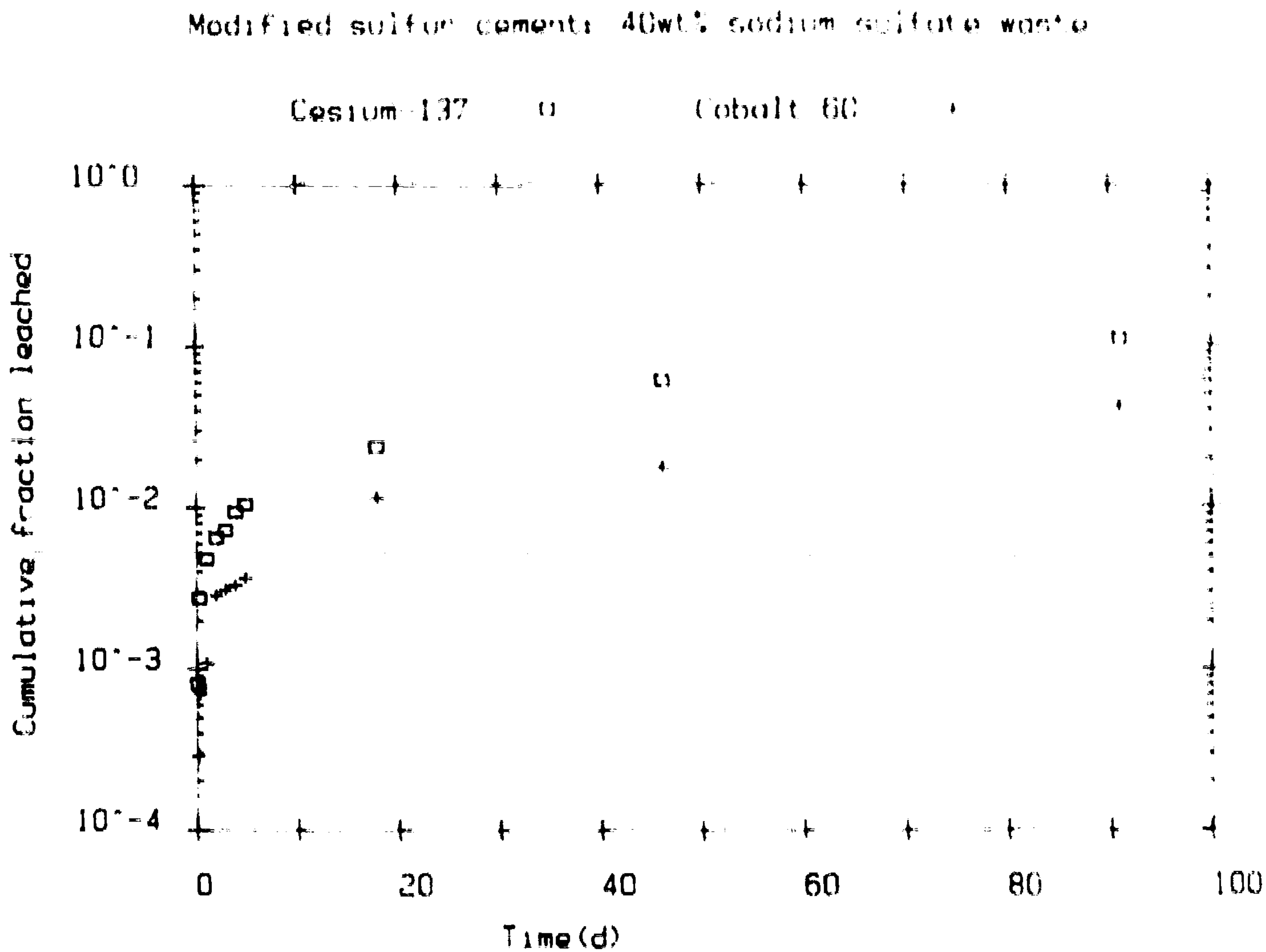


Figure 3.5 **Cumulative fraction leached of Co-60 and Cs-137 as a function of time from modified sulfur cement waste forms containing 40 wt% of sodium sulfate waste.**

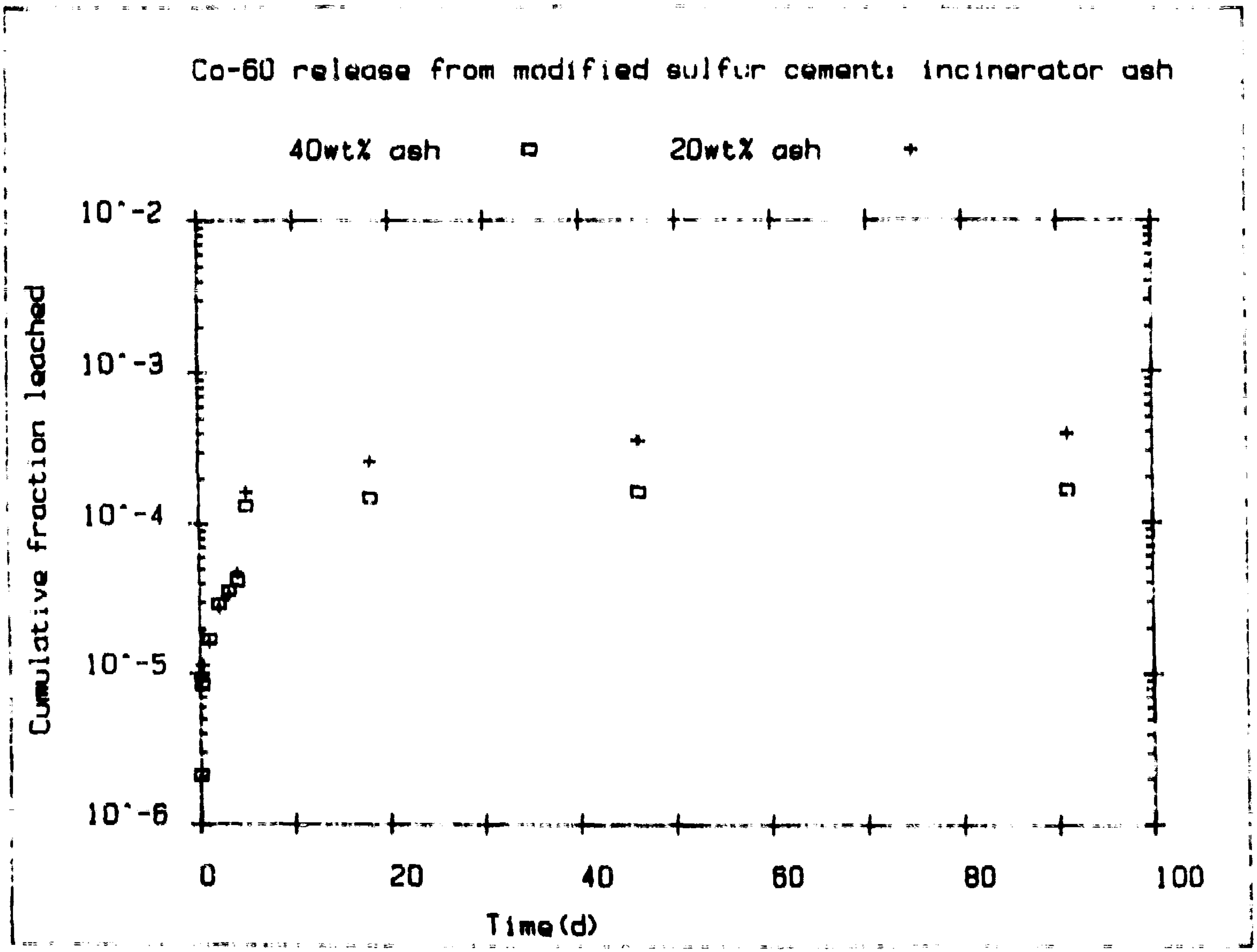


Figure 3.6 Cumulative fraction leached of Co-60 as a function of time from modified sulfur cement waste forms containing 20 and 40 wt% of incinerator ash.

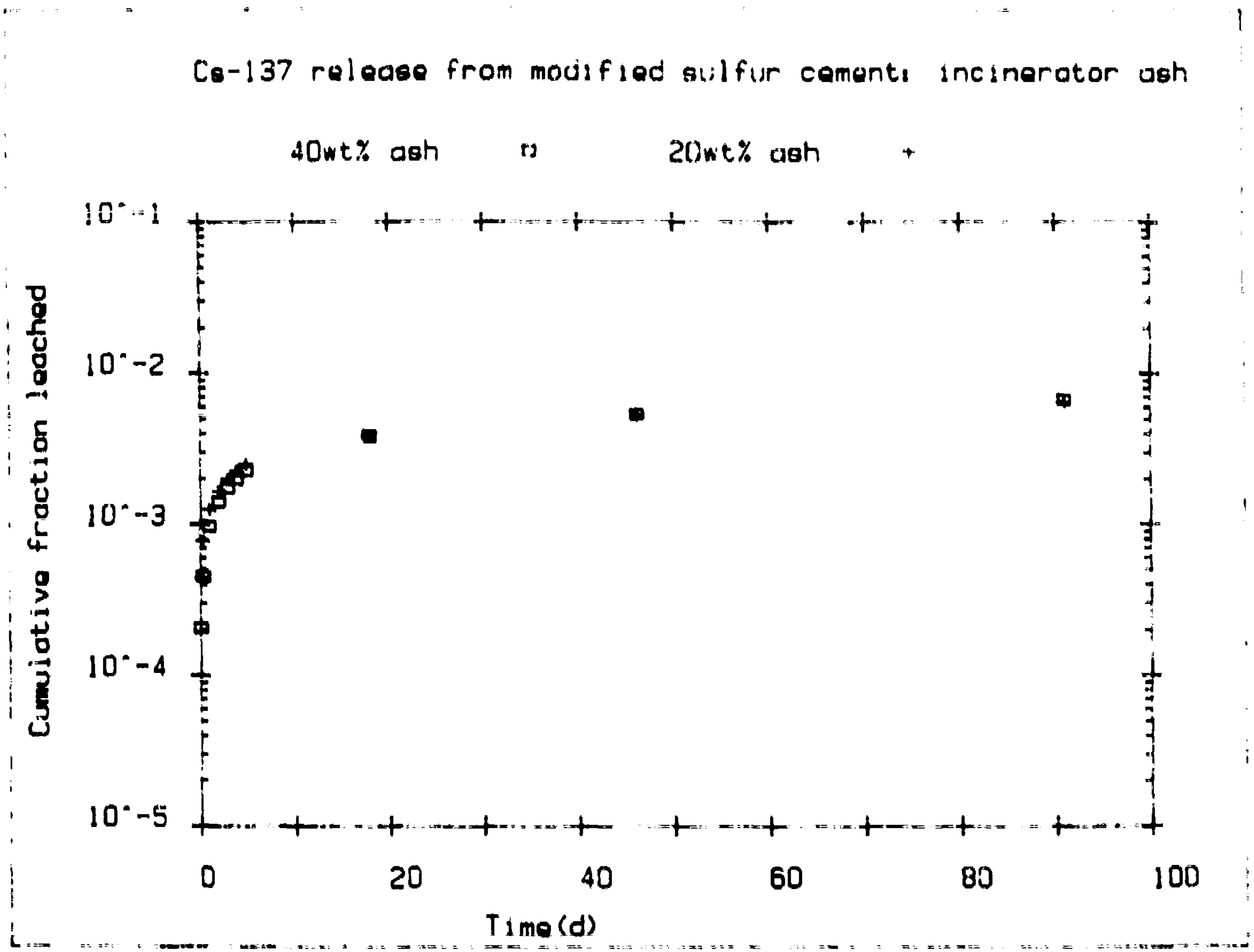


Figure 3.7 Cumulative fraction leached of Cs-137 as a function of time from modified sulfur cement waste forms containing 20 and 40 wt% of incinerator ash.

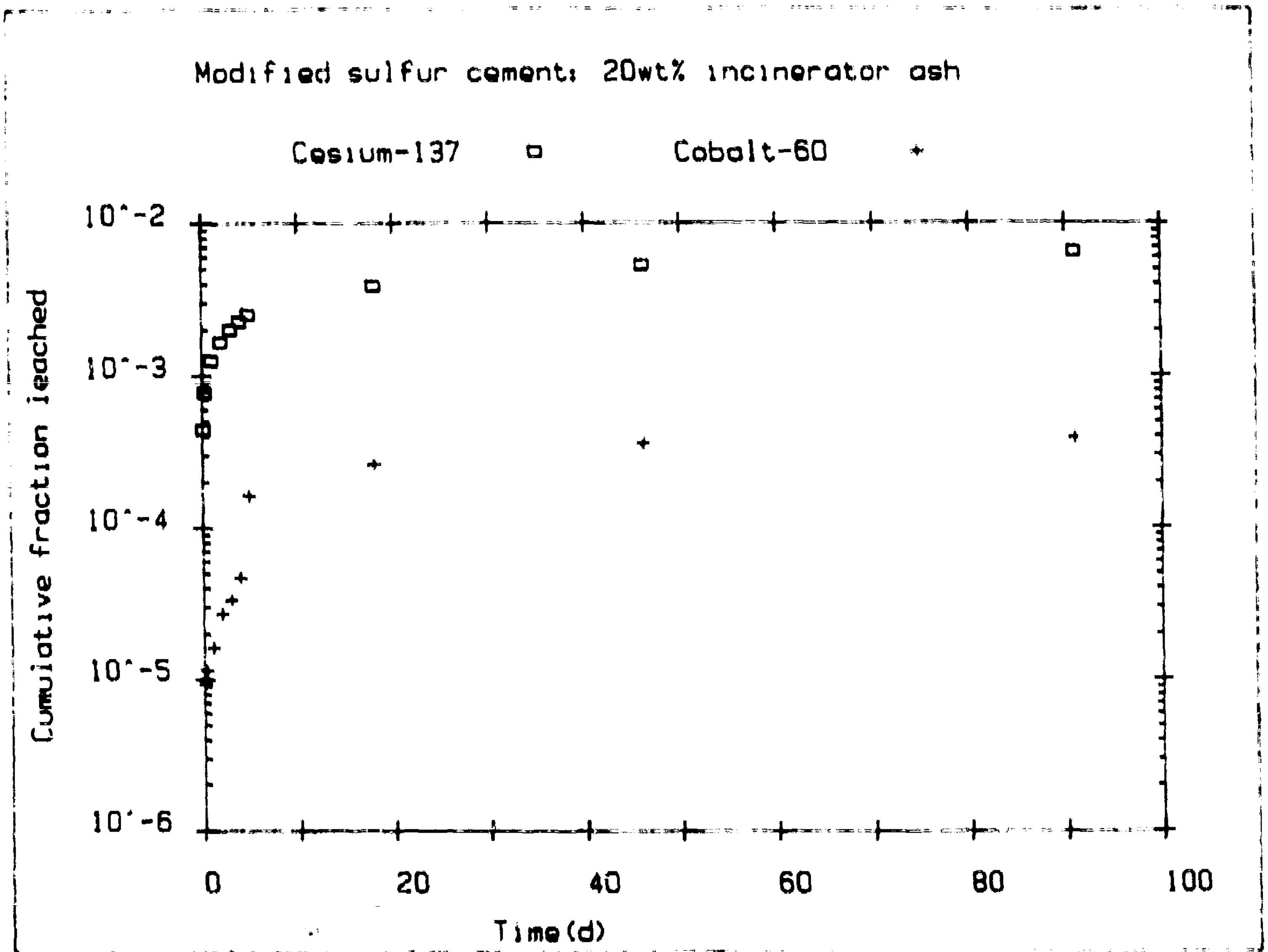


Figure 3.8 Cumulative fraction leached of Co-60 and Cs-137 as a function of time from modified sulfur cement waste forms containing 20 wt% of incinerator ash.

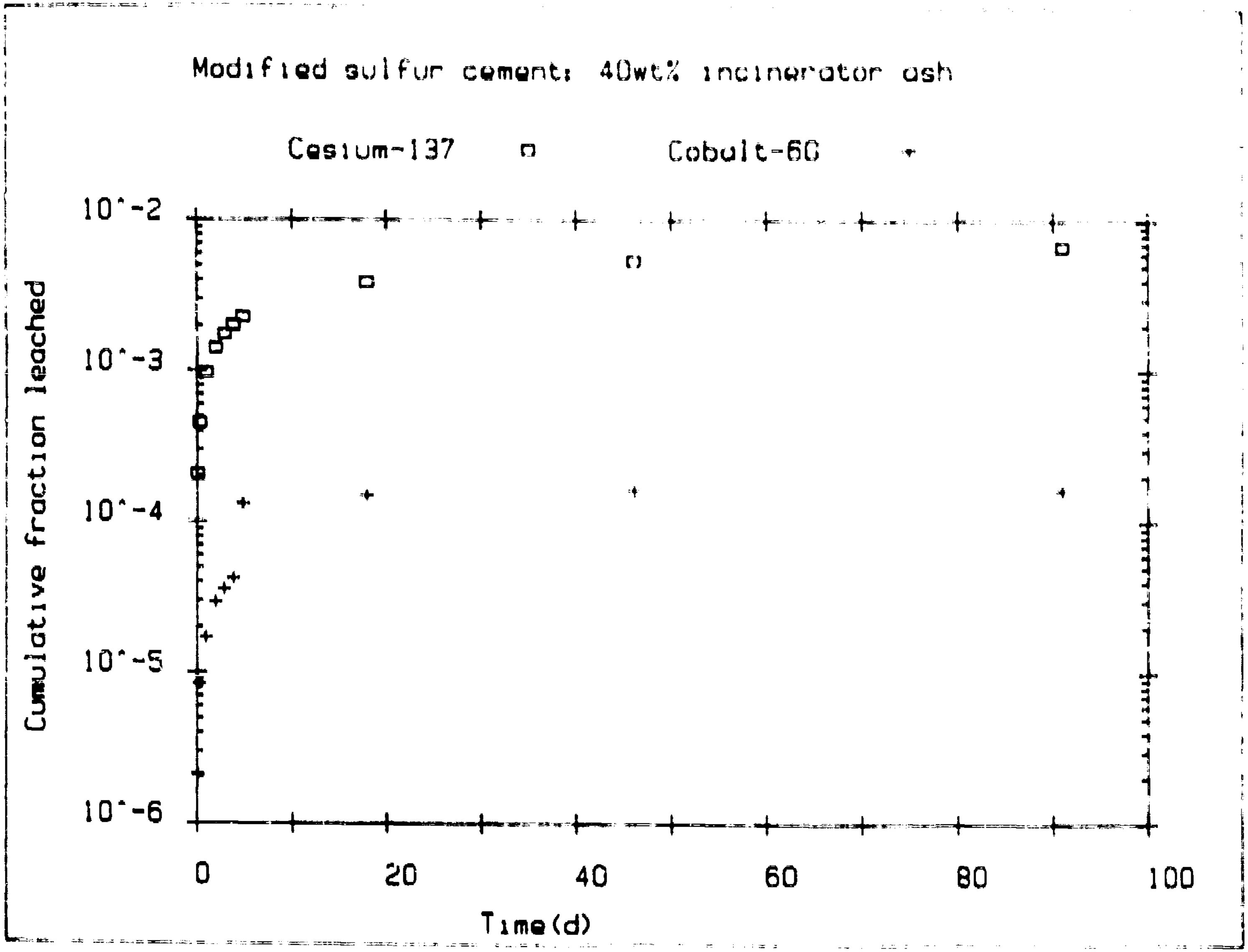


Figure 3.9 Cumulative fraction leached of Co-60 and Cs-137 as a function of time from modified sulfur cement waste forms containing 40 wt% of incinerator ash.

4. CONCLUSIONS

- Laboratory-scale process development studies demonstrate the feasibility of polyethylene and modified sulfur cement as potential solidification agents for LLW.

- The results of waste form stability testing indicate compliance of polyethylene and modified sulfur cement with NRC criteria.

- The optimal recommended waste loadings for polyethylene are 70 wt% sodium sulfate, 50 wt% boric acid, 40 wt% incinerator ash and 30 wt% ion exchange resins, based on the results of the waste form stability tests.

- The optimal recommended waste loadings for modified sulfur cement are 40 wt% each for sodium sulfate, boric acid and incinerator ash, except for ion exchange resins.

- The incorporation of ion exchange resins in modified sulfur cement is not recommended.

- The optimal waste loadings obtained for polyethylene and modified sulfur cement exceed or are comparable to those for portland cement, as shown in Table 4.1.

Table 4.1

Comparison of Optimal Waste Loadings for Polyethylene, Modified Sulfur Cement and Hydraulic Cement Based on Processing and Waste Form Stability Considerations

	Waste Type			
	Sodium Sulfate	Boric Acid	Incinerator Ash	Ion Echange Resins
Solidification in Polyethylene:				
Wt% Waste[a]	70	50	40	30
Drum Wt., kg[b]	358	225	270	210
(lbs)	(789)	(496)	(595)	(463)
Waste/Drum, kg[c]	250	133	108	63
(lbs)	(552)	(248)	(238)	(139)
Solidification in Modified Sulfur Cement:				
Wt% Waste[a]	40	40	40	Not recommended
Drum Wt., kg[b]	415	287	384	
(lbs)	(915)	(633)	(846)	--
Waste/Drum, kg[c]	166	115	182	
(lbs)	(366)	(253)	(360)	--
Solidification in Hydraulic Cement:[d]				
Wt% Waste[a]	9	15	40	13
Drum Wt., kg[b]	307	296	318	318
(lbs)	678	(653)	(700)	(700)
Waste/Drum, kg[c]	28	44	127	41
(lbs)	(61)	(98)	(280)	(91)

a. Based on dry solid weight.
b. 55 gallon drum size waste form.
c. Equivalent quantity of waste which can be incorporated in 55 gallon drum size waste form.
d. Based on previous BNL waste form development studies for waste forms which satisfied free-standing monolithic solid and two-week water immersion criteria[9,10,11].

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APPENDIX A

Leaching Data for Polyethylene Waste Forms

Key

Time = Cumulative Leaching Time, Days

IFL = Incremental Fraction Leached

CFL = Cumulative Fraction Leached

Rate = Incremental Leaching Rate Per Second

LI = Leaching Index

Table A-1

10 Wt% Sodium Sulfate in Polyethylene
Sample: 84-7-1

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0022679	0.0022679	1.15E-007	9.222
2	0.29	0.0024259	0.0026939	2.37E-008	10.575
3	1.00	0.0006599	0.0033627	1.05E-008	10.788
4	2.00	0.0003751	0.0037499	4.47E-009	11.158
5	3.00	0.0002488	0.0039977	2.88E-009	11.327
6	4.00	0.0004471	0.0044449	5.18E-009	10.649
7	5.00	0.0003328	0.0047774	3.84E-009	9.999
8	18.00	0.0010019	0.0057793	8.52E-010	11.697
9	46.00	0.0011255	0.0069047	1.00E-009	10.492
10	91.00	0.0000000	0.0069047	1.67E-015	21.975

AVERAGE Sr LI = [illegible]

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0019351	0.0019351	2.75E-007	9.419
2	0.29	0.0006271	0.0025254	2.89E-008	10.452
3	1.00	0.0002125	0.0027379	3.47E-009	11.755
4	2.00	0.0000451	0.0027827	5.32E-010	13.226
5	3.00	0.0000000	0.0027827	1.15E-013	20.099
6	4.00	0.0000000	0.0027827	1.18E-013	19.952
7	5.00	0.0000001	0.0027833	1.33E-010	12.234
8	18.00	0.0004100	0.0032011	3.71E-010	12.456
9	46.00	0.0025000	0.0042292	3.40E-010	12.273
10	91.00	0.0009267	0.0043515	2.35E-010	12.341

AVERAGE Cs LI = 12.491

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0024670	0.0024670	3.43E-007	9.222
2	0.29	0.0009372	0.0034043	5.21E-008	9.951
3	1.00	0.0005355	0.0039400	8.75E-009	10.362
4	2.00	0.0000034	0.0039437	3.58E-011	15.277
5	3.00	0.0001956	0.0041392	2.26E-009	11.516
6	4.00	0.0002405	0.0043797	2.79E-009	11.155
7	5.00	0.0000592	0.0044389	5.55E-010	12.136
8	18.00	0.0007179	0.0051567	6.29E-010	11.997
9	46.00	0.0011078	0.0062646	4.59E-010	11.915
10	91.00	0.0015469	0.0078115	3.95E-010	11.596

AVERAGE Co LI = 11.582

Table A-2

10 Wt% Sodium Sulfate in Polyethylene
Sample: 84-7-2

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0011916	0.0011916	1.66E-007	9.377
2	0.29	0.0000000	0.0011916	5.56E-010	19.909
3	1.00	0.0000000	0.0011916	1.53E-012	22.424
4	2.00	0.0001464	0.0013380	1.69E-009	12.012
5	3.00	0.0000000	0.0013380	1.16E-012	20.113
6	4.00	0.0001762	0.0015144	2.34E-009	11.473
7	5.00	0.0000000	0.0015144	1.16E-012	15.855
8	18.00	0.0001428	0.0016572	3.05E-010	12.644
9	46.00	0.0000000	0.0016572	4.72E-015	21.919
10	91.00	0.0045499	0.0062069	1.10E-009	10.712

AVERAGE Sr LI = 15.995

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0012639	0.0012639	1.76E-007	9.422
2	0.29	0.0001151	0.0013790	6.06E-009	11.524
3	1.00	0.0000000	0.0013790	1.53E-012	20.434
4	2.00	0.0000000	0.0013790	1.16E-012	20.343
5	3.00	0.0000000	0.0013790	1.15E-012	20.113
6	4.00	0.0000000	0.0013790	1.16E-012	19.965
7	5.00	0.0000000	0.0013790	1.16E-012	19.855
8	18.00	0.0004129	0.0017920	3.68E-010	12.462
9	46.00	0.0006555	0.0024465	2.71E-010	12.284
10	91.00	0.0008728	0.0033193	2.24E-010	12.110

AVERAGE Cs LI = 15.924

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0014901	0.0014901	2.06E-007	9.583
2	0.29	0.0003417	0.0018318	1.90E-008	10.342
3	1.00	0.0003244	0.0021562	5.30E-009	11.412
4	2.00	0.0001824	0.0023386	2.11E-009	11.921
5	3.00	0.0001224	0.0024610	1.42E-009	11.936
6	4.00	0.0000981	0.0025591	1.14E-009	11.931
7	5.00	0.0001828	0.0027419	2.23E-009	11.299
8	18.00	0.0007562	0.0034981	6.73E-010	11.957
9	46.00	0.0011299	0.0046279	4.57E-010	11.810
10	91.00	0.0015118	0.0062390	4.14E-010	11.575

AVERAGE Co LI = 11.431

Table A-3

30 Wt% Sodium Sulfate in Polyethylene
Sample: 84-7-3

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.25	0.0017022	0.0017022	1.37E-007	9.867
2	0.75	0.0008771	0.0025793	4.87E-008	10.222
3	1.00	0.0010734	0.0036527	1.76E-008	10.287
4	2.00	0.0004921	0.0041436	5.67E-009	10.962
5	3.00	0.0001977	0.0043455	2.09E-009	11.521
6	4.00	0.0001462	0.0044327	1.64E-009	11.634
7	5.00	0.0002642	0.0047469	1.94E-009	11.244
8	19.00	0.0011128	0.0058597	8.31E-010	11.594
9	47.00	0.0012627	0.0071223	1.92E-010	11.290
10	90.00	0.0012342	0.0083565	5.22E-010	11.272

AVERAGE Sr LI = 10.948

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.25	0.0014422	0.0014422	1.21E-007	9.712
2	0.75	0.0007955	0.0022197	4.37E-008	10.117
3	1.00	0.0006052	0.0028250	9.39E-009	10.970
4	2.00	0.0002162	0.0030520	2.49E-009	11.578
5	3.00	0.0001243	0.0031745	1.44E-009	11.922
6	4.00	0.0002544	0.0032292	6.31E-010	12.432
7	5.00	0.0000424	0.0032694	4.57E-010	12.543
8	19.00	0.0010051	0.0042745	8.31E-010	11.773
9	47.00	0.0015334	0.0058140	6.61E-010	11.510
10	92.00	0.0013735	0.0072475	3.53E-010	11.713

AVERAGE Cs LI = 11.443

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.25	0.0016373	0.0016379	2.29E-007	9.500
2	0.75	0.0009736	0.0026114	5.41E-008	9.932
3	1.00	0.0008425	0.0034539	1.38E-008	10.563
4	2.00	0.0003226	0.0037765	3.73E-009	11.325
5	3.00	0.0003049	0.0040814	3.53E-009	11.144
6	4.00	0.0002223	0.0043036	2.57E-009	11.271
7	5.00	0.0001377	0.0044413	1.59E-009	11.577
8	19.00	0.0012451	0.0056864	1.03E-009	11.587
9	47.00	0.0016636	0.0073550	6.90E-010	11.473
10	92.00	0.0014160	0.0087720	3.64E-010	11.667

AVERAGE Co LI = 11.018

Table A-4

30 Wt% Sodium Sulfate in Polyethylene
Sample: 84-7-4

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	[illegible]	[illegible]	[illegible]	[illegible]	9.634
2	[illegible]	[illegible]	[illegible]	[illegible]	10.419
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	19.00	[illegible]	[illegible]	[illegible]	[illegible]
9	47.00	[illegible]	[illegible]	[illegible]	[illegible]
10	92.00	[illegible]	[illegible]	4.57E-012	11.474

AVERAGE Sr LI = [illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
[illegible] LEACH DATA					
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	19.00	[illegible]	[illegible]	[illegible]	[illegible]
9	47.00	[illegible]	[illegible]	[illegible]	[illegible]
10	92.00	[illegible]	[illegible]	[illegible]	[illegible]

AVERAGE [illegible] LI = 11.444

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.08	0.0015039	0.0018209	2.50E-007	9.431
2	0.74	0.0007094	0.0001300	5.04E-009	9.976
3	1.00	0.0005554	0.0011473	1.07E-008	10.780
4	2.00	0.0002781	0.0006554	3.00E-009	11.405
5	3.00	0.0002347	0.0007510	3.41E-008	11.158
6	4.00	0.0002281	0.0041831	2.64E-009	11.032
7	5.00	0.0001587	0.2243038	1.74E-009	11.482
8	19.00	0.0010752	0.0054121	9.85E-012	11.702
9	47.00	0.0011094	0.0057155	5.42E-012	11.570
10	92.00	0.0011474	0.0076629	3.95E-012	11.654

AVERAGE Co LI = 11.073

Table A-5

50 Wt% Sodium Sulfate in Polyethylene
Sample: 84-7-5

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	0.08	0.0026855	0.0026855	[illegible]	9.154
2	0.29	0.0021437	0.0050222	1.20E-007	9.160
3	1.00	0.0021443	0.0061760	5.14E-008	9.400
4	2.00	0.0014428	0.0096187	1.57E-008	10.089
5	3.00	0.0024109	0.0124100	3.79E-009	10.279
6	4.00	0.0005947	0.0111049	9.24E-009	10.265
7	5.00	0.0005201	0.0114950	8.12E-009	10.390
8	19.00	0.0035424	0.0151977	2.92E-009	10.567
9	47.00	0.0048331	0.0200160	1.32E-009	10.524
10	92.00	0.0042574	0.0247474	[illegible]	10.715

AVERAGE Sr LI = [illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.08	0.0021229	0.0021229	4.05E-007	9.021
2	0.29	0.0022955	[illegible]	1.70E-007	9.322
3	1.00	0.0042814	[illegible]	5.59E-008	9.194
4	2.00	0.0015124	0.0117975	1.36E-008	[illegible]
5	3.00	0.0012774	0.0130451	1.25E-008	10.000
6	4.00	0.0005423	[illegible]	3.75E-009	10.297
7	5.00	0.0006320	[illegible]	3.22E-009	10.197
8	19.00	0.0051504	0.0193512	4.27E-009	10.336
9	47.00	0.0041977	0.0238632	1.74E-009	10.656
10	92.00	0.0045194	0.0283738	1.18E-009	10.662

AVERAGE Cs LI = [illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.08	0.0025877	0.0025877	3.60E-007	9.187
2	0.29	0.0023677	0.0049554	1.32E-007	9.144
3	1.00	0.0035102	0.0084656	5.74E-008	9.327
4	2.00	0.0014765	0.0099422	1.71E-008	9.969
5	3.00	0.0009834	0.0109256	1.14E-008	10.111
6	4.00	0.0006387	0.0115643	6.09E-009	10.268
7	5.00	0.0006801	0.0122443	7.19E-009	10.252
8	19.00	0.0037933	0.0160393	3.14E-009	10.583
9	47.00	0.0043096	0.0203489	1.78E-009	10.633
10	92.00	0.0037186	0.0240654	9.56E-010	10.932

AVERAGE Co LI = 10.034

Table A-6

50 Wt% Sodium Sulfate in Polyethylene
Sample: 84-7-6

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	0.00	0.0027740	0.0027740	3.85E-007	9.122
2	0.29	0.0022656	0.0050396	1.26E-007	9.178
3	1.00	0.0017174	0.0067570	2.81E-008	9.343
4	2.00	0.0004735	0.0072306	5.49E-009	10.971
5	3.00	0.0008015	0.0080321	9.20E-009	10.234
6	4.00	0.0005945	0.0086266	6.56E-009	10.395
7	5.00	0.0005491	0.0091757	6.26E-009	10.254
8	19.00	0.0034502	0.0126259	2.85E-009	10.591
9	47.00	0.0032892	0.0159151	1.36E-009	10.562
10	92.00	0.0027251	0.0186402	7.21E-010	11.095

AVERAGE Sr LI = 10.299

CESIUM LEACH DATA

1	0.00	0.0035612	0.0035612	4.95E-007	8.900
2	0.29	0.0027445	0.0063056	1.52E-007	9.011
3	1.00	0.0024942	0.0086200	4.08E-008	9.619
4	2.00	0.0006869	0.0095066	7.95E-009	10.548
5	3.00	0.0009239	0.0104306	1.07E-008	10.161
6	4.00	0.0006429	0.0110744	7.45E-009	10.226
7	5.00	0.0007177	0.0117921	8.31E-009	10.122
8	19.00	0.0056675	0.0174596	4.69E-009	10.252
9	47.00	0.0070009	0.0244605	2.29E-009	10.207
10	92.00	0.0063314	0.0307920	1.83E-009	10.355

AVERAGE Cs LI = 9.961

COBALT LEACH DATA

1	0.00	0.0034840	0.0034840	4.73E-007	8.944
2	0.29	0.0021615	0.0055655	1.20E-007	9.219
3	1.00	0.0019969	0.0075624	3.26E-008	9.612
4	2.00	0.0004841	0.0080465	5.60E-009	10.952
5	3.00	0.0008380	0.0088646	9.70E-009	10.245
6	4.00	0.0005930	0.0094775	6.86E-009	10.398
7	5.00	0.0005694	0.0100469	6.59E-009	10.323
8	19.00	0.0036030	0.0136499	2.98E-009	10.644
9	47.00	0.0047467	0.0183966	1.96E-009	10.544
10	92.00	0.0047041	0.0231007	1.21E-009	10.623

AVERAGE Co LI = 10.170

Table A-7

10 Wt% Mixed Bed Ion Exchange Resin in Polyethylene
Sample: 84-7-7

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	[illegible]	0.0000228	[illegible]	[illegible]
2	0.29	[illegible]	[illegible]	5.56E-0[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	1.63E-0[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible].448
5	3.00	[illegible]	[illegible]	9.52E-010	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	18.00	[illegible]	[illegible]	[illegible]	21.782
9	46.00	[illegible]	[illegible]	[illegible]	[illegible]
10	91.00	[illegible]	[illegible]	[illegible]	[illegible]

AVERAGE Sr LI = 16.066

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	[illegible]	[illegible]	4.28E-013	15.2[illegible]
2	0.29	[illegible]	[illegible]	5.55E-01[illegible]	19.895
3	1.00	[illegible]	[illegible]	1.63E-01[illegible]	20.422
4	2.00	[illegible]	[illegible]	1.16E-01[illegible]	20.731
5	3.00	[illegible]	[illegible]	1.16E-01[illegible]	20.101
6	4.00	[illegible]	[illegible]	1.16E-01[illegible]	19.95[illegible]
7	5.00	[illegible]	[illegible]	1.16E-01[illegible]	13.642
8	18.00	[illegible]	[illegible]	8.90E-015	21.782
9	46.00	0.0002734	[illegible]	1.16E-010	13.314
10	91.00	0.00042[illegible]	0.00071[illegible]	1.12E-010	12.780

AVERAGE Cs LI = 18.382

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.09	0.0000[illegible]	0.0000[illegible]	4.61E-009	12.975
2	0.29	0.0000655	0.0001191	4.77E-009	12.229
3	1.00	0.0000886	0.0002879	1.45E-009	12.525
4	2.00	0.0000664	0.0002743	7.68E-010	12.687
5	3.00	0.0000731	0.0003475	8.47E-010	12.372
6	4.00	0.0000742	0.0004217	6.59E-010	12.212
7	5.00	0.0000000	0.0004217	1.16E-013	19.943
8	18.00	0.0000859	0.0005076	7.65E-011	13.934
9	46.00	0.0000177	0.0005253	7.31E-012	15.411
10	91.00	0.0000531	0.0005784	1.37E-011	14.528

AVERAGE Co LI = 13.542

Table A-8

10 Wt% Mixed Bed Ion Exchange Resin in Polyethylene
Sample: 84-7-8

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	0.25	0.0001164	0.0001164	1.55E-008	11.873
2	0.75	0.0003610	0.0004795	1.01E-008	10.755
3	1.00	0.0000000	0.0004795	1.61E-010	20.425
4	2.00	0.0000000	0.0004795	1.16E-010	20.004
5	3.00	0.0000000	0.0004795	1.16E-010	20.124
6	4.00	0.0000000	0.0004795	1.16E-010	19.956
7	5.00	0.0000000	0.0004795	1.16E-010	19.846
8	15.00	0.0000703	0.0005499	6.25E-011	14.012
9	46.00	0.0006861	0.0012361	2.22E-010	12.447
10	91.00	0.0000157	0.0012454	4.25E-011	12.557

AVERAGE Sr LI = 16.077

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.25	0.0000153	0.0000153	2.08E-009	12.664
2	0.75	0.0000000	0.0000153	5.56E-011	13.900
3	1.00	0.0000000	0.0000153	1.50E-010	20.425
4	2.00	0.0000577	0.0000727	6.60E-010	12.755
5	3.00	0.0000000	0.0000729	1.16E-010	20.124
6	4.00	0.0000000	0.0000735	1.16E-010	19.956
7	5.00	0.0000000	0.0000738	1.16E-010	19.946
8	15.00	0.0000000	0.0000739	5.90E-015	21.784
9	46.00	0.0000000	0.0000738	4.12E-015	21.909
10	91.00	0.0052161	0.0052899	1.60E-009	10.397

AVERAGE Cs LI = 16.270

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.25	0.0000720	0.0000720	1.80E-008	10.325
2	0.75	0.0000957	0.0001678	5.32E-009	11.935
3	1.00	0.0000762	0.0002437	1.24E-009	12.654
4	2.00	0.0000701	0.0003139	8.11E-010	12.643
5	3.00	0.0000780	0.0003917	9.80E-010	12.322
6	4.00	0.0001164	0.0005081	1.35E-009	11.923
7	5.00	0.0001085	0.0006167	1.76E-009	11.774
8	18.00	0.0001204	0.0007371	1.07E-010	13.543
9	46.00	0.0002206	0.0009577	9.12E-011	13.222
10	91.00	0.0000000	0.0009577	2.57E-015	21.982

AVERAGE Co LI = 13.421

Table A-9

20 Wt% Mixed Bed Ion Exchange Resin in Polyethylene
Sample: 84-7-9

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0000000	0.0000000	1.39E-012	20.282
2	0.29	0.0000002	0.0000000	5.56E-013	19.982
3	1.00	0.0000922	0.0000920	1.52E-009	12.470
4	2.00	0.0000002	0.0000922	1.15E-012	20.015
5	3.00	0.0002282	0.0003209	2.54E-009	11.372
6	4.00	0.0000002	0.0003229	1.16E-013	19.937
7	5.00	0.0000911	0.0004120	1.05E-009	11.985
8	18.00	0.0002665	0.0006785	2.37E-010	12.235
9	46.00	0.0003651	0.0010437	1.51E-010	12.765
10	91.00	0.0005345	0.0015785	2.15E-010	12.118

AVERAGE Sr LI = 15.362

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0000512	0.0000512	7.11E-009	10.554
2	0.29	0.0000000	0.0000512	5.56E-013	19.982
3	1.00	0.0000000	0.0000512	1.63E-013	20.407
4	2.00	0.0000000	0.0000511	1.16E-013	20.316
5	3.00	0.0000000	0.0000512	1.16E-013	20.055
6	4.00	0.0000000	0.0000512	1.16E-012	19.937
7	5.00	0.0000000	0.0000511	1.16E-013	19.827
8	18.00	0.0000009	0.0000521	8.01E-013	17.778
9	46.00	0.0000000	0.0000521	4.13E-015	21.891
10	91.00	0.0052964	0.0057485	1.36E-009	10.514

AVERAGE Cs LI = 18.322

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0000749	0.0000749	1.84E-008	10.252
2	0.29	0.0000191	0.0000940	1.06E-009	13.321
3	1.00	0.0000112	0.0001043	1.79E-010	14.326
4	2.00	0.0000539	0.0001589	6.24E-010	12.852
5	3.00	0.0000167	0.0001755	1.93E-010	13.640
6	4.00	0.0000277	0.0002032	3.20E-010	13.053
7	5.00	0.0000229	0.0002261	2.65E-010	13.106
8	18.00	0.0000181	0.0002442	1.61E-011	15.170
9	46.00	0.0000749	0.0003191	3.10E-011	14.142
10	91.00	0.0000403	0.0003595	1.04E-011	14.751

AVERAGE Co LI = 13.562

Table A-10

20 Wt% Mixed Bed Ion Exchange Resin in Polyethylene
Sample: 84-7-10

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0000026	0.0000026	4.54E-008	12.972
2	0.29	0.0000000	0.0000517	5.55E-010	19.892
3	1.00	0.0000748	0.0001074	1.22E-009	12.857
4	2.00	0.0001437	0.0002511	1.66E-009	11.999
5	3.00	0.0000419	0.0002972	4.85E-010	12.578
6	4.00	0.0002591	0.0003622	6.00E-010	12.250
7	5.00	0.0001459	0.0005030	1.69E-009	11.493
8	19.00	0.0000000	0.0005013	6.92E-015	21.664
9	46.00	0.0005102	0.0010134	2.11E-010	12.473
10	91.00	0.0006927	0.0017051	1.78E-010	12.292

AVERAGE Sr LI = 14.054

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0000000	0.0000000	1.39E-012	20.000
2	0.29	0.0000000	0.0000000	5.55E-012	19.580
3	1.00	0.0000000	0.0000000	1.62E-012	20.425
4	2.00	0.0000000	0.0000000	1.16E-012	20.714
5	3.00	0.0000000	0.0000001	1.16E-012	20.384
6	4.00	0.0000000	0.0000001	1.16E-012	19.926
7	5.00	0.0000000	0.0000001	1.16E-012	19.508
8	19.00	0.0000000	0.0000001	6.92E-015	21.854
9	46.00	0.0000000	0.0000321	4.13E-015	21.999
10	91.00	0.0035155	0.0035156	2.27E-009	12.270

AVERAGE Cs LI = 19.423

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0000457	0.0000457	6.38E-008	12.679
2	0.29	0.0000233	0.0000790	1.95E-009	12.576
3	1.00	0.0000134	0.0000824	2.19E-010	14.151
4	2.00	0.0000295	0.0001120	3.42E-012	13.277
5	3.00	0.0000450	0.0001712	5.67E-010	12.724
6	4.00	0.0000342	0.0002052	3.96E-010	12.868
7	5.00	0.0000022	0.0002252	1.16E-013	19.826
8	19.00	0.0000276	0.0002529	4.24E-011	14.329
9	46.00	0.0000000	0.0002528	4.13E-015	21.599
10	91.00	0.0000419	0.0002947	1.85E-011	14.717

AVERAGE Co LI = 14.937

Table A-11

30 Wt% Mixed Bed Resin in Polyethylene
Sample: 84-7-11

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	0.08	0.0002590	0.0002590	9.83E-008	[illegible]
2	0.29	0.0001000	0.0001725	5.74E-009	11.672
3	1.00	0.0000627	0.0002350	1.02E-009	12.929
4	2.00	0.0000000	0.0002350	1.16E-017	[illegible]
5	3.00	0.0000294	0.0002640	3.41E-010	[illegible]
6	4.00	0.0000000	0.0002649	[illegible]	19.954
7	5.00	0.0000001	0.0002651	[illegible]	15.137
8	15.00	[illegible]	0.0002651	[illegible]	21.725
9	46.00	0.0000000	0.0002651	[illegible]	[illegible]
10	91.00	[illegible]	0.0002756	[illegible]	[illegible]

AVERAGE Sr LI = 15.[illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.08	0.0000000	0.0000000	1.00E-010	[illegible]
2	0.29	[illegible]	0.0001771	9.55E-009	11.419
3	1.00	0.0000000	0.0001771	1.53E-010	20.403
4	2.00	0.0000000	0.0001771	1.16E-010	[illegible]
5	3.00	0.0000000	0.0001773	1.16E-010	[illegible]
6	4.00	0.0000000	[illegible]	1.16E-012	19.994
7	5.00	0.0000000	0.0001733	1.15E-012	19.944
8	15.00	0.0000000	0.0001733	6.30E-015	21.723
9	46.00	0.0000155	0.0001694	6.47E-012	15.518
10	91.00	0.0000000	[illegible]	2.57E-015	21.979

AVERAGE Cs LI = 18.128

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.08	0.0000356	0.0000356	5.51E-009	10.922
2	0.29	0.0000359	0.0000715	2.16E-009	10.717
3	1.00	0.0000020	0.0000735	1.63E-010	[illegible]
4	2.00	0.0000199	0.0000934	2.20E-010	10.739
5	3.00	0.0000294	0.0001228	3.40E-010	10.166
6	4.00	0.0000312	0.0001540	3.02E-010	[illegible]
7	5.00	0.0000212	0.0001752	2.45E-010	10.159
8	15.00	0.0000249	0.0002001	2.21E-011	14.914
9	46.00	0.0000071	0.0002071	2.95E-012	16.201
10	91.00	0.0000179	0.0002250	4.59E-012	15.477

AVERAGE Co LI = 14.375

Table A-12

30 Wt% Mixed Bed Resin in Polyethylene
Sample: 84-7-12

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	0.08	0.0000000	0.0000000	1.39E-012	20.000
2	0.29	0.0000000	0.0000000	5.56E-013	19.902
3	1.00	0.0000810	0.0000810	1.03E-009	12.607
4	2.00	0.0000457	0.0001271	5.29E-010	12.016
5	3.00	0.0000000	0.0001271	1.15E-010	20.105
6	4.00	0.0000673	0.0001944	7.09E-012	12.302
7	5.00	0.0000000	0.0001944	1.16E-010	12.843
8	19.00	0.0001135	0.0003079	9.39E-011	13.661
9	47.00	0.0002031	0.0005110	1.03E-010	12.800
10	90.00	0.0002055	0.0007165	2.48E-011	14.027

AVERAGE Sr LI = 15.340

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.08	0.0000000	0.0000000	1.39E-012	20.000
2	0.29	0.0000000	0.0000000	5.56E-013	19.902
3	1.00	0.0000000	0.0000000	1.62E-012	20.407
4	2.00	0.0000000	0.0000000	1.16E-011	20.338
5	3.00	0.0000000	0.0000001	1.16E-012	20.125
6	4.00	0.0000000	0.0000001	1.16E-012	19.950
7	5.00	0.0000000	0.0000001	1.16E-012	19.843
8	19.00	0.0000000	0.0000001	6.27E-015	21.771
9	47.00	0.0000000	0.0000001	4.13E-015	21.911
10	90.00	0.0000243	0.0000244	6.26E-012	15.210

AVERAGE Cs LI = 19.943

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.08	0.0000177	0.0000177	2.46E-009	13.505
2	0.29	0.0000184	0.0000362	1.02E-009	13.371
3	1.00	0.0000122	0.0000484	2.18E-010	14.165
4	2.00	0.0000579	0.0001063	6.24E-010	12.672
5	3.00	0.0000234	0.0001297	3.26E-010	13.262
6	4.00	0.0000104	0.0001401	1.21E-010	13.921
7	5.00	0.0000216	0.0001617	2.52E-010	13.181
8	19.00	0.0000243	0.0001861	2.01E-011	14.993
9	47.00	0.0000513	0.0002473	2.55E-011	14.329
10	90.00	0.0000003	0.0002479	2.57E-015	21.957

AVERAGE Co LI = 14.552

Table A-13

25 Wt% Incinerator Ash in Polyethylene
Sample: 84-7-13

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.09	0.0000600	0.0000602	9.74E-009	10.451
2	0.29	0.0001075	0.0001675	7.25E-009	11.692
3	1.00	0.0000000	0.0001675	1.50E-013	20.426
4	2.00	0.0000000	0.0001675	1.18E-017	20.335
5	3.00	0.0000221	0.0002197	2.57E-010	10.413
6	4.00	0.0002170	0.0004169	2.51E-009	11.283
7	5.00	0.0000972	0.0005247	1.13E-009	11.365
8	18.00	0.0000922	0.0006170	9.22E-011	13.774
9	46.00	0.0000000	0.0006170	4.13E-015	21.910
10	91.00	0.0000080	0.0006250	2.12E-012	15.152

AVERAGE Sr LI = 15.[illegible]

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	0.0007124	0.0007124	1.00E-007	10.325
2	0.29	0.0002017	0.0009141	1.12E-008	11.287
3	1.00	0.0003501	0.0012611	2.59E-009	12.028
4	2.00	0.0000188	0.0011122	3.33E-010	13.417
5	3.00	0.0000223	0.0011429	2.59E-010	13.124
6	4.00	0.0000000	0.0011429	1.16E-013	19.955
7	5.00	0.0000240	0.0011655	2.94E-012	13.055
8	18.00	0.0002739	0.0014394	2.44E-012	12.930
9	46.00	0.0001125	0.0015502	4.57E-011	13.300
10	91.00	0.0005593	0.0021197	1.47E-010	12.472

AVERAGE Cs LI = 12.[illegible]

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.29	0.0000255	0.0000255	3.54E-009	12.229
2	0.29	0.0000427	0.0000691	2.37E-009	12.641
3	1.00	0.0000462	0.0001143	7.55E-012	13.095
4	2.00	0.0000723	0.0001866	8.27E-010	12.517
5	3.00	0.0000296	0.0002162	3.43E-010	12.161
6	4.00	0.0000432	0.0002595	5.01E-012	12.684
7	5.00	0.0000000	0.0002595	1.16E-013	19.946
8	18.00	0.0000432	0.0003027	3.55E-011	14.433
9	46.00	0.0000549	0.0003576	2.27E-011	14.431
10	91.00	0.0000477	0.0004053	1.23E-011	14.624

AVERAGE Co LI = 14.274

Table A-14

25 Wt% Incinerator Ash in Polyethylene
Sample: 84-7-14

STRONTIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	[illegible]	[illegible]	[illegible]	[illegible]
2	0.29	[illegible]	[illegible]	[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	19.00	[illegible]	[illegible]	[illegible]	21.781
9	47.00	[illegible]	[illegible]	[illegible]	[illegible]
10	92.00	[illegible]	[illegible]	[illegible]	[illegible]

AVERAGE OF LI = [illegible]

CESIUM LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	[illegible]	[illegible]	[illegible]	[illegible]
2	0.29	[illegible]	[illegible]	[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	0.0025354	1.75E-010	[illegible]
8	19.00	[illegible]	[illegible]	4.85E-012	[illegible]
9	47.00	[illegible]	[illegible]	[illegible]	[illegible]
10	92.00	[illegible]	[illegible]	1.42E-012	[illegible]

AVERAGE OF LI = [illegible]

COBALT LEACH DATA

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
1	0.08	[illegible]	0.0000430	[illegible]	[illegible]
2	0.29	[illegible]	[illegible]	[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	0.0001665	4.57E-010	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	19.00	[illegible]	[illegible]	[illegible]	14.900
9	47.00	[illegible]	[illegible]	7.54E-012	[illegible]
10	92.00	[illegible]	[illegible]	[illegible]	15.345

AVERAGE OF LI = 13.[illegible]

Table A-15

35 Wt% Incinerator Ash in Polyethylene
Sample: 84-7-15

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
STRONTIUM LEACH DATA					
1	0.09	[illegible]	[illegible]	[illegible]	[illegible]
2	0.29	[illegible]	[illegible]	[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	[illegible]
6	4.00	[illegible]	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

AVERAGE SR LI = [illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.08	[illegible]	[illegible]	[illegible]	[illegible]
2	0.29	[illegible]	[illegible]	[illegible]	[illegible]
3	1.00	[illegible]	[illegible]	[illegible]	[illegible]
4	2.00	[illegible]	[illegible]	[illegible]	[illegible]
5	3.00	[illegible]	[illegible]	[illegible]	11.439
6	4.00	0.0002147	[illegible]	[illegible]	[illegible]
7	5.00	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	46.00	0.0001505	[illegible]	[illegible]	11.497
10	91.00	[illegible]	[illegible]	[illegible]	[illegible]

AVERAGE CS LI = [illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.08	0.0002591	0.0001591	[illegible]	[illegible]
2	0.29	0.0002245	[illegible]	1.29E-009	[illegible]
3	1.00	0.0002510	[illegible]	5.74E-009	[illegible]
4	2.00	0.0001441	0.0007793	1.57E-009	12.213
5	3.00	0.0000974	[illegible]	1.31E-009	12.218
6	4.00	0.0002751	0.0009415	8.81E-010	12.190
7	5.00	0.0002563	[illegible]	5.52E-010	12.341
8	19.00	0.0001376	0.0011057	1.22E-010	13.424
9	46.00	0.0000633	0.0011245	2.85E-011	14.229
10	91.00	0.0000469	0.0011515	1.21E-011	14.625

AVERAGE CO LI = 1[illegible].663

APPENDIX B

Leaching Data for Modified Sulfur Cement Waste Forms

Key

Time = Cumulative Leaching Time, Days

IFL = Incremental Fraction Leached

CFL = Cumulative Fraction Leached

Rate = Incremental Leaching Rate Per Second

LI = Leaching Index

Table B-1

25 Wt% Sodium Sulfate in Modified Sulfur Cement
Sample: 85-8-1

[illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	91.00	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Table B-2

25 Wt% Sodium Sulfate in Modified Sulfur Cement
Sample: 35-8-2

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]					
[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]					

Table B-3

40 Wt% Sodium Sulfate in Modified Sulfur Cement
Sample: 85-8-3

[illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Table B-4

40 Wt% Sodium Sulfate in Modified Sulfur Cement
Sample: 85-8-4

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.08	0.0002162	0.0002361	7.91E-009	11.151
2	0.29	0.0017738	0.0020500	5.66E-008	9.446
3	1.00	0.0005521	0.0025421	3.51E-009	10.979
4	2.00	0.0017858	0.0044279	2.27E-008	9.774
5	3.00	0.0007987	0.0052266	9.14E-009	10.240
6	4.00	0.0025264	0.0077530	2.94E-008	9.191
7	5.00	0.0011249	0.0088579	1.26E-008	9.802
8	19.00	0.0094206	0.0182985	5.42E-009	9.790
9	45.00	0.0377775	0.0556000	1.34E-009	9.109
10	91.00	0.0446070	0.1002650	1.15E-009	9.779

AVERAGE Cs LI = 9.803

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.08	0.0001555	0.0001555	2.17E-008	11.679
2	0.29	0.0004567	0.0006145	2.55E-008	10.607
3	1.00	0.0001851	0.0007997	3.02E-009	11.924
4	2.00	0.0020777	0.0028774	2.35E-008	9.760
5	3.00	0.0002150	0.0030924	3.00E-009	11.301
6	4.00	0.0002280	0.0033204	2.75E-009	11.247
7	5.00	0.0002072	0.0035277	2.40E-009	11.257
8	19.00	0.0013277	0.0048554	1.17E-009	11.509
9	45.00	0.0064258	0.0112812	2.56E-009	10.377
10	91.00	0.0229905	0.0342719	5.91E-009	9.301

AVERAGE Co LI = 10.957

Table B-5

20 Wt% Incinerator Ash in Modified Sulfur Cement
Sample: 85-5-5

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
CESIUM LEACH DATA					
1	0.09	0.0005818	0.0005819	8.08E-009	10.519
2	0.29	0.0004668	0.0010465	2.59E-008	10.599
3	1.00	0.0006765	0.0017258	1.11E-008	10.792
4	2.00	0.0005480	0.0022738	6.34E-009	10.864
5	3.00	0.0005006	0.0027736	5.79E-009	10.731
6	4.00	0.0003941	0.0031676	4.56E-009	10.792
7	5.00	0.0003839	0.0035515	4.44E-009	10.784
8	18.00	0.0007982	0.0043498	7.11E-010	11.927
9	46.00	0.0022256	0.0065754	9.20E-010	11.241
10	91.00	0.0019195	0.0084949	4.34E-010	11.441

AVERAGE Cs LI = 10.962

#	Time(d)	IFL	CFL	Rate(1/sec)	LI
COBALT LEACH DATA					
1	0.09	0.0000033	0.0000033	4.56E-012	15.816
2	0.29	0.0000000	0.0000033	0.00E+000	--
3	1.00	0.0000056	0.0000096	1.07E-010	14.319
4	2.00	0.0000068	0.0000164	7.59E-011	14.729
5	3.00	0.0000082	0.0000246	9.49E-011	14.384
6	4.00	0.0000115	0.0000361	1.33E-010	13.863
7	5.00	0.0001279	0.0001640	1.40E-009	11.659
8	18.00	0.0001525	0.0003164	1.36E-010	13.365
9	46.00	0.0000099	0.0003263	4.07E-012	15.951
10	91.00	0.0000279	0.0003541	7.17E-012	15.117

AVERAGE Co LI = 14.314

Table B-6

20 Wt% Incinerator Ash in Modified Sulfur Cement
Sample: 85-5-6

#	Time(d)	IFL	CFL	Rate(1/sec)	LI

CESIUM LEACH DATA

#	TIME d	IFL	CFL	RATE 1/sec	LI
1	0.03	0.0002970	0.0002970	4.13E-008	11.115
2	0.29	0.0002828	0.0004999	1.13E-008	11.[illegible]
3	1.00	0.0002927	0.0007925	4.78E-009	11.5[illegible]
4	2.00	0.0002608	0.0010533	3.32E-009	11.54[illegible]
5	3.00	0.0001507	0.0012040	1.74E-009	11.788
6	4.00	0.0001420	0.0013460	1.64E-009	11.681
7	5.00	0.0001[illegible]	0.0014591	1.40E-009	11.725
8	18.00	0.0012545	0.0027136	1.66E-009	11.22[illegible]
9	45.00	0.0005427	0.0029563	2.56E-010	12.[illegible]
10	91.00	0.0004926	0.0034595	1.27E-010	12.[illegible]

AVERAGE Cs LI = 11.688

COBALT LEACH DATA

#	TIME d	IFL	CFL	RATE 1/sec	LI
1	0.03	0.0000155	0.0000155	2.15E-009	13.[illegible]
2	0.29	0.0000042	0.0000197	3.74E-010	14.881
3	1.00	0.0000028	0.0000225	4.59E-011	15.558
4	2.00	0.0000155	0.0000379	1.79E-010	13.[illegible]
5	3.00	0.0000042	0.0000421	4.85E-011	14.[illegible]
6	4.00	0.0000155	0.0000575	1.79E-010	13.818
7	5.00	0.0001054	0.0001578	1.22E-009	11.340
8	18.00	0.0000[illegible]	0.0002[illegible]	3.58E-011	14.555
9	45.00	0.0001770	0.0003[illegible]	7.30E-011	13.457
10	91.00	0.0000[illegible]	0.0004157	1.21E-011	14.[illegible]

AVERAGE Co LI = 14.11[illegible]

Table B-7

40 Wt% Incinerator Ash in Modified Sulfur Cement
Sample: 85-5-7

#	Time(d)	IFL	CFL	Rate(1/sec)	LI

CESIUM LEACH DATA

#	TIME(d)	IFL	CFL	RATE(1/sec)	LI
1	0.08	0.0001759	0.0001759	2.44E-008	11.519
2	0.29	0.0002427	0.0004165	1.34E-008	11.127
3	1.00	0.0004995	0.0009162	8.16E-009	11.219
4	2.00	0.0004228	0.0013395	4.92E-009	11.269
5	3.00	0.0003110	0.0016529	3.60E-009	11.129
6	4.00	0.0002750	0.0019259	3.18E-009	11.057
7	5.00	0.0003215	0.0022475	3.72E-009	10.801
8	19.00	0.0017080	0.0039555	1.50E-009	11.229
9	46.00	0.0016045	0.0055600	5.63E-010	11.488
10	91.00	0.0013810	0.0069410	3.55E-010	11.690

AVERAGE Cs LI = 11.214

COBALT LEACH DATA

#	TIME(d)	IFL	CFL	RATE(1/sec)	LI
1	0.08	0.0000011	0.0000011	1.57E-010	15.824
2	0.29	0.0000028	0.0000039	4.59E-010	14.222
3	1.00	0.0000059	0.0000098	1.13E-010	14.727
4	2.00	0.0000110	0.0000161	1.01E-010	14.219
5	3.00	0.0000083	0.0000244	7.28E-011	14.499
6	4.00	0.0000075	0.0000319	6.71E-011	14.192
7	5.00	0.0001148	0.0001467	1.73E-009	11.716
8	19.00	0.0000332	0.0001799	2.27E-011	14.383
9	46.00	0.0000144	0.0001943	5.96E-012	15.581
10	91.00	0.0000019	0.0001962	4.94E-013	17.421

AVERAGE Co LI = 14.723

Table B-8

40 wt% Incinerator Ash in Modified Sulfur Cement
Sample: 35-5-8

#	Time(d)	IFL	CFL	Rate(1/sec)	LI

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]