Engineered Sorbent Barriers for Low-Level Waste Disposal

**H. D. Freeman
S. J. Mitchell
J. L. Buelt**

December 1986

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government of any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or Battelle Memorial Institute.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

ENGINEERED SORBENT BARRIERS
FOR LOW-LEVEL WASTE DISPOSAL

H. D. Freeman
S. J. Mitchell
J. L. Buelt

December 1986

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

ACKNOWLEDGMENTS

The authors would like to thank the following individuals for their contributions to this report: Monty Elmore for initial laboratory studies; Lane Bray, Rich Peters, Jack Ryan, Jeff Serne, and John Swanson for consultation; Mike Longaker, Tom Hinkle, and Bill Riemath for performing experimental work; Renie McVeety and Janna Shaw for editing; and Benita Gottsch, Shirley Flink, Debra Perez, and Paulette Goodenough for typing the final manuscript.

SUMMARY

The Engineered Sorbent Barriers Program at Pacific Northwest Laboratory is investigating sorbent materials to prevent the migration of soluble radionuclides from low-level waste sites. These materials would allow water to pass, preventing the bathtub effect at humid sites. Laboratory studies identified promising sorbent materials for three key radionuclides: for cesium, greensand; for cobalt, activated charcoal; and for strontium, synthetic zeolite or clinoptilolite. Mixtures of these sorbent materials were tested in 0.6-m-diameter columns using radioactive leachates. To simulate expected worst-case conditions, the leachate solution contained the radionuclides, competing cations, and a chelating agent and was adjusted to a pH of 5. A sorbent barrier comprised of greensand (1 wt%), activated charcoal (6 wt%), synthetic zeolite (20 wt%), and local soil (73 wt%) achieved the decontamination factors necessary to meet the regulatory performance requirements established for this study. Sorbent barriers can be applied to shallow-land burial, as backfill around the waste or engineered structures, or as backup to other liner systems.

CONTENTS

ACKNOWLEDGMENTS	iii
SUMMARY	v
INTRODUCTION	1
LABORATORY STUDIES	3
MATERIALS IDENTIFICATION	3
SELECTION CRITERIA	4
Relative Cost-Effectiveness	4
Long-Term Stability	5
Selectivity	5
Availability	5
BATCH CONTACT STUDIES	6
FORMULATION TESTING	10
SELECTION OF ADDITIONAL STRONTIUM SORBENTS	12
Strontium Precipitants	14
Additional Sorbent Materials	15
Additional Batch Contact Tests	15
EFFECT OF COMPETING ION CONCENTRATION	18
EFFECT OF pH	21
ENGINEERING EVALUATIONS OF SELECTED SORBENT BARRIERS	25
TEST EQUIPMENT	25
TEST CONDITIONS	27
ENGINEERING EVALUATIONS--FIRST SERIES	28
ENGINEERING EVALUATIONS--SECOND SERIES	32
RECOMMENDATIONS FOR FUTURE WORK	37

REFERENCES	39
APPENDIX A - RESULTS OF LABORATORY STUDIES	A.1
APPENDIX B - RESULTS OF ENGINEERING EVALUATIONS	B.1

FIGURES

1	Concentration Versus Time Curves for Batch Contact Tests of Sorbent Barrier Materials	7
2	Example Results of Tests of Sorbent Barrier Formulations	13
3	Plan View of Equipment for Sorbent Barrier Engineering Evaluations ...	26
4	Exposure Column Used in Engineering Evaluations of Selected Sorbent Barrier Materials	27
5	First Series of Engineering Evaluations--Decontamination Factors for Strontium	29
6	First Series of Engineering Evaluations--Decontamination Factors for Cobalt	30
7	First Series of Engineering Evaluations--Core Analysis for Column A ..	31
8	First Series of Engineering Evaluations--Core Analysis for Column B ..	31
9	First Series of Engineering Evaluations--Core Analysis for Column C ..	32
10	Second Series of Engineering Evaluations--Decontamination Factors for Strontium	34
11	Second Series of Engineering Evaluations--Decontamination Factors for Cobalt	34
12	Second Series of Engineering Evaluations--Core Analysis for Column A	35
13	Second Series of Engineering Evaluations--Core Analysis for Column B	36
14	Second Series of Engineering Evaluations--Core Analysis for Column C	36

TABLES

1	Soluble Water Limits and Reduction Factors for Selected Radionuclides	5
2	Distribution Coefficients for Candidate Sorbent Materials, mL/g	9
3	Sorbent Barrier Formulations and Relative Costs	11
4	Composition of Leachates Used in Formulation Tests	12
5	Identification Codes for Materials Tested for Strontium Kd	16
6	Kd Values for Strontium Sorbent Materials, mL/g	17
7	Sorbent Materials Used in Effect of Calcium Concentration Tests	19
8	Effect of Calcium Concentration on Strontium Sorption	20
9	Effect of Calcium Concentration on Cesium Sorption	21
10	Effect of Calcium Concentration on Cobalt Sorption	22
11	Effect of pH on Kd Values at a Calcium Concentration of 100 ppm	23
12	Effect of pH on Kd Values at a Calcium Concentration of 1000 ppm	24

INTRODUCTION

This paper describes experimental work on technology for restricting the migration of radionuclides from low-level wastes using sorbent and ion-exchange materials as engineered barriers. Unlike impermeable barriers, sorbent barriers allow moisture to pass while selectively sorbing contaminants. Their sorptive behavior is similar to the ion-exchange properties that many soils possess for certain radionuclides. However, the degree of sorption of radionuclides is dependent on the type of soil, the specific radionuclides, and the presence of competing ions and organics. In many cases, appropriate soils are not available and/or the radionuclides form mobile complexants. Therefore, the use of sorptive soil additives as radionuclide barriers is recommended to prevent radionuclide migration from the waste site.

With relatively impermeable barriers such as membranes or clays, the rate of moisture infiltration could exceed the rate of evapotranspiration and seepage, producing a "bathtub" effect by eventually filling the waste site with water. The resultant over-saturated conditions can create difficulties with waste leachability and waste site stability. Water containing leached radionuclides can spill over the top of the disposal trench and flow away from the site due to the "bathtub" effect. A leachate collection system with continuous maintenance would be required to ensure prevention of the "bathtub" effect.

Sorbent barriers are applicable to a variety of low-level waste isolation situations because of their advantageous radionuclide retention and moisture permeability properties. They may be used as the primary barrier for low-level waste disposal, as a backup to another liner system, or as a backfill around the waste or an engineered structure. Sorbent barrier technology is applicable not only for shallow land burial sites, but also for engineered structures and for deeper disposal practices. Sorbent materials could also be added to the waste itself to improve the waste form. Radionuclides would be more tightly bound in the waste form due to the presence of the sorbent materials.

The experimental work discussed in this paper was directed at the identification and evaluation of sorbent materials for three radionuclides of major concern in defense low-level wastes: cesium-137 (^{137}Cs), cobalt-60 (^{60}Co) and

strontium-90 (^{90}Sr). The work was conducted over a two-year period in two major phases. The first phase, completed in FY 1985, consisted of laboratory-scale studies of sorbent materials. The second phase, completed in FY 1986, consisted of engineering evaluations of four sorbent barrier formulations in large-scale columns.

LABORATORY STUDIES

The objective of the laboratory studies was to: 1) identify potential sorbent materials; 2) develop criteria for selecting materials for testing; 3) obtain distribution coefficients (Kds) from batch contact studies; and 4) test the effectiveness of barrier formulations.

MATERIALS IDENTIFICATION

During the laboratory studies, several references were reviewed. A number of references cited distribution coefficients for various sorbent materials and soils. However, data pertinent to the conditions of low-level waste sites for all three radionuclides of greatest concern (Cs, Co, and Sr) at defense sites were not apparent. However, some data on individual radionuclides of concern were available to help select promising materials for the sorbent barriers (Mercer et al. 1978; Schultz 1980; Swanson 1984; Winslow 1986). The sorbent materials originally considered for testing were:

- greensand (glauconite)
- synthetic zeolite, IE-95
- synthetic zeolite, IE-96
- synthetic zeolite, X-61
- synthetic zeolite, A-51
- ion-exchange resin Dowex 21-K
- insoluble starch xanthate
- decomplexant DX-2000
- sodium titanate
- carbon sorbate
- activated charcoal
- natural zeolite, clinoptilolite -3
- natural zeolite, clinoptilolite -12
- natural zeolite, clinoptilolite -20
- ion-exchange resin (IRC-718)
- ion-exchange resin (ARC-359)
- ion-exchange resin (Cs-100)

- vermiculite
- Indian red pottery clay
- ion-exchange resin (XFS-43271.00).

The relative merits of these materials have been briefly discussed by Freeman, Buelt and Hartley (1984). Natural and synthetic zeolites were obvious choices as sorbent materials because they possess desirable properties such as high-exchange capacity, selectivity, and durability. In addition they have been used successfully in the past as ion-exchange material for processing waste water containing radioactive Cs and Sr (Winslow 1980).

SELECTION CRITERIA

Before the results of the laboratory tests could be analyzed, a set of selection criteria had to be developed to rank the relative performance of the sorbent barrier formulations developed in this study. The four criteria are discussed below:

- relative cost-effectiveness
- long-term stability
- selectivity for radionuclides over more prevalent cations
- availability.

Relative Cost-Effectiveness

The relative cost-effectiveness criterion was based on the cost of the sorbent material required to increase the effective K_d of the soil/sorbent material barrier to a value sufficient to meet the U.S. Nuclear Regulatory Commission (NRC) 10 CFR Part 20, Appendix B, Table II water concentrations for soluble contaminants. The limits and reduction factors required to meet these limits are shown in Table 1. The calculations were based on a 30-cm barrier and a leachate composed of 1 $\mu\text{Ci/L}$ each of ^{137}Cs , ^{60}Co and ^{90}Sr (Robertson 1982). A fixed-bed model with sorption by linear equilibrium ion exchange (Winslow 1980) was used to calculate the concentration of the leachate passing through the barrier.

TABLE 1. Soluble Water Limits and Reduction Factors
for Selected Radionuclides^(a)

<u>Radionuclide</u>	<u>NRC Table II Limit ($\mu\text{Ci/mL}$)</u>	<u>Reduction Factor^(b)</u>
^{60}Co	5×10^{-5}	20
^{137}Cs	2×10^{-5}	50
^{90}Sr	3×10^{-7}	3333

(a) NRC 10 CFR Part 20, Appendix B, Table II.

(b) Simulated leachate concentration, divided
by NRC Table II limit.

Long-Term Stability

The ion-exchange properties of the sorbent barrier must not degrade significantly with time. A period of about 300 years is necessary to allow radionuclides such as ^{90}Sr and ^{137}Cs to decay to safe levels; after 300 years, the activity of the waste would be reduced by a factor of more than 1000.

Selectivity

Because the mass of the radionuclides in low-level waste is quite small, it is unlikely that the sorbent capacity of the engineered barrier will be exceeded by sorption of the radionuclides. However, if the sorbent barrier also sorbs other more abundant species such as iron or calcium, these species could load the barrier until it becomes ineffective as a radionuclide sorbent. This consideration is the basis for the selectivity criterion. This criterion will be applied to the sorbent barrier evaluations where the effects of competing ions are being studied.

Availability

The candidate sorbent material must be available in sufficient quantities for use at low-level waste disposal sites. Other sorbent materials that could be generated in larger quantities, pending a demand for the material, will also be considered.

The selection criteria were applied, where appropriate, to the candidate sorbent materials to determine if some materials could be eliminated from

consideration before laboratory testing began. The long-term stability criteria were used to eliminate carbon sorbates, decomplexant DX-2D00 and insoluble starch xanthate; none of these materials was considered to be chemically stable for 300 years. Two ion-exchange resins, Cs-100 and ARC-359, were eliminated because they are no longer available in large quantities and are not considered stable for 300 years. The remaining 15 materials were used for the batch contact laboratory studies.

BATCH CONTACT STUDIES

The batch contact studies were designed to obtain Kd values for the three radionuclides relative to the 15 sorbent materials selected for testing. Distribution coefficients were obtained for two different simulated low-level waste leachate compositions: with and without ethylenediaminetetracetic acid (EDTA), a chelating agent. The simulated leachates contained approximately 1 $\mu\text{Ci/L}$ each of ^{137}Cs , ^{60}Co , and ^{85}Sr at pH 5 (Robertson 1982). The standard leachate contained no EDTA (complexant-forming organic), but the other leachate contained 1 ppm EDTA. Strontium-85 was used in the simulated leachate instead of ^{90}Sr to allow all three radionuclides to be measured simultaneously using gamma spectroscopy.

To derive the Kd values, 200 mL of simulated leachate were placed in contact with 10 g of sorbent material. A wrist shaker was used to gently mix the leachate and sorbent materials. The shaker was stopped periodically, 20 mL of solution were sampled and centrifuged, and the solution was analyzed for radionuclides. Radionuclide concentrations were plotted as a function of time to determine the equilibrium solution concentration. The Kd values were calculated from the equilibrium net counts by the following equation:

$$K_d (\text{mL/g}) = \frac{(\text{volume solution})}{(\text{wt material})} \frac{(\text{initial net counts} - \text{final net counts})}{(\text{final net counts})} \quad (1)$$

Solution concentration graphs for the more promising sorbent materials along with local and Dak Ridge, Tennessee, soils are shown in Figure 1. A compilation of calculated Kd values for all of the sorbent materials tested in the first phase of the laboratory studies are presented in Table 2. Some of the Kd

FIGURE 1. Concentration Versus Time Curves for Batch Contact Tests of Sorbent Barrier Materials

FIGURE 1. (contd)

TABLE 2. Distribution Coefficients for Candidate Sorbent Materials, mL/g

Material	Code	Strontium Kd Value	Cesium Kd Value	Cobalt Kd Value
Activated charcoal	AC(a)	917	8	1143
	AC(b)	2010	14	4540
Amberlite	AMBR(a)	1250	49	6
	AMBR(b)	2050	31	1
A-51 zeolite	A51(a)	2030	53	72
	A51(b)	9790	85	3
Clinoptilolite-3	CL3(a)	241	156	11
	CL3(b)	317	0	1
Clinolite-12	CL12(a)	105	154	15
	CL12(b)	139	169	0
Clinolite-20	CL20(a)	200	88	29
	CL20(b)	268	76	1
Dowex 21-K	D21K(a)	2	1	1
	D21K(b)	20	43	1128
Dowex XFS	DXFS(a)	778	9820	9040
	DXFS(b)	333	1890	2
Greensand	GS(a)	4	9950	4
	GS(b)	4	9490	1
Local soil (coarse)	HSC(a)	84	171	98
	HSC(b)	88	228	1
Local soil (fine)	HSF(a)	68	115	72
	HSF(b)	72	180	1
IE-95 zeolite	IE95(a)	890	249	292
	IE95(b)	1020	370	0
IE-96 zeolite	IE96(a)	305	187	28
	IE96(b)	458	307	1
Oak Ridge soil	ORS(a)	1265	9950	1143
	ORS(b)	970	9490	14
Red clay	RC(a)	121	4905	4515
	RC(b)	127	1890	2
Sodium titanate	NaTi(a)	75	81	17
	NaTi(b)	317	180	2
Vermiculite	VER(a)	384	139	141
	VER(b)	402	136	1
X-61 zeolite	X61(a)	6290	51	155
	X61(b)	2050	49	0

(a) Standard leachate (1 μ Ci/L each of cesium, cobalt, and strontium).

(b) Leachate with 1 ppm EDTA.

values shown may be smaller than the actual values. The detection limit of the gamma spectroscopy system was typically 6 pCi/mL for ^{85}Sr , 10 pCi/mL for ^{137}Cs , and 1 pCi/mL for ^{60}Co . If the contacted leachate concentrations were below these detection limits, the actual Kd would be greater than those shown.

The Kd values for the worse-case EDTA leachate and the unit costs of the sorbent materials were used to calculate the most cost-effective barrier formulations that would result in a leachate concentration past the engineered barrier below the NRC Table II limits. The leachate concentrations exiting the barrier were calculated using the model reported in Winslow (1980). The overall effective Kd for the barrier was assumed to be a weighted average of the Kds for each of the components in the barrier. More complicated models incorporating nonlinear effects may be used in future barrier design.

Six sorbent barrier formulations were selected for laboratory testing. The barrier formulations and approximate material costs per m^3 of barrier are presented in Table 3. The total installed costs of the barriers have not been estimated at this stage of the study. Activated charcoal was the only sorbent material that was effective in sorbing ^{60}Co complexed with EDTA. Hence, to meet the NRC Table II limits, it was included in each formulation.

FORMULATION TESTING

The formulation tests were designed to test the effectiveness of the barrier formulations on a small scale under a variety of conditions. The major parameters included the effect of increased radionuclide concentration and the addition of competing ions to simulate the expected worst-case conditions at a low-level waste site. Four leachates were used to qualitatively investigate the effects of different radionuclide and competing ion concentrations. The compositions of the four simulated leachates are presented in Table 4.

For the formulation tests, each of the six sorbent barrier formulations listed in Table 3 was packed into four 30-mL syringes and placed on a mechanical extractor. The mechanical extractor pulled simulated leachate solutions through the barriers at a constant rate. The solutions were periodically sampled, centrifuged, and analyzed.

TABLE 3. Sorbent Barrier Formulations and Relative Costs

<u>Cost Ranking</u>	<u>Component</u>	<u>Weight Fraction</u>	<u>Cost, \$/m³</u>
1	Local soil	0.88	777
	Activated charcoal	0.06	
	Greensand	0.01	
	A51 zeolite	0.05	
2	Local soil	0.85	777
	Activated charcoal	0.06	
	Red pottery clay	0.05	
	A51 zeolite	0.04	
3	Local soil	0.72	1165
	Activated charcoal	0.26	
	Greensand	0.02	
4	Local soil	0.68	1165
	Activated charcoal	0.26	
	Red pottery clay	0.06	
5	Local soil	0.69	1942
	Activated charcoal	0.25	
	Dowex XFS resin	0.06	
(a)	Dak Ridge soil	0.96	5
	Activated charcoal	0.04	

(a) Although local soil was chosen for use in the formulation tests, a formulation using Oak Ridge soil was included for comparison.

Results of the formulation tests are shown in Figure 2, illustrating the effectiveness of the barriers under conditions of low competing ions. No detectable radionuclides broke through the barriers even after greater than 150 pore volumes. However, the sorbent barriers were not able to sorb enough strontium from solution in the presence of high competing ions. The many orders-of-magnitude greater calcium (Ca) concentration saturated the sorbent materials responsible for the sorption of Sr. The chemistry of Sr and Ca are so similar that it is unlikely the barriers can be made specific for Sr when Ca is present.

TABLE 4. Composition of Leachates Used in Formulation Tests

Component	Leachate 1	Leachate 2	Leachate 3	Leachate 4
^{60}Co , $\mu\text{Ci/L}$	1	1	100	100
^{85}Sr , $\mu\text{Ci/L}$	1	1	100	100
^{137}Cs , $\mu\text{Ci/L}$	1	1	100	100
Ca^{++} , ppm	10	1000	10	1000
Mg^{+} , ppm	10	1000	10	1000
Na^{+} , ppm	10	1000	10	1000
Fe^{++} , ppm ^(a)	~1	~1	~1	~1
EDTA, ppm	1	1	1	1
pH	5	5	5	5

(a) The Fe ions precipitate at a pH of 5, resulting in a concentration of 1 ppm.

Two barriers were selected for testing in the engineering evaluation studies. Because the effectiveness of all of the barrier formulations tested was similar, cost-effectiveness was used as the selection criteria. The two barriers are:

1. 6 wt% activated charcoal, 1 wt% greensand, 5 wt% A-51 synthetic zeolite, and 88 wt% local soil.
2. 6 wt% activated charcoal, 5 wt% red pottery clay, 4 wt% A-51 zeolite, and 85 wt% local soil.

SELECTION OF ADDITIONAL STRONTIUM SORBENTS

It was apparent from the results of the formulation tests that the presence of high concentrations of Ca in the low-level waste leachate would significantly reduce the effectiveness of the sorbent barrier for Sr removal. Therefore, a laboratory study was launched in FY 1986 to identify additional methods and materials for removal of Sr from the leachate. The new materials would be used in two additional engineering-scale column tests to be run in

FIGURE 2. Example Results of Tests of Sorbent Barrier Formulations

FY 1986. The approach was to investigate new sorbent materials not tested previously and to examine Sr precipitants that could be used as part of a precipitation/sorption barrier.

Strontium Precipitants

Several Sr salts, including sulfides, di-basic phosphate, and phosphate/fluoride, are relatively insoluble. Hence, the objective of the precipitation barrier would be to precipitate the Sr as one of these insoluble salts. The problem with implementing this type of barrier is providing a source of the precipitating anion over the 300-year life of the barrier. One approach is to use a precipitating anion that is only slightly soluble. Unfortunately, if the salt is too insoluble, there may not be a high enough concentration of precipitating anion to cause precipitation to occur. A second approach is to bind or sorb a more soluble form of the precipitant onto a substrate that will prevent the precipitant from being washed from the barrier with time.

It seemed unlikely that a slightly soluble precipitant, effective over the lifetime of the barrier, could be found. The second approach mentioned above was chosen for further investigation. The substrates selected were activated charcoal and clinoptilolite, due to their availability, cost, and sorption properties. The reagents selected to sorb onto the substrates were K_2HPO_4 , Na_2S , and equal molar ratios of $Na_3PO_4 \cdot 12H_2O$ and KF . These reagents were selected to form $SrHPO_4$, SrS , and $Sr_5(PO_4)_3F$, respectively.

Two methods were used to sorb the reagents onto the substrates. The first method was to soak the substrates in a saturated solution of the precipitant for a minimum of 24 hours. It was hoped that the reagent would diffuse into the pores of the substrate and become immobile. The second approach was to force the precipitant into the pores of the substrate under pressure. The substrate was placed into a pressure vessel filled with a saturated solution of the precipitant and placed under 95 psi pressure for two hours. The resultant precipitant was air-dried and then washed with distilled water to remove crystals of salt from the surface of the substrate.

Additional Sorbent Materials

Review of additional literature and discussions with radionuclide removal experts identified eight new materials with potential for effective sorption of Sr. These materials (and their identification codes) are -20 mesh aluminum hydroxide (AH), AH heated to 400°C for four hours, zirconium phosphate (ZP), titanium phosphate (TiP), tin phosphate (SnP), poly antimonite acid (PAA), manganese oxide (MnO), and titanium A (TiA). Many of these materials have shown promise as Sr getters in the limited use they have had. Their major drawback is that they are quite costly when compared to the sorbent materials tested up to this point.

Additional Batch Contact Tests

The Kd values for the materials discussed above were determined using a similar procedure described for the FY 1985 batch contact studies. Three changes were made to improve the range of Kds that could be measured and to simplify the experimental procedure: 1) the amount of material used in each test was reduced from 10 grams to 1 gram to increase the maximum measurable Kd by an order of magnitude; 2) the materials and leachates were contacted for 72 hours before sampling instead of periodically sampling and analyzing solutions; this resulted in a significant reduction in the number of samples that had to be analyzed; 3) the solutions were filtered through a 0.45 µm millipore filter instead of using a centrifuge. The smaller solids sample size made this feasible. The simulated leachate used in the tests contained competing ions, and consisted of ~1 µCi/L ⁸⁵Sr, 1 ppm EDTA, 1000 ppm Ca, 1000 ppm Na, 1000 ppm Mg, and ~1 ppm Fe, adjusted to a pH of approximately 5. This leachate was selected to represent the expected worst-case conditions at a low-level waste site.

A total of 28 sorbent materials, including 7 materials previously tested, were tested in duplicate using the modified batch contact procedure. The sorbent materials tested and their identification codes are listed in Table 5. The precipitants that were sorbed onto substrates were tested in the same manner as the other sorbent materials. The Kd values are based on the total

TABLE 5. Identification Codes for Materials Tested for Strontium Kd

Code	Material
<u>Previously Tested Materials</u>	
CL1	Clinoptilolite from Oregon deposit
CL2	Clinoptilolite from Texas deposit
CL3	Clinoptilolite from Arizona deposit
AC	Activated charcoal
A51	A51 synthetic zeolite
IE95	IE95 synthetic zeolite
IE96	IE96 synthetic zeolite
<u>Precipitants on Substrates</u>	
ACP	Activated charcoal soaked in K_2HPO_4
ACPP	Activated charcoal pressurized with K_2HPO_4
ACS	Activated charcoal soaked in Na_2S
ACSP	Activated charcoal pressurized with Na_2S
ACPF	Activated charcoal soaked in $Na_3PO_4 \cdot 12H_2O$ and KF
ACFPF	Activated charcoal pressurized with $Na_3PO_4 \cdot 12H_2O$ and KF
CLP	Clinoptilolite soaked in K_2HPO_4
CLPP	Clinoptilolite pressurized with K_2HPO_4
CLS	Clinoptilolite soaked in Na_2S
CLSP	Clinoptilolite pressurized with Na_2S
CLPF	Clinoptilolite soaked in $Na_3PO_4 \cdot 12H_2O$ and KF
CLFPF	Clinoptilolite pressurized with $Na_3PO_4 \cdot 12H_2O$ and KF
<u>New Sorbent Materials</u>	
AH	Aluminum hydroxide (-20 mesh)
AHH	Aluminum hydroxide heated to 400°C for 4 h
ZP	Zirconium phosphate
TiP	Titanium phosphate
SnP	Tin phosphate
PAA	Poly antimonite acid
MnO	Manganese oxide
TiA	Titanium A
KP	Potassium phosphate

weight of the precipitant and substrate because the effective Kd of the material is needed to design the sorbent barriers. Results of the tests are presented in Table 6.

Of the 28 materials tested for Sr sorption, only three materials stand out as exceptionally effective: A51 synthetic zeolite, PAA, and MnO. Unfortunately, the two most effective materials, PAA and MnO, are prohibitively expensive at this time. The forms of the materials used for these tests are only produced in Belgium in limited quantities. However, the cost of the material

TABLE 6. Kd Values for Strontium Sorbent Materials, mL/g

Code	Run 1		Run 2	
	pH	Kd	pH	Kd
CL1	6.16	60.7	6.19	92.1
CL2	6.09	60.0	6.42	84.1
CL3	6.98	45.1	7.84	58.9
AC	9.28	0.0	9.38	23.7
A51	7.05	288.2	8.64	310.8
IE95	6.88	43.5	7.32	71.7
IE96	7.41	65.1	7.72	74.0
ACP	9.13	7.1	9.16	19.7
ACPP	7.74	5.1	7.75	22.1
ACS	8.85	4.9	8.60	6.5
ACSP	9.09	0.0	9.10	29.2
ACPF	9.13	2.5	9.21	18.5
ACFPF	8.91	16.5	8.93	23.2
CLP	6.79	44.8	6.88	47.9
CLPP	6.84	56.3	6.82	48.7
CLS	8.23	64.1	8.25	60.1
CLSP	8.27	71.2	8.18	71.3
CLPF	8.41	61.1	8.41	59.0
CLPFPP	8.38	69.9	8.34	68.4
AH	7.80	7.2	7.79	23.8
AHH	7.63	12.7	7.68	32.8
ZP	2.25	13.7	2.22	30.0
TiP	2.13	6.2	2.12	31.9
SnP	2.97	31.4	2.97	54.6
PAA	1.96	432.7	1.94	531.5
MnO	7.00	514.4	7.35	506.4
TiA	2.68	60.1	2.67	67.0
KP	6.94	69.7	7.02	84.1

could potentially be reduced substantially if there were sufficient demand. The A51 zeolite is much more reasonable in cost and should be included in future barrier designs. Because of its extremely low cost and fair Kd value, clinoptilolite should also be considered as an effective barrier for Sr.

The precipitation materials did not work as well as hoped. In fact, the presence of the precipitant did not significantly enhance the Kd of the substrate material over what would normally be found. This lack of performance could be due to: a) the particular reagents selected for use in the study or b) more fundamental problems in precipitating very small concentrations of ions from solution.

EFFECT OF COMPETING ION CONCENTRATION

The simulated leachates used in the tests run in FY 1985 and early FY 1986 were designed to simulate the worst expected conditions of competing ions in solution. In reality, these conditions would probably not be found at a significant number of low-level waste sites. To understand the performance of the sorbent barriers under less severe conditions of competing ions, a set of batch contact tests were run where the Ca concentration was reduced to 100 ppm and 10 ppm. For comparison, an additional set of tests were also run at the standard conditions of 1000 ppm Ca. For these tests the other competing ions (Na, Mg, and Fe) remained the same as used previously (1000 ppm, 1000 ppm, and 1 ppm respectively). The batch contact experimental procedure used was the same as that used for the Sr Kd tests in FY 1986. Six sorbent materials were chosen for testing based on previous Kd results. In addition, three natural clays were tested to obtain more data on natural materials. The materials used in these tests are listed in Table 7.

Three series of duplicate tests were run using the three different leachates described above (10 ppm Ca, 100 ppm Ca, and 1000 ppm Ca). The materials were contacted with the leachates for 72 hours with gentle continuous shaking. The samples were then filtered through a 0.45- μ m millipore filter and 20 mL were placed in a vial for analysis. Results of the Kds calculated from the analytical data are presented in Tables 8 through 10.

TABLE 7. Sorbent Materials Used in Effect of Calcium Concentration Tests

<u>Sample ID</u>	<u>Material</u>
AC	Activated charcoal
CaB	Calcium bentonite
CaM	Calcium montmorillonite
CL1	Clinoptilolite from Oregon deposit
GS	Greensand
IRC	Indian red pottery clay
NaM	Sodium montmorillonite
LS	Local soil
A51	A51-zeolite

In general, increasing Ca concentration results in decreasing Sr Kd values for all materials tested. The magnitude of the decrease, however, varies significantly between materials. For instance, at a Ca concentration of 10 ppm, activated charcoal is a fairly good sorbent for Sr with an average Kd of 88.1 mL/g. When the Ca concentration is increased to 1000 ppm, the Kd value for activated charcoal decreases to 8.6 mL/g, by a factor of about 10. On the other hand, A51 synthetic zeolite decreases by a factor of almost 17 for the same increase in Ca concentration. The decrease in Kd for A51 zeolite is greater from 100 ppm Ca to 1000 ppm Ca than the decrease from 10 ppm Ca to 100 ppm Ca. These data show that the sorbent barriers will be much more effective for Sr removal under expected average Ca leachate concentrations, less than 100 ppm.

The effect of increased Ca concentration was not as dramatic for Cs and Co as it was for Sr. Some noteworthy examples of materials that showed a slight decrease in Cs Kd with increase in Ca concentration from 10 to 1000 ppm are a) clinoptilolite with a 28% decrease, b) Indian red pottery clay with a 48% decrease, and c) local soil with a 42% decrease. These differences in Kd are not significant, in terms of barrier design. This is due to their high Kd values and relatively low decontamination factors (Df) required to meet the

TABLE 8. Effect of Calcium Concentration on Strontium Sorption

Sample ID	Kd, mL/g		
	10 ppm	100 ppm	1000 ppm
AC-A	91.0	24.7	7.4
AC-B	85.2	29.4	9.7
CaB-A	57.4	26.5	10.8
CaB-B	58.5	20.7	6.3
CaM-A	61.7	12.3	4.8
CaM-B	50.4	20.0	3.2
CL-A	432.7	161.8	67.1
CL-B	363.0	167.3	59.9
GS-A	49.7	8.1	2.7
GS-B	45.6	3.7	7.9
IRC-A	51.3	17.1	3.3
IRC-B	54.5	14.5	1.1
NaM-A	53.8	13.4	4.8
NaM-B	51.8	19.0	5.7
LS-A	60.3	18.6	-1.0
LS-B	53.9	9.3	5.8
A51-A	4582.7	1762.2	271.2
A51-B	4139.8	1676.7	247.0

A and B designate duplicate runs.

criteria for this study. The decontamination factor (Of) is the ratio of the initial concentration of a radionuclide in the leachate to the concentration of the radionuclide exiting the barrier.

The effect of increased Ca concentration on Co Kd values follows a behavior that is difficult to explain. Several materials including calcium bentonite, Indian red pottery clay, sodium bentonite, local soil, and A51 zeolite show an increase in Kd when the Ca concentration is increased from 10 ppm to 100 ppm. However, the materials show a relatively sharp drop in Kd when the Ca concentration in the leachate is increased from 100 ppm to

TABLE 9. Effect of Calcium Concentration on Cesium Sorption

Sample ID	Kd, mL/g		
	10 ppm	100 ppm	1000 ppm
AC-A	41.3	24.7	30.5
AC-B	31.8	32.2	27.6
CaB-A	2083.3	1928.0	1655.8
CaB-B	1855.6	1725.2	1411.1
CaM-A	402.6	357.3	303.2
CaM-B	425.7	411.2	280.7
CL1-A	1342.9	1064.2	925.3
CL1-B	1300.2	1196.4	974.7
GS-A	7310.2	3774.5	9664.8
GS-B	9655.3	6516.8	9956.1
IRC-A	21671.9	13619.5	9746.3
IRC-B	19588.9	15830.7	11657.1
NaM-A	207.3	240.5	193.8
NaM-B	245.3	230.5	192.9
LS-A	8548.8	6111.3	4652.8
LS-B	7921.8	6573.5	4954.2
A51-A	1778.9	1102.6	1044.6
A51-B	1564.6	1106.8	1040.1

1000 ppm. This "100 ppm peak" is only of academic importance since activated charcoal, the only material effective for cobalt sorption, shows a slight increase in Kd with increase in calcium concentration. Hence, a high Ca concentration should not adversely effect the performance of the barrier in sorbing cobalt.

EFFECT OF pH

Two additional duplicate sets of batch contact tests using the materials in Table 7 were run to determine the effect of increasing the pH of the simulated leachate from 5 to 7. One of the reasons for this set of tests was to determine if an error that was made in adjusting the pH of the simulated

TABLE 10. Effect of Calcium Concentration on Cobalt Sorption

Sample ID	Kd, mL/g		
	10 ppm	100 ppm	1000 ppm
AC-A	422.4	628.1	652.2
AC-B	422.4	594.0	569.1
CaB-A	10.2	105.5	30.2
CaB-B	14.8	112.1	22.8
CaM-A	4.8	6.7	11.1
CaM-B	4.3	14.0	3.2
CL1-A	19.2	28.2	15.9
CL1-B	13.6	104.6	19.0
GS-A	4.2	-1.0	5.0
GS-B	1.3	-3.5	2.4
IRC-A	19.0	125.0	27.6
IRC-B	12.5	137.2	23.3
NaM-A	11.4	70.4	18.2
NaM-B	12.0	73.3	22.6
LS-A	4.8	30.1	16.3
LS-B	10.9	30.0	19.5
A51-A	32.1	209.7	36.4
A51-B	15.1	222.0	33.6

leachate for the engineering tests (discussed in next section) had affected the test results. During the first set of engineering evaluations, the pH had increased from 5 to 7 without adjustment. Two different leachates were used in these tests: the standard simulated leachate with 1000 ppm Ca and pH 7, and a simulated leachate with 100 ppm Ca and pH 7. The same materials were used in these tests as the tests described in the previous section; consequently, the results from the effect of competing ion tests were used as the pH 5 comparison for the tests described here. The same procedures as described in the previous section were used for these batch contact tests. The results of these tests (run at pH 7) are compared to the corresponding results for pH 5 in Tables 11 and 12.

TABLE 11. Effect of pH on Kd Values at a Calcium Concentration of 100 ppm

Sample ID	Kd, mL/g					
	⁸⁵ Sr		¹³⁷ Cs		⁶⁰ Co	
	pH 5	pH 7	pH 5	pH 7	pH 5	pH 7
AC-A	24.7	24.4	24.7	42.6	628.1	880.0
AC-B	29.4	22.8	32.2	48.2	594.0	786.1
CaB-A	26.5	29.2	1928	2065	105.5	113.8
CaB-B	20.7	26.8	1725	2269	112.1	114.9
CaM-A	12.3	16.0	357.3	446.8	6.7	42.3
CaM-B	20.0	20.8	411.2	449.5	14.0	42.5
CL1-A	161.8	207.0	1064	1167	28.2	74.0
CL1-B	167.3	193.9	1196	1250	104.6	82.0
GS-A	8.1	7.7	3774	9260	-1.0	35.5
GS-B	3.7	15.7	6516	10800	-3.5	22.1
IRC-A	17.1	20.5	13600	24800	125.0	86.7
IRC-B	14.5	--	15800	--	137.2	--
NaM-A	13.4	18.0	240.5	254.4	70.4	47.9
NaM-B	19.0	19.2	230.5	264.3	73.3	47.8
LS-A	18.6	32.2	6111	8311	30.1	95.6
LS-B	9.3	25.7	6573	9993	30.0	93.9
A51-A	1762	1785	1102	1251	209.7	106.8
A51-B	1676	1920	1106	1181	222.0	102.5

The materials of most concern in this test are activated charcoal, green-sand, A51 zeolite, Indian red pottery clay, and local soil. These were the materials that made up the first set of engineering evaluation barriers when the pH adjustment error was made. The only one of these materials that showed a significant difference in Kd with increased pH was the Indian red pottery clay, which showed a ~50% increase in Kd when the pH was increased from 5 to 7. The effect of this result is that the materials in column B were more effective in sorbing Cs than would be expected if the proper leachate were used. This fact is of little consequence, however, since Cs was not difficult to sorb in any of the tests.

TABLE 12. Effect of pH on Kd Values at a Calcium Concentration of 1000 ppm

Sample ID	Kd, mL/g					
	⁸⁵ Sr		¹³⁸ Cs		⁶⁰ Co	
	pH 5	pH 7	pH 5	pH 7	pH 5	pH 7
AC-A	7.4	12.4	30.5	16.5	652.2	430.9
AC-B	9.7	14.0	27.6	31.0	569.1	474.0
CaB-A	10.8	12.6	1655	1533	30.2	19.6
CaB-B	6.3	9.8	1411	1683	22.8	14.2
CaM-A	4.8	9.8	303.2	289.7	11.1	7.2
CaM-B	3.2	12.7	280.7	356.2	3.2	7.4
CL1-A	67.1	71.3	925.3	886.0	15.9	-0.1
CL1-B	59.9	70.3	974.7	897.4	19.0	22.7
GS-A	2.7	6.3	9664	8010	5.0	1.1
GS-B	7.9	10.7	9956	9500	2.4	-2.9
IRC-A	3.3	15.8	9746	15730	27.6	16.0
IRC-B	1.1	9.8	11660	14840	23.3	13.9
NaM-A	4.8	8.2	193.8	185.6	18.2	13.8
NaM-B	5.7	10.3	192.9	204.6	22.6	4.0
LS-A	-1.0	11.1	4652	5230	16.3	9.7
LS-B	5.8	6.4	4954	5181	19.5	9.3
A51-A	271.2	284.9	1044	1204	36.4	19.2
A51-B	247.0	335.7	1040	1278	33.6	18.3

ENGINEERING EVALUATIONS OF SELECTED SORBENT BARRIERS

The purpose of the sorbent barriers engineering evaluations was to verify the performance of the four sorbent barrier formulations identified in the laboratory studies. Since the selection of these barriers was based on experimental results from batch contact interactions and laboratory-scale column studies, field conditions were not adequately represented. In addition, because of the high detection limit in small sample volumes, the laboratory-scale studies did not identify sorption trends under low radionuclide breakthrough conditions. The engineering evaluations were designed to more accurately simulate many field conditions by using large-diameter (0.6-m) columns. The columns simulated water infiltration, physical pressure from the weight of the solid wastes above the sorbent barrier, and hydrostatic head of the leachate expected in the field. The columns also produced larger sample volumes of leachate passing through the sorbent barriers to significantly improve radionuclide analytical detectability. In some cases, the laboratory-scale column studies did not generate enough leachate through the sorbent materials for the radionuclides to be detectable.

The four sorbent materials were tested in two phases in three 0.6-m-diameter exposure columns. The first phase exposed two sorbent barrier formulations and one control material (local soil) to radioactive leachates for five months. The second phase tested the two remaining barriers and repeated the testing of the most effective formulation from the first phase tests. The breakthrough of radioactive contaminants was measured under controlled conditions. These measurements were compared with the breakthrough from the control material (local soil) with no sorbent material additions. This approach was taken to conclusively verify the effectiveness of the sorbent material additions.

TEST EQUIPMENT

The test equipment was arranged as shown in Figure 3. A self-priming pump periodically transferred simulated leachate from 208-L (55-gal) supply drum to the exposure columns. After the leachate had interacted with and flowed

FIGURE 3. Plan View of Equipment for Sorbent Barrier Engineering Evaluations

through the sorbent barriers in the columns, it was drained through a glass marble and frit sublayer into a 20-L container. A geotextile separated the sorbent material from the glass marble drainage layer. The leachate in the 20-L containers was sampled weekly and transferred to the waste drum at the sampling station.

Each stainless steel exposure column (Figure 4) had a hydraulic piston that simulated the forces exerted on the sorbent barriers by the weight of the overlying soil and solid wastes. Each column was capable of simulating a hydraulic head of leachate over the sorbent barrier by applying a pneumatic pressure of up to 690 kPa (100 psig) to the upper portion of the column. Water infiltration (132 cm of water per year) was simulated by adding the appropriate amount of leachate to the column above the sorbent barrier. Each exposure column had a sight glass in the upper section to determine the leachate level inside the column. To prevent material from entering the sight glass, a fine mesh screen was attached to the inside wall of the exposure column where the sight glass pipe was located.

FIGURE 4. Exposure Column Used in Engineering Evaluations of Selected Sorbent Barrier Materials

TEST CONDITIONS

The simulated leachate was prepared to represent the maximum credible concentrations of Cs, Co, Sr, EDTA, and competing ions expected at a low-level waste disposal site (Robertson 1982). The concentration of each of these components is given below:

- EDTA (1 ppm)
- Ca (1000 ppm, nitrate form)
- Na (1000 ppm, nitrate form)
- Mg (1000 ppm, nitrate form)
- Fe (1 ppm, nitrate form)
- concentrated HNO_3 (to maintain pH 5)
- ^{85}Sr (1.24 $\mu\text{Ci/L}$, chloride form)
- ^{60}Co (1 $\mu\text{Ci/L}$, chloride form)
- ^{137}Cs (1 $\mu\text{Ci/L}$, chloride form)

A 175-L batch of this simulated leachate was prepared every seven weeks for weekly introduction into the three columns. The higher concentration of 1.24 $\mu\text{Ci/L}$ ^{85}Sr was used because of its short half-life. At the end of the seven-week period, the average concentration exposed to the sorbent barriers was 1 $\mu\text{Ci/L}$.

Each week 8.3 L of simulated radioactive leachate was introduced to each column and allowed to drain through the barrier into a 20 L leachate collection vessel. A ~1-L sample of this leachate was saved for gamma spectroscopy analysis for any radionuclides that broke through. This sequence was repeated for ~21 weeks for both of the series of engineering evaluations. At the end of the 21 weeks, the barriers in the columns were cored for analysis of radionuclides retained by the sorbent materials.

ENGINEERING EVALUATIONS--FIRST SERIES

The barrier formulations selected for the first series of engineering evaluations were the most cost-effective based on results of K_d values determined from the laboratory studies. It was expected that these barriers would show premature breakthrough of Sr since the sorbent barriers were selected prior to the identification of additional Sr sorbents. The three barriers (one control) tested were:

Column A

5 wt% A-51 zeolite, 6 wt% activated charcoal, 1 wt% greensand, and 88 wt% local soil (A51/AC/GS/LS).

Column B

4 wt% A-51 zeolite, 6 wt% activated charcoal, 5 wt% red pottery clay, and 85 wt% local soil (A51/AC/RPC/LS).

Column C

100 wt% local soil (control column).

No Cs breakthrough was observed in any of the columns, including the control column with no sorbent materials added to the soil. Figure 5 shows that Column A performed well for Sr removal during the entire exposure period.

FIGURE 5. First Series of Engineering Evaluations--
Decontamination Factors for Strontium

There is only one point that was near the required Df. Column B, however, showed Df below that required after ~1.5 bed volumes of simulated leachate had passed through. Similarly, the local soil did not meet the required Df except for one point. This illustrates the fact that sorbent barriers are needed to retard Sr migration in many soils. A properly designed sorbent barrier retards Sr migration greater than 2000 times most soils.

Figure 6 shows that Co is not quite as mobile as Sr for the two barriers tested. Most of the fluctuations in the Kds for Column A are due to variations in the detection limits. The leachate samples were below the detection limits during most of the sample analyses. The calculated minimum detection limit was used to calculate the decontamination factor in these cases. Both Columns A and B were able to exceed the required decontamination factors for the duration of this test. The fluctuations in the curves make it very difficult to calculate a total capacity for the barriers. Longer-term testing would be required

FIGURE 6. First Series of Engineering Evaluations--
Decontamination Factors for Cobalt

to reach a point of equilibrium between the leachate and barrier. The soil column (Column C) responded almost identically for Co as it did for Sr. Again this illustrates the mobility of complexed Co in soils without sorbent material additions.

Seven weeks of testing in addition to the usual 21-week exposure period were performed to correct an error in adjusting the pH of the simulated leachate solution (from pH 7 to pH 5). As discussed in the section on effect of pH, this error was not expected to significantly affect the test results.

At the conclusion of the exposure period, each column was disassembled and two core samples were taken through the thickness of the barriers. These core samples were sectioned, canned and analyzed to give radionuclide concentration profiles through the barriers. These data are shown in Figures 7 through 9.

As shown in the figures, the largest amount of radioactivity was retained in

FIGURE 7. First Series of Engineering Evaluations--Core Analysis for Column A

FIGURE 8. First Series of Engineering Evaluations--Core Analysis for Column B

lower percentage of A-51 zeolite) was repeated to determine repeatability of the results. The three formulations tested were:

Column A

20 wt% A-51 zeolite, 6 wt% activated charcoal, 1 wt% greensand, and 73 wt% local soil (A51(20)/AC/GS/LS).

Column B

93 wt% clinoptilolite, 6 wt% activated charcoal, and 1 wt% greensand (CL/AC/GS).

Column C

(repeat from FY 1985) 5 wt% A-51 zeolite, 6 wt% activated charcoal, 1 wt% greensand, and 88 wt% local soil (A51(5)/AC/GS/LS).

Samples of the leachates collected from these columns were analyzed and the results are presented in Figures 10 and 11. No breakthrough for Cs was observed, indicating a Df of >8000 for each column. Tabulated values are also presented in Appendix B.

Results showed that one barrier formulation met all the performance requirements established for this study. This formulation was tested in column A, and the sorbent materials comprising this barrier were 20 wt% A-51 zeolite, 6 wt% activated charcoal, and 1 wt% greensand. This barrier showed no breakthrough for strontium or cesium and only minor breakthrough for cobalt (within performance requirements).

The clinoptilolite-containing barrier did not perform as predicted by the laboratory-scale experiments (Figure 10). This formulation was tested in column B, and both Sr and Co broke through the column after a two week exposure period. No Cs was observed in the leachate. The clinoptilolite may not be performing as expected due to insufficient contact time. The barrier is fairly permeable, which allows the leachate to percolate through the barrier at a rapid rate. The rate of percolation could be controlled by using finer clinoptilolite or by adding small amounts of clay to decrease the permeability.

Column C, which was a repeat of one of the first series of column tests, showed some breakthrough of Sr and Co similar to the previous series results

FIGURE 10. Second Series of Engineering Evaluations--
Decontamination Factors for Strontium

FIGURE 11. Second Series of Engineering Evaluations--
Decontamination Factors for Cobalt

(Figure 7). The higher concentration of A-51 zeolite used in column A (20 wt%) is necessary for adequate Sr removal. The composition of column C was the same except for a lower amount of A-51 zeolite (5 wt%).

Two core samples were taken from each of the three columns for radio-nuclide profile analysis, and the columns were dismantled. Results of these core analyses are shown in Figures 12 through 14, and tabulated data are included in Appendix B.

FIGURE 12. Second Series of Engineering Evaluations--
Core Analysis for Column A

FIGURE 13. Second Series of Engineering Evaluations--
Core Analysis for Column B

FIGURE 14. Second Series of Engineering Evaluations--
Core Analysis for Column C

RECOMMENDATIONS FOR FUTURE WORK

This report covers a body of experimental work that was primarily designed to identify promising materials for use in sorbent barriers and to evaluate their effectiveness under simulated laboratory- and engineering-scale conditions. Questions that remain to be answered concern the mechanisms involved in radionuclide removal by the sorbent barriers and the total capacity of the barriers for removal of each radionuclide. These points need to be addressed to predict the lifetime expectancy of the barriers, the period of time during which satisfactory performance is maintained. If the barrier capacity was known, the barrier could be designed to have a thickness sufficient to retain the radionuclides for the period of time necessary for decay to innocuous levels (approximately 300 years). After the required barrier thickness is determined, accurate material cost estimates could be prepared for a conceptual sorbent barrier system design.

To address these concerns, experiments on the kinetics and breakthrough characteristics of sorbent barrier systems are recommended. The effects of radionuclide concentration, residence time, and competing ion concentration would be studied. Reversibility of the sorption reaction would be tested to determine if the barriers act in a classical ion exchange manner, as expected. If not, mechanisms such as molecular sieve phenomenon and precipitation would be investigated. Tests would be run to determine if the sorbent barrier mechanism is represented by a linear isotherm or if nonlinearity occurs at higher loadings. These experiments would provide the input necessary to model sorbent barrier systems to predict their lifetime performance.

Before actual implementation of sorbent barrier technology, the demonstration of sorbent barrier performance on a field scale would be required to ensure that the techniques available for barrier installation would not affect performance. Also, field test monitoring must be conducted for a sufficient period of time to extrapolate the data with confidence for the established 300-year criteria period. Sorbent barriers must be designed specifically for

the waste, soil, climate, and design of each disposal site. Experience with field testing would contribute to the application of sorbent barrier technology at specific sites.

REFERENCES

- Freeman, H. D., J. L. Buelt and J. N. Hartley. 1984. "Engineered Sorbent Barriers for Low-Level Waste." In Proceedings of the Sixth Annual Participants' Information Meeting DOE Low-Level Waste Management Program, CONF-8409115. National Technical Information Service, Springfield, Virginia.
- Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, Inc., New York.
- Mercer, B. W., et al. 1978 "Zeolite Ion Exchange in Radioactive and Municipal Waste Water Treatment." In Natural Zeolite: Occurrence, Properties, Use. pp. 451-462. Pergamon Press, Oxford, England.
- Robertson, D. E., K. H. Abel and A. P. Toste. 1982. "Radionuclide Migration in Groundwater." In Proceedings of Fourth Annual Participants Information Meeting DOE Low-Level Waste Management Program, CONF-820854, August 31 - September 2, 1982, Denver, Colorado, pp. 607-618.
- Schultz, W. W. 1980. Removal of Radionuclides from Hanford Defense Waste Solutions. RHO-SA-51, Rockwell Hanford Operations, Richland, Washington.
- Swanson, J. L. 1984. "Organic Complexant-Enhanced Mobility of Toxic Elements in Low-Level Wastes." In Proceedings of the Sixth Annual Participants' Information Meeting DOE Low-Level Waste Management Program. CONF-8409115, National Technical Information Service, Springfield, Virginia.
- Winslow, C. C. 1980. The Sorption of Cesium and Strontium from Concentrated Brines by Backfill Barrier Materials. SAND 80-2046, Sandia National Laboratories, Albuquerque, New Mexico.

APPENDIX A

RESULTS OF LABORATORY STUDIES

TABLE A.1. Results of Small-Scale Column Tests of Multicomponent Barriers

Strontium Concentration in Column Extracts (pCi/g) and C/Co versus Pore Volumes

Column Description		Leachate #1 Column 1			Leachate #2 Column 2			Leachate #3 Column 3			Leachate #4 Column 4		
		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
Columns 1-4		3.86	0	0.00	3.82	625	0.64	3.87	0	0.00	3.87	513	0.52
Oak Ridge soil	96%	11.62	0	0.00	11.44	779	0.80	11.64	0	0.00	11.59	756	0.76
Act. charcoal	4%	23.19	0	0.00	22.86	902	0.93	23.29	0	0.00	23.14	902	0.91
		34.76	0	0.00	34.27	911	0.94	34.93	0	0.00	34.75	833	0.84
		46.31	2	0.00	45.67	878	0.91	46.57	0	0.00	46.33	885	0.89
Column Description		Column 5			Column 6			Column 7			Column 8		
		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
Columns 5-8		4.85	0	0.00	4.86	0	0.00	4.85	0	0.00	4.81	5	0.01
Local soil	88%	14.48	0	0.00	14.52	69	0.07	14.49	0	0.00	14.38	89	0.09
Act. charcoal	6%	28.98	0	0.00	28.96	251	0.26	28.92	0	0.00	28.68	288	0.29
Greensand	1%	43.51	0	0.00	43.42	346	0.36	43.39	0	0.00	43.08	413	0.42
A51 zeolite	5%	57.67	0	0.00	57.85	522	0.54	57.86	0	0.00	57.48	582	0.59
Column Description		Column 9			Column 10			Column 11			Column 12		
		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
Columns 9-12		4.77	0	0.00	4.72	0	0.00	4.67	0	0.00	4.77	3	0.00
Local soil	85%	11.99	0	0.00	14.11	109	0.11	11.27	0	0.00	14.30	106	0.11
Act. charcoal	6%	20.65	0	0.00	27.91	247	0.25	18.97	0	0.00	28.49	312	0.32
Red clay	5%	34.91	0	0.00	42.07	360	0.37	32.98	0	0.00	42.82	343	0.35
A51 zeolite	4%	49.23	0	0.00	56.18	544	0.56	47.17	0	0.00	57.07	534	0.54

A.1

Column Description		Column 13			Column 14			Column 15			Column 16		
Columns 13-16		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
		3.17	0	0.00	3.54	131	0.14	2.58	0	0.00	3.73	182	0.18
Local soil	72%	10.33	0	0.00	11.13	628	0.65	9.83	0	0.00	11.60	639	0.65
Act. charcoal	26%	21.09	0	0.00	22.52	802	0.83	20.73	0	0.00	23.39	795	0.80
Greensand	2%	31.85	11	0.01	33.92	811	0.84	31.64	0	0.00	35.21	734	0.74
		42.66	51	0.06	45.29	839	0.86	42.56	0	0.00	47.02	816	0.82

Column Description		Column 17			Column 18			Column 19			Column 20		
Columns 17-20		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
		3.63	0	0.00	3.54	67	0.07	2.95	0	0.00	3.48	81	0.08
Local soil	68%	12.01	1	0.00	11.63	664	0.68	10.58	0	0.00	11.58	659	0.67
Act. charcoal	26%	24.46	11	0.01	23.78	839	0.86	20.19	0	0.00	23.76	816	0.82
Red clay	6%	37.04	188	0.21	35.95	822	0.85	31.82	0	0.00	35.92	811	0.82
		49.58	286	0.32	48.13	848	0.87	43.43	0	0.00	47.95	--	--

Column Description		Column 21			Column 22			Column 23			Column 24		
Columns 21-24		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
		3.46	0	0.00	3.96	61	0.06	3.81	0	0.00	3.99	116	0.12
Local soil	69%	10.74	0	0.00	12.01	456	0.47	11.47	0	0.00	12.11	496	0.50
Act. charcoal	25%	21.73	0	0.00	24.13	742	0.76	23.05	7	0.01	24.28	723	0.73
Dowex XFS resin	6%	32.68	0	0.00	36.21	790	0.81	34.58	7	0.01	36.42	736	0.74
		43.62	0	0.00	48.28	--	--	46.08	--	--	48.59	--	--

TABLE A.2. Results of Small-Scale Column Tests of Multicomponent Barriers

Cobalt Concentration in Column Extracts (C/Co) vs. Pore Volumes

Column Description		Leachate #1 Column 1			Leachate #2 Column 2			Leachate #3 Column 3			Leachate #4 Column 4		
		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
Columns 1-4		3.86	0	0.00	3.82	193	0.22	3.87	0	0.00	3.87	3	0.00
Oak Ridge soil	96%	11.62	0	0.00	11.44	372	0.42	11.64	0	0.00	11.59	134	0.13
Act. charcoal	4%	23.19	0	0.00	22.86	818	0.91	23.29	0	0.00	23.14	325	0.31
		34.76	0	0.00	34.27	858	0.96	34.93	0	0.00	34.75	323	0.31
		46.31	4	0.00	45.67	833	0.93	46.57	0	0.00	46.33	399	0.39
Column Description		Column 5			Column 6			Column 7			Column 8		
		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
Columns 5-8		4.85	0	0.00	4.86	0	0.00	4.85	0	0.00	4.81	0	0.00
Local soil	88%	14.48	0	0.00	14.52	0	0.00	14.49	4	0.01	14.38	0	0.00
Act. charcoal	6%	28.98	0	0.00	28.96	0	0.00	28.92	3	0.00	28.68	85	0.08
Greensand	1%	43.51	0	0.00	43.42	0	0.00	43.39	4	0.01	43.08	156	0.15
A51 zeolite	5%	57.67	0	0.00	57.85	1	0.00	57.86	4	0.01	57.48	269	0.26
Column Description		Column 9			Column 10			Column 11			Column 12		
		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
Columns 9-12		4.77	0	0.00	4.72	0	0.00	4.67	0	0.00	4.77	0	0.00
Local soil	85%	11.99	0	0.00	14.11	0	0.00	11.27	0	0.00	14.3	0	0.00
Act. charcoal	6%	20.65	0	0.00	27.91	0	0.00	18.97	0	0.00	28.49	41	0.04
Red clay	5%	34.91	0	0.00	42.07	0	0.00	32.98	7	0.01	42.82	71	0.07
A51 zeolite	4%	49.23	0	0.00	56.18	2	0.00	47.17	8	0.01	57.07	155	0.15

Column Description		Column 13			Column 14			Column 15			Column 16		
Columns 13-16		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
		3.17	0	0.00	3.54	0	0.00	2.58	0	0.00	3.73	0	0.00
Local soil	72%	10.33	0	0.00	11.13	0	0.00	9.83	0	0.00	11.6	0	0.00
Act. charcoal	26%	21.09	0	0.00	22.52	0	0.00	20.73	0	0.00	23.39	6	0.01
Greensand	2%	31.85	0	0.00	33.92	0	0.00	31.64	0	0.00	35.21	12	0.01
		42.66	0	0.00	45.29	2	0.00	42.56	0	0.00	47.02	25	0.02

Column Description		Column 17			Column 18			Column 19			Column 20		
Columns 17-20		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
		3.63	0	0.00	3.54	0	0.00	2.95	0	0.00	3.48	0	0.00
Local soil	68%	12.01	0	0.00	11.63	0	0.00	10.58	0	0.00	11.58	0	0.00
Act. charcoal	26%	24.46	0	0.00	23.78	0	0.00	20.19	0	0.00	23.76	0	0.00
Red clay	6%	37.04	0	0.00	35.95	0	0.00	31.82	0	0.00	35.92	0	0.00
		49.58	0	0.00	48.13	0	0.00	43.43	0	0.00	47.95	0	0.00

Column Description		Column 21			Column 22			Column 23			Column 24		
Columns 21-24		P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co	P.V.	pCi/g	C/Co
		3.46	0	0.00	3.96	4	0.00	3.81	0	0.00	3.99	0	0.00
Local soil	69%	10.74	0	0.00	12.01	9	0.01	11.47	0	0.00	12.11	0	0.00
Act. charcoal	25%	21.73	0	0.00	24.13	13	0.01	23.05	0	0.00	24.28	34	0.03
Dowex XFS resin	6%	32.68	0	0.00	36.21	16	0.02	34.58	0	0.00	36.42	40	0.04
		43.62	0	0.00	48.28	--	--	46.08	0	0.00	48.59	--	--

APPENDIX B

RESULTS OF ENGINEERING EVALUATIONS

TABLE B.1. Analytical Results of First Series of Engineering Evaluations

Bed Volume	pCi/mL								
	Column A			Column B			Column C		
	Sr	Cs	Co	Sr	Cs	Co	Sr	Cs	Co
0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	2.3
0.7	0.0	0.0	0.0	0.0	0.0	0.0	ND	ND	ND
0.9	0.0	0.0	0.0	0.0	0.0	0.0	ND	ND	ND
1.1	0.0	0.0	0.0	0.0	0.0	0.0	59.8	0.0	32.8
1.3	0.0	0.0	0.0	0.0	0.0	0.0	81.5	0.0	36.8
1.5	0.0	0.0	0.0	0.0	0.0	0.0	137.0	0.0	48.0
1.7	0.0	0.0	0.0	0.3	0.0	12.6	200.0	0.0	58.8
1.9	0.0	0.0	0.0	0.9	0.0	2.1	234.0	0.0	95.6
2.0	0.0	0.0	0.0	2.3	0.0	2.0	274.0	0.0	111.0
2.2	0.0	0.0	0.0	2.0	0.0	2.3	235.0	0.0	99.8
2.4	0.0	0.0	0.0	3.6	0.0	1.2	260.0	0.0	94.9
2.6	0.0	0.0	0.0	7.2	0.0	5.0	304.0	0.0	95.9
2.8	0.0	0.0	0.0	6.2	0.0	1.4	290.0	0.0	95.3
3.0	0.0	0.0	0.0	6.7	0.0	1.0	302.0	0.0	98.1
3.2	0.0	0.0	0.0	6.6	0.0	1.1	293.0	0.0	91.1
3.4	0.0	0.0	0.0	7.0	0.0	0.8	214.0	0.0	57.2
3.5	0.0	0.0	0.0	7.1	0.0	0.5	252.0	0.0	63.0
3.7	0.0	0.0	0.0	8.1	0.0	0.7	245.0	0.0	54.8
3.9	0.3	0.0	0.0	12.4	0.0	2.0	301.0	0.0	39.1
4.1	1.7	0.0	0.0	18.2	0.0	1.8	325.0	0.0	29.4
4.3	1.9	0.0	0.0	16.6	0.0	0.7	315.0	0.0	27.2

Simulated Leachate (pCi/mL)

	Sr	Cs	Co
Batch #1	476.0	969.0	490.0
Batch #2	629.0	581.0	520.0
Batch #3	715.0	921.0	807.0
Batch #4	1000.0	993.0	818.0

TABLE B.2. Radionuclide Concentrations in First Series of Column Cores (pCi/mL)

Core ^(a) ID	Depth	Sr-85 Conc	Cs-137 Conc	Co-60 Conc
<u>Column A</u>				
A-5	1.3	4,421.3	15,891.6	14,020.6
A-4	2.6	2,501.5	255.0	2,900.1
A-3	3.9	696.7	30.4	247.7
A-2	5.2	144.0	8.0	56.3
A-1	6.5	40.0	29.3	32.2
<u>Column B</u>				
B-4	1.3	2,606.4	10,496.5	6,390.9
B-3	2.6	1,581.0	90.0	574.0
B-2	3.9	623.4	25.7	201.7
B-1	5.2	188.7	17.2	89.8
<u>Column C</u>				
C-5	1.3	472.2	8,737.7	5,065.2
C-4	2.6	533.4	69.1	366.5
C-3	3.9	470.1	6.6	60.9
C-2	5.2	382.0	57.1	79.1
C-1	6.5	354.8	1,124.9	558.7

(a) All cores taken in the center of the column.

TABLE B.3. Leachate Concentrations From Second Series
of Engineering Evaluations^(a) (pCi/mL)

Bed Volume	Column A			Column B			Column C		
	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co	⁸⁵ Sr	¹³⁷ Cs	⁶⁰ Co
0.37	0	0.00	0.00	4.16	0	0.99	0.00	0	0.00
0.56	0	0.00	0.00	5.63	0	1.74	0.32	0	0.51
1.12	0	0.00	0.00	26.66	0	17.85	0.00	0	0.45
1.31	0	0.00	0.15	36.01	0	20.53	0.00	0	3.03
1.49	0	0.00	0.18	17.11	0	11.04	0.53	0	2.59
1.68	0	0.00	0.17	14.74	0	9.74	0.36	0	1.73
1.87	0	0.00	0.00	22.28	0	12.28	1.09	0	1.85
2.24	0	0.00	0.18	51.84	0	28.72	1.73	0	1.53
2.50	0	0.22	0.57	45.56	0	20.87	3.37	0	2.15
2.80	0	0.00	0.45	93.26	0	46.19	6.44	0	2.00
3.17	0	0.00	2.39	117.62	0	53.47	15.01	0	2.12
3.54	0	0.14	1.77	116.00	0	56.82	24.74	0	2.35
3.73	0	0.00	0.00	87.33	0	53.14	32.22	0	6.07

Simulated Leachate

	<u>Sr</u>	<u>Cs</u>	<u>Co</u>
Batch #5	775	866	511
Batch #6	1090	980	697
Batch #7	1970	888	716

(a) Detection limit ~0.1 pCi/mL for all radionuclides.

TABLE B.4. Radionuclide Concentrations in Second Series of Column Cores

<u>Sample ID</u>	<u>Depth, cm</u>	<u>⁸⁵Sr Conc, pCi/g</u>	<u>¹³⁷Cs Conc, pCi/g</u>	<u>⁶⁰Co Conc, pCi/g</u>
COLUMN A CENTER				
A-C-0	2.86	10402.2	15474.3	5993.8
A-C-1	5.87	592.9	3.9	220.7
A-C-2	8.73	47.9	8.4	64.5
A-C-3	11.58	0.0	0.0	13.3
A-C-4	14.12	4.1	1.9	9.1
COLUMN B 6" FROM EDGE NEAR INLET				
B-E-0	3.65	12684.7	55206.2	5660.3
B-E-1	7.3	8705.4	3244.7	5243.6
B-E-2	10.48	6403.5	58.3	4377.6
B-E-3	13.34	5382.3	0.0	4155.9
B-E-4	16.19	2385.9	0.0	2000.0
COLUMN B CENTER				
B-C-0	3.18	12606.0	35808.0	6409.3
B-C-1	6.35	8159.0	1123.4	5322.7
B-C-2	9.84	6072.3	41.8	4282.2
B-C-3	13.02	4041.3	0.0	3224.5
B-C-4	15.24	1492.2	213.0	1128.0
COLUMN C CENTER				
C-C-0	2.54	6030.4	12040.4	4820.6
C-C-1	5.24	3141.8	17.0	1711.7
C-C-2	7.78	1468.7	0.0	271.6
C-C-3	10.32	652.2	2.1	53.2
C-C-4	12.86	262.5	2.0	19.4

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>	
	<u>OFFSITE</u>		V. Stello Office of Executive Director for Operations Mail Station 6209 Nuclear Regulatory Commission Washington, DC 20555
6	Geologic Repository Division DOE Office of Civilian Radioactive Waste Management Forrestal Building Washington, DC 20585 ATTN: C. R. Cooley, RW-4 J. R. Hilley W. J. Purcell, RW-20 B. C. Rusche, RW-1 D. E. Shelor R. Stein, RW-23		G. L. Sjoblom Environmental Protection Agency Office of Radiation Programs 401 M Street, S.W. Washington, DC 20460
3	DOE Office of Defense Waste & Byproducts Management GTN Washington, DC 20545 ATTN: R. K. Heusser J. E. Lytle, OP-12 R. D. Walton, Jr., DP-123		J. M. McGough DOE Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87185
6	DOE Office of Terminal Waste Disposal & Remedial Action GTN Washington, DC 20545 ATTN: J. A. Coleman, NE-25 T. W. McIntosh, NE-25 H. Stelling, NE-25 W. R. Voigt, NE-20 H. F. Walter, NE-25 J. B. Zorn, NE-25		P. G. Hagen Joint Integration Office Bldg. 3, 2nd Floor 2201 San Pedro N.E. Albuquerque, NM 87110
30	DOE Technical Information Center A. T. Clark Division of Fuel Material Safety Nuclear Regulatory Commission Washington, DC 20555	2	DOE Idaho Operations Office 550 Second Street Idaho Falls, ID 83401 ATTN: M. J. Barainca J. P. Hamric
			F. T. Fong DOE San Francisco Operations 1333 Broadway Oakland, CA 94612

No. of
Copies

M. R. Jugan
DOE Oak Ridge Operations Office
P.O. Box E
Oak Ridge, TN 37830

W. J. Brumley
DOE Savannah River Operations
Office
P.O. Box A
Aiken, SC 29801

M. J. Steindler
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

C. S. Abrams
Argonne National Laboratory
P.O. Box 2528
Idaho Falls, ID 83401

B. D. Shipp
Battelle Memorial Institute
Office of Crystalline
Repository Development
9800 South Cass Avenue
Argonne, IL 60439

3 Battelle Memorial Institute
Project Management Division
505 King Avenue
Columbus, OH 43201
ATTN: W. A. Carbeiner
W. S. Madia
B. Rawles

D. T. Oakley, MS 671
Los Alamos Scientific
Laboratory
P.O. Box 1663
Los Alamos, NM 87544

8 Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830
ATTN: J. O. Blomeke
W. D. Burch
N. H. Cutshall

No. of
Copies

Oak Ridge National Laboratory
(contd)
ATTN: F. J. Homan
R. T. Jubin
L. J. Mezga
T. H. Row
B. P. Spalding

4 Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87185
ATTN: D. R. Anderson
R. W. Lynch
W. Weart
Technical Library

J. R. Berreth
Westinghouse Idaho Nuclear Co.,
Inc.
P.O. Box 4000
Idaho Falls, ID 83401

6 E. I. du Pont de Nemours
Company
Savannah River Laboratory
Aiken, SC 29801
ATTN: H. D. Boersma
J. G. Glasscock
E. J. Hennelly
J. R. Knight
M. J. Plodinec
C. T. Randall

6 EG&G Idaho
P.O. Box 1625
Idaho Falls, ID 83401
ATTN: J. Bradford
R. Dodge
D. K. Halford
E. A. Jennrich
J. Logan
S. C. Minkin

No. of
Copies

- 2 Electric Power Research
Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94304
ATTN: R. A. Shaw
R. Williams
- 5 West Valley Nuclear Services
Company
P.O. Box 191
West Valley, NY 14171
ATTN: C. C. Chapman
J. C. Cwynar
J. E. Krauss
S. J. Marchette
J. M. Pope
- J. L. Larocca, Chairman
Energy Research & Development
Authority
Empire State Plaza
Albany, NY 12223
- 3 Brookhaven National Laboratory
Upton, NY 11973
ATTN: P. Colombo
C. R. Kempf
T. Sullivan
- A. Pasternak
California Radioactive
Materials Management Forum
455 Capitol Mall
Suite 380
Sacramento, CA 95814
- L. D. Ramspott
Lawrence Livermore National
Laboratory
University of California
P.O. Box 808
Livermore, CA 94550

No. of
Copies

ONSITE

- 3 DOE Richland Operations Office
E. A. Bracken
N. T. Karagianes
J. D. White
- 11 Rockwell Hanford Operations
R. N. Gurley
J. M. Henderson
N. W. Kirch
H. E. McGuire
R. D. Prosser
I. E. Reep
R. J. Thompson
T. B. Venziano
D. D. Wodrich
R. D. Wojtasek
File Copy
- UNC United Nuclear Industries
T. E. Dabrowski/W. J. Kyriazis
- 2 Westinghouse Hanford Company
R. E. Lerch
J. D. Watrous
- 38 Pacific Northwest Laboratory
C. R. Allen
W. W. Ballard, Jr.
W. F. Bonner
L. A. Bray
J. L. Buelt
H. C. Burkholder
M. R. Elmore
V. F. Fitzpatrick
H. O. Freeman
H. A. Haerer
M. S. Hanson
J. N. Hartley
J. H. Jarrett
W. W. Laity
L. T. Lakey

No. of
Copies

Pacific Northwest Laboratory

(contd)

J. M. Latkovich
D. McCarthy
E. D. McClanahan
J. L. McElroy
J. E. Minor
D. H. Mitchell
S. J. Mitchell
D. A. Myers
R. D. Peters
J. A. Powell
W. A. Ross
J. L. Ryan
R. J. Serne
R. L. Skaggs
J. L. Straalsund
J. L. Swanson
Publishing Coordination (2)
Technical Information (5)