*Distributions of 15 Elements on 58 Absorbers
from Simulated Hanford Double-Shell
Slurry Feed (DSSF)*

S. Fredric Marsh*

Zita V. Svitra

Scott M. Bowen

*Sandia National Laboratories/New Mexico, Albuquerque, NM 87185-0734

Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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 any of their employees, make any warranty, express 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 or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	x
TRADEMARKS	x
ABSTRACT	1
EXECUTIVE SUMMARY	1
I. INTRODUCTION	2
II. EXPERIMENTAL PARAMETERS	3
A. Simulant Solution	3
B. Radiotracers	4
C. Absorbers	4
D. Solution/Absorber Contacts	6
E. Calculation of Kd Values	6
F. Corrections	7
G. Other Sources of Error	8
H. Data Transfer and Processing	8
I. Calculation of Detection Limits	8
III. RESULTS AND DISCUSSION	9
A. Individual Elements	9
1. Cerium	9
2. Cesium	10
3. Strontium	11
4. Technetium	12
5. Yttrium	12
6. Chromium	13
7. Cobalt	13
8. Iron	14
9. Manganese	15
10. Nickel	15
11. Vanadium	16
12. Zinc	16
13. Zirconium	17
14. Uranium	17
15. Americium	18
B. Individual Absorbers	18
1. Commercially Available Absorbers	18
a. Amberlite™ DP-1 Cation Exchange Resin	19
b. Amberlite™ IRC-76 Cation Exchange Resin.	19
c. Amberlite™ IRC-718 Cation Exchange Resin	20
d. Bone Char Absorber	20

e.	Chelex™ 100 Cation Exchange Resin	21
f.	Diphonix™ Cation Exchange Resin	21
g.	Duolite™ CS-100 Cation Exchange Resin	22
h.	Duolite™ C-467 Cation Exchange Resin	22
i.	Durasil™ 190 Resin	23
j.	Durasil™ 230 Resin	23
k.	Ionac™ SR-3 Anion Exchange Resin	24
l.	Ionac™ SR-6 Anion Exchange Resin	24
m.	Ionsiv™ TIE-96 Absorber	25
n.	Ionsiv™ TIE-96 (Modified) Absorber	25
o.	Nusorb™ Ferroc carbon A Absorber	26
p.	Nusorb™ LP-70-S Absorber	26
q.	Nusorb™ Magnetite Absorber	27
r.	Nusorb™ Unitane Absorber	27
s.	Purolite™ A-520-E Anion Exchange Resin	28
t.	Reillex™ HPQ Anion Exchange Resin	28
u.	Resin Tech™ 3972 Resin	29
v.	SRS Resorcinol/Formaldehyde (BSC-187) Resin	29
w.	Tannin Absorber	30
2.	Experimental Inorganic Materials	30
a.	KW-3-21x	30
b.	KW-3-58x	31
c.	KW-4-40x	31
d.	KW-4-41x	32
e.	KW-4-42x	32
f.	MgAlHT	33
3.	Experimental Resins	33
a.	NK 120B Resin	33
b.	NK 194 Resin	34
c.	Sybron (Et) ₃ N Anion Exchange Resin	34
d.	Sybron (Pr) ₃ N Anion Exchange Resin	35
4.	Polyacrylonitrile (PAN) Composite Absorbers	35
a.	AMP-PAN Ammonium Molybdophosphate Composite	35
b.	Ba(Ca)SO ₄ -PAN Barium/Calcium Sulfate Composite	36
c.	CSbA-PAN Crystalline Polyantimonic Acid Composite	36
d.	M315-PAN Synthetic Mordenite Composite	37
e.	MgO-PAN Magnesium Oxide Composite	37
f.	MnO-PAN Manganese Dioxide Composite	38
g.	NaTiO-PAN Sodium Titanate Composite	38
h.	NiFC-PAN Nickel Hexacyanoferrate Composite	39
i.	NM-PAN Nickel Hexacyanoferrate/Manganese Dioxide Composite	39
j.	SnSbA-PAN Stannic Antimonate Composite	40
k.	TiO-PAN Titanium Dioxide Composite	40
l.	TiP-PAN Titanium Phosphate Composite	41
m.	TiSbA-PAN Titanium Antimonate Composite	41
n.	ZrO-PAN Zirconium Oxide Composite	42
o.	ZrOP-PAN Zirconium Oxide/Zirconium Phosphate Composite	42
p.	ZrP-PAN Zirconium Phosphate Composite	43
5.	Phenolsulfonic-Formaldehyde (PSF) Composite Absorbers	43
a.	CoFC-PSF Cobalt Hexacyanoferrate Composite	43
b.	TiFC-PSF Titanium Hexacyanoferrate Composite	44

6. Liquid Extractants	44
a. Aliquat™ 336.	44
b. Cyanex™ 923	45
c. LIX™-54	45
7. Sandia/NM Absorbers	46
a. SNL/CST 120 Crystalline Silico-Titanate	46
b. SNL/CST 141 Crystalline Silico-Titanate	47
c. SNL/CST 149 Crystalline Silico-Titanate	47
d. SNL/HTO Amorphous Hydrous Titanium Dioxide	48
IV. FUTURE STUDIES	48
V. CONCLUSIONS	48
A. Experimental Procedure	48
B. Individual Elements	48
C. Individual Absorbers	49
ACKNOWLEDGMENTS	49
REFERENCES	49

TABLES

Table 1. Number of Absorbers Capable of Sorbing Each of 15 Elements from Simulated Hanford DSSF Solution	2
Table 2. Composition of Simulated Hanford DSSF Solution Used in This Study	3
Table 3. Radiotracers Used in This Study	4
Table 4. Absorbers Evaluated in This Study	5

Individual Elements

Table 5. Cerium Distribution Data	9
Table 6. Cesium Distribution Data	10
Table 7. Strontium Distribution Data	11
Table 8. Technetium Distribution Data	12
Table 9. Yttrium Distribution Data	12
Table 10. Chromium Distribution Data	13
Table 11. Cobalt Distribution Data	13
Table 12. Iron Distribution Data	14
Table 13. Manganese Distribution Data	15
Table 14. Nickel Distribution Data	15
Table 15. Vanadium Distribution Data	16
Table 16. Zinc Distribution Data	16
Table 17. Zirconium Distribution Data	17
Table 18. Uranium Distribution Data	17
Table 19. Americium Distribution Data	18

Individual Absorbers

Commercially Available Absorbers

Table 20. Amberlite™ DP-1 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	19
Table 21. Amberlite™ IRC-76 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	19

Table 22.	Amberlite™ IRC-718 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	20
Table 23.	Bone Char Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	20
Table 24.	Chelex™ 100 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	21
Table 25.	Diphonix™ Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	21
Table 26.	Duolite™ CS-100 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	22
Table 27.	Duolite™ C-467 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	22
Table 28.	Durasil™ 190 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	23
Table 29.	Durasil™ 230 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	23
Table 30.	Ionac™ SR-3 Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	24
Table 31.	Ionac™ SR-6 Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	24
Table 32.	Ionsiv™ TIE-96 Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	25
Table 33.	Ionsiv™ TIE-96 (Modified) Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	25
Table 34.	Nusorb™ Ferrocen A Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	26
Table 35.	Nusorb™ LP-70-S Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	26
Table 36.	Nusorb™ Magnetite Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	27
Table 37.	Nusorb™ Unitane Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	27
Table 38.	Purolite™ A-520-E Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	28
Table 39.	Reillex™ HPQ Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	28
Table 40.	Resin Tech™ 3972 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	29
Table 41.	SRS Resorcinol/Formaldehyde (BSC-187) Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	29
Table 42.	Tannin Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution	30

Experimental Inorganic Materials

Table 43.	KW-3-21x: Distribution of 15 Elements from Simulated Hanford DSSF Solution	30
Table 44.	KW-3-58x: Distribution of 15 Elements from Simulated Hanford DSSF Solution	31
Table 45.	KW-4-40x: Distribution of 15 Elements from Simulated Hanford DSSF Solution	31
Table 46.	KW-4-41x: Distribution of 15 Elements from Simulated Hanford DSSF Solution	32
Table 47.	KW-4-42x: Distribution of 15 Elements from Simulated Hanford DSSF Solution	32
Table 48.	MgAlHT: Distribution of 15 Elements from Simulated Hanford DSSF Solution	33

Experimental Resins

Table 49.	NK 120B Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	33
Table 50.	NK 194 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	34
Table 51.	Sybron (Et) ₃ N Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	34
Table 52.	Sybron (Pr) ₃ N Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution	35

Composite Absorbers

Table 53.	AMP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	35
Table 54.	Ba(Ca)SO ₄ -PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	36
Table 55.	CSbA-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	36
Table 56.	M315-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	37
Table 57.	MgO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	37
Table 58.	MnO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	38
Table 59.	NaTiO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	38
Table 60.	NiFC-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	39
Table 61.	NM-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	39
Table 62.	SnSbA-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	40
Table 63.	TiO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	40
Table 64.	TiP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	41
Table 65.	TiSbA-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	41
Table 66.	ZrO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	42
Table 67.	ZrOP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	42
Table 68.	ZrP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	43
Table 69.	CoFC-PSF Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	43
Table 70.	TiFC-PSF Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution	44

Liquid Extractants

Table 71.	Aliquat ^{TM} 336: Distribution of 15 Elements from Simulated Hanford DSSF Solution	44
Table 72.	Cyanex ^{TM} 923: Distribution of 15 Elements from Simulated Hanford DSSF Solution	45
Table 73.	LIX ^{TM} -54: Distribution of 15 Elements from Simulated Hanford DSSF Solution	45

Sandia/NM Absorbers

Table 74.	SNL/CST 120: Distribution of 15 Elements from Simulated Hanford DSSF Solution	46
Table 75.	SNL/CST 141: Distribution of 15 Elements from Simulated Hanford DSSF Solution	47
Table 76.	SNL/CST 149: Distribution of 15 Elements from Simulated Hanford DSSF Solution	47
Table 77.	SNL/HTO: Distribution of 15 Elements from Simulated Hanford DSSF Solution	48

FIGURES

Fig. 1.	Hypodermic syringe, with porous Kynar™ filter in tip, as used for solution/absorber contacts. An uninstalled Kynar™ filter is shown below the syringe.	7
Fig. 2.	Tube rotator used to mix the solution/absorber combinations.	7

TRADEMARKS

Aliquat is a registered trademark of the Henkel Corporation, Tucson, AZ, Tel. 602-622-8891.

Amberlite is a registered trademark of Rohm & Haas, Philadelphia, PA, Tel. 215-592-3000.

Ambersorb is a registered trademark of Rohm & Haas, Philadelphia, PA, Tel. 215-592-3000.

Chelex is a registered trademark of the Dow Chemical Company, Midland, MI, Tel. 800-441-4369.

Cyanex is a registered trademark of the American Cyanamid Company, Wayne, NJ, Tel. 800-438-5615.

Diphonix is a registered trademark of EIChroM Industries, Inc., Darien, IL, Tel. 800-424-9300.

Duolite is a registered trademark of Rohm & Haas, Philadelphia, PA, Tel. 215-592-3000.

Durasil is a registered trademark of the Duratek Corporation, Columbia, MD, Tel. 410-312-5100.

EXCEL is a registered trademark of Microsoft Corporation, Redmond, WA, Tel. 800-426-9400.

Ionac is a registered trademark of Sybron Chemicals, Inc., Birmingham, NJ, Tel. 609-893-1100.

Ionsiv is a registered trademark of the UOP Corporation, Des Plaines, IL, Tel. 609-727-9400.

Kynar is a registered trademark of the Pennwalt Corporation, Philadelphia, PA, Tel. 215-587-7516.

LIX is a registered trademark of the Henkel Corporation, Tucson, AZ, Tel. 602-622-8891.

Nusorb is a registered trademark of Nucon International, Inc., Columbus, OH, Tel. 614-846-5710.

Purolite is a registered trademark of the Purolite Company, Bala Cynwyd, PA, Tel. 215-668-9090.

Reillex is a registered trademark of Reilly Industries, Inc., Indianapolis, IN, Tel. 317-638-7531.

Resin Tech is a registered trademark of Resin Tech, Inc., Cherry Hill, NJ, Tel. 609-354-1152.

DISTRIBUTIONS OF 15 ELEMENTS ON 58 ABSORBERS FROM SIMULATED HANFORD DOUBLE-SHELL SLURRY FEED (DSSF)

by

S. Fredric Marsh, Zita V. Svitra, and Scott M. Bowen

ABSTRACT

As part of the Hanford Tank Waste Remediation System program at Los Alamos, we evaluated 58 commercially available or experimental absorber materials for their ability to remove hazardous components from high-level waste. These absorbers included cation and anion exchange resins, inorganic exchangers, composite absorbers, pillared layered materials, and a series of liquid extractants sorbed on porous support-beads. We tested these absorbers with a solution that simulates Hanford double-shell slurry feed (DSSF) (pH 14.0). To this simulant solution we added the appropriate radionuclides and used gamma spectrometry to measure fission products (Ce, Cs, Sr, Tc, and Y), actinides (U and Am), and matrix elements (Cr, Co, Fe, Mn, Ni, V, Zn, and Zr). For each of 870 element/absorber combinations, we measured distribution coefficients for dynamic contact periods of 30 min, 2 h, and 6 h to obtain information about sorption kinetics. On the basis of these 2610 measured distribution coefficients, we determined that many of the tested absorbers may be suitable for processing DSSF solutions.

EXECUTIVE SUMMARY

Successful remediation of the large quantities of hazardous waste stored in underground tanks at the Hanford Reservation near Richland, Washington, requires the identification of reliable partitioning agents and the development of suitable technologies. To address this need, we measured the sorption of 15 elements onto 58 different absorbers from a simulant that represents Hanford double-shell slurry feed (DSSF) solution.

After each completed segment of our absorber screening studies, we review the performance of the tested absorbers, eliminate those that perform poorly, and replace them with new absorbers. Thus, although this study using DSSF simulant solution may resemble our previous study, it includes 24 absorbers not tested in our Hanford Tank 102-SY study.¹ We also add or eliminate specific radiotracers depending on their availability and solubility in the simulant solutions being studied.

The results from this absorber screening study and our previous study of three simulant solutions for Hanford Tank 102-SY¹ indicate that many existing

partitioning agents may be suitable for remediating high-level waste (HLW) tanks. The identification of reliable partitioning agents could allow the processing of HLW in Hanford tanks to begin and be completed sooner, and at a lower cost, than would otherwise be possible. The findings of our studies could have a major beneficial impact on decommissioning and environmental remediation efforts at Hanford and elsewhere within the U.S. Department of Energy (DOE) complex.

Our screening studies, intended to identify the most promising absorbers and extractants, include mainly absorbers that either are already commercially available or could be produced in commercial quantities at acceptable cost and within a reasonable time. Distribution coefficients for each element/absorber combination were measured for dynamic contact periods of 30 min, 2 h, and 6 h to provide information about the sorption kinetics of each system.

In many cases, the observed behavior of the element/absorber combination in the simulant solution was significantly different from the expected behavior, based on published measurements from solutions of more simple

chemical composition. We attribute such differences to the effects of other cations that compete for absorber sites, as well as the competition from anions that form soluble complexes with metal ions that would otherwise be sorbed. Such matrix-dependent differences in absorber performance demonstrate the value of using realistic simulant solutions for such measurements.

We also found numerous inexpensive commercial materials that outperform specialty products costing much more.

Table 1 summarizes the number of absorbers identified as effective in each of six distribution coefficient (Kd) ranges.

From simulated DSSF solution, all elements except vanadium show good to excellent sorption on at least one absorber. Strontium, iron, and manganese are sorbed with Kd values greater than 1000 by many absorbers.

Absorbers that perform well in our screening studies will be evaluated with increasingly realistic simulants that contain degraded organic constituents known to form competing complexes with multivalent cations. We then plan to evaluate the best identified absorbers with actual radioactive waste solutions as soon as such waste can be obtained. We also suggest an accelerated effort to identify or develop partitioning agents to achieve separations for which we have identified no satisfactory absorbers.

I. INTRODUCTION

The Hanford Reservation near Richland, Washington, incorporates 177 underground tanks that store more than 65 million gallons of radioactive waste containing some 165 million curies. These high-level wastes (HLWs) are a byproduct of the production of nuclear materials for national defense needs during the past half-century. Because Hanford operating contractors used numerous chemical processes during this period, many different reagents and waste streams were generated and combined in underground tanks. The resulting wastes consist of complex and sometimes unstable mixtures of sludges, saltcakes, slurries, and supernates. Adding significantly to the stored-waste problem is the fact that 67 of these underground waste storage tanks are known, or are presumed, to have leaked.

The U.S. Department of Energy (DOE) is committed to the remediation of hazardous wastes stored at Hanford and has directed Los Alamos National Laboratory (LANL) and Sandia National Laboratories/New Mexico (SNL) to support the Hanford Tank Waste Remediation System (TWRS) mission, which is to store, treat, and dispose of all tank waste in a safe, cost-effective, and environmentally sound manner. An essential prerequisite for achieving this goal is the identification of suitable partitioning agents and technologies.

Table 1. Number of Absorbers Capable of Sorbing Each of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Values					
	>1000	300-1000	100-300	20-100	10-20	5-10
Ce	2	5	4	10	5	10
Cs	0	2	1	4	5	8
Sr	26	7	6	7	4	2
Tc	0	7	2	1	1	10
Y	1	11	7	23	5	3
Cr	1	1	0	0	0	8
Co	0	1	0	6	1	3
Fe	10	7	7	10	2	5
Mn	6	8	11	9	3	6
Ni	1	2	2	9	9	10
V	0	0	0	1	1	1
Zn	1	6	3	8	7	2
Zr	3	5	9	8	11	2
U	2	2	0	9	6	3
Am	0	5	4	13	10	16

Ion exchange is a partitioning technology that has been extensively used in the nuclear industry. Anion exchange has been used for many decades to recover plutonium² and neptunium³ from a wide variety of impure nuclear materials. Cation exchange resins also have been used in the nuclear industry,⁴ although they generally are considered to be less selective than anion exchange resins.

Although most of the absorbers we tested in this study and in our previous study with three simulant solutions for Hanford Tank 102-SY¹ are cation exchangers, we also included anion exchange resins, inorganic exchangers, composite resins, pillared layered materials, and a series of liquid ion exchangers (sorbed on porous carbon beads). Our intent was to obtain more comprehensive data as well as to supply convenient reference points for other studies. We also included some experimental absorbers to provide guidance for future research activities.

Some of the absorbers included in our study have been reported by others to offer high selectivity for specific ions; however, few of these absorbers have been evaluated with media approaching the complexity of the HLW solutions stored at Hanford. Nor have any other investigators, to our knowledge, measured the distribution of as many elements (15) onto so many different absorber materials (58) from a realistic Hanford double-shell slurry feed (DSSF) simulant solution under identical test conditions. Moreover, because we measured the sorption of so many different elements, our study provides selectivity information that specifies which unwanted elements are most likely to interfere by competing for absorber sites.

After each completed segment of our absorber screening studies, we review the performance of the tested absorbers, eliminate those that perform poorly, and replace them with new absorbers. Thus, although this study using DSSF simulant solution may resemble our previous study, it includes 24 absorbers not tested in our Hanford Tank 102-SY study.¹ We also add or eliminate specific radiotracers depending on their availability and solubility in the simulant solutions being studied.

Our objective was to evaluate numerous potentially useful absorber materials, including some not previously studied, for their ability to recover selected elements from a realistic DSSF simulant solution. Because no simulant can accurately represent the contents of any HLW storage tank, the most promising absorbers eventually must be tested with actual waste. However, because actual waste samples are expensive and difficult to obtain, we continue to advocate preliminary screening of candidate absorbers with simulants before testing with actual tank waste solutions.

Although we include comments and observations about our experimental data, we intentionally refrain from recommending specific absorbers. Our purpose is to identify options from which the designated engineers can develop reliable process flow sheets. Which partitioning options they select will, of course, depend on the specific objectives of their flow sheet.

II. EXPERIMENTAL PARAMETERS

A. Simulant Solution

The simulated DSSF solution was prepared by Garrett Brown of Battelle Pacific Northwest Laboratory (PNL). The composition of this solution, as supplied by PNL, is given in Table 2.

We initially passed the DSSF simulant through a 0.45- μ m filter to remove any suspended solids and then refiltered it after adding the radiotracers to remove any portion not in solution. Finally, we filtered each portion of precontacted and postcontacted simulant solution again through a 0.45- μ m filter before gamma-spectrometric assay.

Table 2. Composition of Simulated Hanford DSSF Solution Used in This Study

Concentration (M)	
Cations	
Na	7.0
K	0.945
Cs	7.0×10^{-5}
Al	0.721
Anions	
Cl	0.102
NO ₃	3.52
NO ₂	1.51
PO ₄	0.014
SO ₄	0.008
CO ₃	0.147
OH ⁻ (total)	4.63
OH ⁻ (free)	1.75
Theoretical pH = 14.56	
Measured pH = 14.0	

B. Radiotracers

Having selected gamma spectrometry as the technique for measuring the distribution of the selected elements, we obtained suitable radiotracers to be added to the simulant solutions. The selected tracers and the gamma energies measured are listed in Table 3.

The two actinides were isolated and purified in the Los Alamos Plutonium Facility. We purchased ^{51}Cr , ^{141}Ce , and ^{60}Co from DuPont New England Nuclear Products, Boston, Massachusetts. The Medical Isotopes Program of the Brookhaven National Laboratory Medical Department supplied ^{56}Ni and ^{48}V . The ^{137}Cs , ^{85}Sr , $^{95\text{m}}\text{Tc}$, ^{59}Fe , ^{54}Mn , ^{88}Y , ^{65}Zn , and ^{88}Zr were obtained from the Medical Radioisotopes and Reactor Applications Group at Los Alamos.

To minimize interference among gamma rays with similar energies, we divided the 15 radiotracers into two easily resolved groups. One group consisted of ^{241}Am , ^{141}Ce , ^{51}Cr , ^{137}Cs , ^{85}Sr , and $^{95\text{m}}\text{Tc}$. The other group contained ^{60}Co , ^{59}Fe , ^{54}Mn , ^{56}Ni , ^{237}U , ^{48}V , ^{88}Y , ^{65}Zn , and ^{88}Zr . We divided the simulant solution into two equal portions and added six tracers to one portion and nine tracers to a separate portion. Both portions were tested with all 58 absorbers.

C. Absorbers

The absorbers evaluated in this study are listed in Table 4. Details about the supplier or preparation of the absorbers are provided in Section III.B. These absorbers, which encompassed a wide range of particle sizes and porosities, were air-dried and used without further treatment except where otherwise noted.

Although the suppliers of the polyacrylonitrile (PAN) composites, tannin, and Diphonix^{TM} prefer that their absorbers not be dried, we intentionally air-dried all absorbers before testing to put them all on a directly comparable basis. We also sought to avoid diluting the simulant solution by adding as-received wet resins, which in the worst case would have diluted the simulant by 23%. Because the DSSF simulant was essentially saturated with various salts, large dilutions could significantly change the chemical properties of the solution, which could substantially affect the performance of many absorbers.

The concern expressed by a few colleagues about the adverse effects of air-drying absorbers appears to be overstated. Specifically, our study using air-dried absorbers yielded a distribution coefficient (K_d) value of 7000 for one element with Diphonix^{TM}

Table 3. Radiotracers Used in This Study

Radiotracer	Gamma Energy (MeV)	Gamma Branching (%) ^a	Estimated Concentration ^b
^{241}Am	0.0595	35.9	30 $\mu\text{g/L}$
^{141}Ce	0.145	48	50 $\mu\text{g/L}$
^{56}Ni	0.158	100	60 $\mu\text{g/L}$
$^{95\text{m}}\text{Tc}$	0.204	100	2 $\mu\text{g/L}$
^{237}U	0.208	23.3	20 mg/L
^{51}Cr	0.320	10	0.3 $\mu\text{g/L}$
^{88}Zr	0.394	97	50 $\mu\text{g/L}$
^{85}Sr	0.514	100	3 $\mu\text{g/L}$
^{137}Cs	0.662	85	6 $\mu\text{g/L}$
^{54}Mn	0.835	100	3 $\mu\text{g/L}$
^{88}Y	0.898	92	50 $\mu\text{g/L}$
^{48}V	0.983	100	80 $\mu\text{g/L}$
^{59}Fe	1.099	56	20 $\mu\text{g/L}$
^{65}Zn	1.115	51	6 $\mu\text{g/L}$
^{60}Co	1.173	100	2 $\mu\text{g/L}$

^aGamma branching information is provided to indicate the assay sensitivity.

^bThe elemental concentrations given for the radiotracers are based on the best information available from suppliers; however, these values do not account for low levels of these elements that could have been unintentionally added as impurities in the reagents used to prepare the simulant.

Table 4. Absorbers Evaluated in This Study

Absorber Type/Source	Trademark^a or Other Identification
Commercial Absorbers	Amberlite™ DP-1 cation resin Amberlite™ IRC-76 cation resin Amberlite™ IRC-718 cation resin Bone char absorber Chelex™ 100 cation resin (iminodiacetic acid) Diphonix™ cation resin (polyfunctional) Duolite™ CS-100 cation resin (phenolic) Duolite™ C-467 cation resin (phosphonic acid) Durasil™ 190 resin Durasil™ 230 resin Ionac™ SR-3 anion resin (trimethyl amine) Ionac™ SR-6 anion resin (tributyl amine) Ionsiv™ TIE-96 (TiO ₂ -loaded zeolite) Ionsiv™ TIE-96, modified (TiO ₂ -loaded zeolite) Nusorb™ Ferroc carbon A absorber Nusorb™ LP-70-S absorber Nusorb™ Magnetite absorber Nusorb™ Unitane absorber Purolite™ A-520-E anion resin (triethyl amine) Reillex™ HPQ anion resin (polyvinylpyridine) Resin Tech™ 3972 resin SRS RF BSC-187 (resorcinol/formaldehyde) Tannin absorber
Experimental Absorbers	KW-3-21x (pillared layered material) KW-3-58x (pillared layered material) KW-4-40x (pillared layered material) KW-4-41x (pillared layered material) KW-4-42x (pillared layered material) MgAlHT (hydrotalcite) NK 120B (hydroxamic acid functionality) NK 194 (amidoxime functionality) Sybron (Et) ₃ N anion resin Sybron (Pr) ₃ N anion resin
Composite Absorbers	AMP-PAN ammonium molybdophosphate Ba(Ca)SO ₄ -PAN barium/calcium sulfate CSbA-PAN crystalline polyantimonic acid M315-PAN synthetic mordenite MgO-PAN magnesium oxide MnO-PAN manganese dioxide NaTiO-PAN sodium titanate NiFC-PAN nickel hexacyanoferrate NM-PAN nickel hexacyanoferrate/manganese dioxide SnSbA-PAN stannic antimonate TiO-PAN titanium dioxide TiP-PAN titanium phosphate TiSbA-PAN titanium antimonate ZrO-PAN zirconium oxide ZrOP-PAN zirconium oxide/zirconium phosphate ZrP-PAN zirconium phosphate
F. Sebesta, Czech Republic (polyacrylonitrile matrix)	
J. Narbutt, Poland (phenolsulfonic- formaldehyde matrix)	CoFC-PSF cobalt hexacyanoferrate TiFC-PSF titanium hexacyanoferrate

Table 4. Absorbers Evaluated in This Study (Cont.)

Absorber Type/Source	Trademark ^a or Other Identification
LANL-Prepared Extractant Beads	Aliquat ^{TM} 336 (methyltricaprylammonium chloride) Cyanex ^{TM} 923 (trialkylphosphine oxide) LIX ^{TM} -54 (a beta diketone)
Sandia/NM Absorbers	SNL/CST 120 crystalline silico-titanate SNL/CST 141 crystalline silico-titanate SNL/CST 149 crystalline silico-titanate SNL/HTO amorphous hydrous titanium dioxide

^aTrademark owners are identified on page x.

(Section III.B.1.f), three triple-digit K_d values and two four-digit K_d values with tannin (Section III.B.1.w), and four-digit or higher K_d values with 13 of 16 PAN absorbers (Sections III.B.4.c and III.B.4.e through III.B.4.p). Moreover, these high K_d values may qualify the cited absorbers for future column tests, in which none of the tested absorbers will require drying.

D. Solution/Absorber Contacts

In most cases, a 250-mg portion of each air-dried absorber was contacted with a measured 6-mL volume of simulant solution in a specially modified 20-mL disposable hypodermic syringe. We modified these syringes by inserting cylindrical plugs cut from 1/4-in.-thick porous Kynar^{TM}, obtained from Porex Technologies, Fairburn, Georgia, into the tapered tips as filters, which permitted only liquid to pass through (Fig. 1).

Each group of experiments usually consisted of six syringes, each containing a different absorber. A measured volume of the simulant solution was transferred by pipet into a plastic beaker and then drawn into a syringe through the Kynar^{TM} filter. We then sealed the tip of each syringe and placed the syringes on a 48-rpm tube rotator (Fig. 2) for dynamic contact periods of 30 min, 2 h, and 6 h. At the end of each contact period, approximately 25% of the total solution volume was expelled from the syringe through an attached 0.45 μ m filter (center left in Fig. 1) into a tared counting vial. We then weighed the dispensed solution and used that figure in the calculation of K_d values.

The described filter-tip syringes were unsuitable for the crystalline silico-titanate (CST) absorbers from Sandia/NM and for the pillared layered materials because these small particles often plugged the filters. For these finely divided materials, we pipetted 6 mL of

solution directly into a 30-mL centrifuge tube that contained 250 mg of absorber and mixed each absorber/solution on the rotator for the prescribed time. At the end of each contact period, the tubes were centrifuged at high speed for 10 min. We then transferred approximately 1.5 mL of the centrifuged solution into a 2.5-mL hypodermic syringe with a 0.45- μ m filter (center left in Fig. 1) attached to the Luer-lock tip. The centrifuged solution was expelled through this filter into a tared counting vial, from which we determined the solution weight.

E. Calculation of K_d Values

Distribution coefficients (K_ds) normally are calculated in terms of the dry absorber weight;⁵ optionally, K_ds can be calculated in terms of the wet absorber volume. Because most of the absorbers we tested were received in dry form, we tested all absorbers on a comparable, dry basis to conform to a consistent K_d convention. We recognize that air-drying moist absorbers to constant weight at room temperature causes some polymers to temporarily shrink as they lose physically sorbed water; however, such polymers swell again when they recontact aqueous solution. Therefore, the only adverse effect of air-drying might be a temporary decrease in polymer porosity that could result in slower kinetics until the polymer regains its lost water. To protect the air-dried absorbers from any lasting damage, we never applied heat during the drying cycles.

Each portion of postcontact solution was assayed by gamma spectrometry using the characteristic gamma energies of the added radionuclides. The fraction of each element sorbed was determined indirectly from the difference in the measured gamma activity of the selected radionuclide before and after contact with each specified absorber.

Fig. 1. Hypodermic syringe, with porous Kynar™ filter in tip, as used for solution/absorber contacts. An uninstalled Kynar™ filter is shown below the syringe.

The Kd value for each element was calculated as follows:

$$K_d = \frac{Pr - Po}{Po} \frac{S}{A},$$

where Pr = measured precontact activity,
Po = measured postcontact activity,
S = milliliters of solution contacted, and
A = grams of dry absorber contacted.

Uncertainties are larger when Kd values are very low (when the numerator in the first fraction represents a small difference between two large numbers), as well as when Kd values are very high (when the denominator in the first fraction becomes very small). However, the objective of this screening study was to identify absorbers that sorb specific elements poorly or very well.

Although we report most Kd values below 5000 as calculated, this obviously should not be taken to indicate that all four figures are significant. The uncertainty associated with our highest and lowest Kd values appears to be within a factor of 2 or 3. We estimate the uncertainty associated with our best Kd values to range from 10% to 20%. To avoid implying more precision than is justified, we report Kd values above 5000 as the next

Fig. 2. Tube rotator used to mix the solution/absorber combinations.

lower thousand (K) value. In some cases where we feel the uncertainty is unusually high, even though the Kd value is less than 5000, we report the Kd as the next lower hundred value.

The need for highly precise Kd values decreases as the Kd values increase. For example, the difference between a Kd value of 5000 (99.98% sorbed) and a Kd value of 10,000 (99.99% sorbed) is only 0.01%. We therefore elected to evaluate a larger number of candidate absorbers, rather than spend a comparable effort trying to increase the number of significant figures in our measured Kd values. If it is necessary to determine Kd values with higher accuracy, such data can be obtained in follow-up studies, which would be limited to the most promising absorbers identified in our screening studies.

F. Corrections

Because the solution weights of the postcontact assay portions usually differed slightly from that of the precontact standard solution, each postcontact solution was normalized to the same weight basis as the standard.

We also made appropriate corrections to account for the fact that the liquid/solid ratio and the remaining activity of every radionuclide decreased as successive assay portions were removed.

To determine the quantities of sorbed radionuclides, we compared the activity of each radionuclide in the postcontact solution with the activity of that same radionuclide in the precontact standard. Because most absorbers were initially added in air-dried form, the aqueous solvent was often preferentially sorbed, which decreased the aqueous volume and simultaneously increased the concentration of the solutes. Consequently, the activity of certain radionuclides was at times slightly higher in the postcontact solution than in the precontact solution. Whenever the postcontact/precontact solution activity ratio of a radionuclide exceeded unity, we assigned a value of 1.000 to the ratio having the highest value and normalized all other radionuclides in that same portion of solution accordingly.

We also made time-dependent corrections for the decay of ^{237}U (6.8-day half-life), ^{56}Ni (6.1-day half-life), and ^{48}V (16-day half-life) during the gamma assay period. All calculations and corrections were performed in an EXCEL^{TM} spreadsheet.

G. Other Sources of Error

Each combination of element/absorber/contact time was measured only once. The absence of duplicates is offset by the fact that we measured individual Kd values for three consecutive contact periods. Any abrupt change in the expected smooth trend of these three data points indicates an unreliable point.

Poor precision is also indicated by excessive variation within a set of three data points where no trend is evident. For very low or very high Kd values, the variation is expected to be large for reasons already discussed.

The difficulties in accurately correcting for the complex background under the low-energy (59.5-keV) gamma peak of ^{241}Am resulted in Kd values with unusually large uncertainties for this element.

H. Data Transfer and Processing

To save time and also minimize the human errors that can be introduced in transcribing large quantities of data, we automated the data transfer and calculation process. We used *Gamanal*⁶ to determine the area of each gamma peak from the raw data in the multichannel analyzer memory. *Gamanal* provides a complete qualitative and quantitative analysis of mixtures of radionuclides by computer interpretation of high-resolution gamma spectra. *Gamanal* determines background,

fits and resolves complex peak groupings, determines the energies and absolute intensities of the gamma rays, and calculates the quantities of the source radionuclides. All interferences are resolved by a least-squares solution of the matrix of equations for the gamma intensities.

The *Gamanal* output was electronically imported into an EXCEL^{TM} spreadsheet in which the described calculations and corrections were applied. Finally, all calculated Kd values were combined into one master spreadsheet and converted to a database to provide tabulated comparisons of the measured Kd values according to element and absorber. Because small Kd values always have large associated uncertainties, we rounded all Kd values to not more than one place beyond the decimal point.

I. Calculation of Detection Limits

When peaks in a gamma spectrum were too small to be detected by the *Gamanal* program, we used a simple method⁷ to calculate the appropriate detection limits. First, for each radionuclide of interest, the same detector was used to determine the peak position and full width at half maximum (FWHM) from a spectrum with a strong gamma signal. The FWHM then was doubled to include the entire gamma-peak region (and always rounded up to the next integer) to define the position and width of the region of interest to be applied to the background spectra. The number of background counts in this region was summed, and the square root of the sum multiplied by a confidence-limit scale factor. A scale-factor value of 2.772 was used to ensure that 95% of the signal peaks of this magnitude would be statistically detected on the observed background.

The scale factor was determined as follows. Counting statistics dictate that the square root of the number of counts in a region is an estimate of the standard deviation uncertainty of those counts. The detection of a peak requires that the background in the region of interest be subtracted; the single standard deviation of their difference is the square root of the sum of the squares of the single-standard-deviation values for each of the two spectra. Thus, the standard deviation is the square root of the sums of the counts in the two corresponding regions of interest.

Because the hypothetical sample spectrum contains no detectable peak signal, the number of counts in the sample region of interest is equal to the number of counts in the background. Therefore, an estimate of the single-standard-deviation uncertainty (the confidence limits of

detection) is the square root of twice the number of background counts, or 1.414 times the square root of the number of background counts. Scaling to exactly two standard deviations (95.44% confidence) would yield a scale factor of 2.828. Standard math tables permit the scale factor to be calculated to any desired confidence limit.

Using these calculated minimum peak area values that could be detected with a 95% confidence level to calculate the corresponding minimum Kd values, we report Kd values in terms of *greater than* (>) the computed minimum Kd values.

III. RESULTS AND DISCUSSION

A. Individual Elements

Tables 5 through 19 list the most promising absorbers for each element, ranked in order of Kd value, for sorption from simulated DSSF solution. Partitioning agents that sorb the specified element poorly are generally omitted from these tables, although absorbers designated as baseline technologies for TWRS are always included, even when they perform poorly. A complete listing for all elements for each absorber is presented in Section III.B, Individual Absorbers.

1. **Cerium.** Many absorbers offer at least triple-digit Kd values for sorbing cerium from DSSF simulant.

Table 5. Cerium Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
ZrP-PAN	>1500	>1500	>1500
MgAlHT	378	664	673
SNL/HTO	282	416	542
Bone char	160	>1500	>1600
TiSbA-PAN	65	212	376
Nusorb™ Ferroc carbon A	15	124	920
TiP-PAN	10	34	65
NM-PAN	8.5	18	29
NiFC-PAN	7.6	9.3	19
SNL/CST 141	6.5	9.6	17
Durasil™ 230	6.1	21	45
MnO-PAN	4.1	26	193
Ionsiv™ TIE-96 (mod.)	1.8	14	41
Nusorb™ LP-70-S	1.6	17	124
Nusorb™ Unitane	1.3	18	112
TiO-PAN	0.6	34	>100

2. **Cesium.** The CSTs, CoFC-PSF composite, and resorcinol/formaldehyde (RF) resin all offer triple-digit Kd values for sorbing cesium from DSSF simulant.

Table 6. Cesium Distribution Data			
Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
SNL/CST 141	530	649	736
SNL/CST 149	436	570	612
CoFC-PSF	55	213	354
Duolite™ CS-100	46	49	50
SRS RF BSC-187	46	140	236
M315-PAN	29	30	29
SNL/CST 120	20	26	27
NiFC-PAN	16	2.6	2.4
TiFC-PSF	14	20	23
Ionsiv™ TIE-96	9.1	11	12
Ionsiv™ TIE-96 (mod.)	8.2	11	12

3. Strontium. The number of effective absorbers for removing strontium from alkaline solution is especially large. More than 20 absorbers offer four-digit Kd values for sorbing strontium from DSSF simulant.

Table 7. Strontium Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
KW-4-40x	>26K	>25K	>26K
SNL/HTO	23K	10K	>24K
SNL/CST 120	13K	>32K	>32K
KW-4-41x	11K	>26K	>25K
MnO-PAN	8K	>27K	>27K
TiO-PAN	6K	24K	>29K
ZrP-PAN	6K	>26K	>27K
CSbA-PAN	5K	18K	19K
NM-PAN	>5K	27K	>28K
TiP-PAN	2708	6K	9K
NaTiO-PAN	2415	9K	25K
SNL/CST 149	2047	3808	4692
Diphonix™	1930	4921	7K
NiFC-PAN	1750	5K	12K
SNL/CST 141	1319	1839	2343
SnSbA-PAN	1105	4911	9K
TiSbA-PAN	935	1671	3644
MgO-PAN	751	1214	1690
Bone char	713	2378	4836
Duolite™ C-467	324	604	777
MgAlHT	301	513	710
Amberlite™ IRC-718	244	632	969
Ionsiv™ TIE-96	235	484	657
Ionsiv™ TIE-96 (mod.)	222	578	1053
Nusorb™ Ferroc carbon A	215	723	1753
NK 120B	211	251	273
Tannin	203	476	761
TiFC-PSF	147	1076	1716
Chelex™ 100	135	345	358
Duolite™ CS-100	70	106	126
ZrO-PAN	43	398	2077
SRS RF BSC-187	42	88	124
CoFC-PSF	34	140	1222
LIX™-54	32	108	185
Amberlite™ DP-1	25	32	34
Nusorb™ Unitane	19	117	504
AMP-PAN	18	26	33
ZrOP-PAN	15	113	1031

4. **Technetium.** Many anion exchange resins and several extractants whose structures mimic anion exchange functional groups provide triple-digit Kd values for sorbing technetium from DSSF simulant.

Table 8. Technetium Distribution Data			
Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
Reillex™ HPQ	254	293	332
Purolite™ A-520-E	189	392	527
Aliquat™ 336	177	464	524
Sybron (Et) ₃ N	167	401	471
Cyanex™ 923	121	244	230
Ionac™ SR-3	115	279	312
Sybron (Pr) ₃ N	96	257	390
Ionac™ SR-6	45	105	188
Nusorb™ LP-70-S	15	24	26

5. **Yttrium.** More than 15 absorbers offer at least triple-digit Kd values for yttrium.

Table 9. Yttrium Distribution Data			
Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
ZrP-PAN	456	644	1340
SNL/HTO	245	288	465
NiFC-PAN	174	379	940
NM-PAN	128	316	635
MgAlHT	121	258	332
TiO-PAN	108	429	622
Bone char	97	529	723
MgO-PAN	83	164	394
Ionsiv™ TIE-96 (mod.)	82	221	410
Ionsiv™ TIE-96	72	133	241
MnO-PAN	60	336	665
NaTiO-PAN	52	135	389
Duolite™ CS-100	52	123	187
TiSbA-PSF	51	167	413
Diphonix™	44	66	71
SNL/CST 120	32	67	93
Ba(Ca)SO ₄ -PAN	28	74	197
Amberlite™ DP-1	21	42	76
TiP-PAN	19	37	66
Durasil™ 230	16	44	165
Nusorb™ Ferroc carbon A	11	30	146

6. Chromium. Only tannin and the RF resin offer high Kd values for sorbing chromium from DSSF simulant; moreover, the sorption kinetics are very slow in both cases.

Table 10. Chromium Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
Ba(Ca)SO ₄ -PAN	7.7	11	14
Tannin	6.7	59	2213
Resin Tech™ 3972	5.3	6.5	6.4
SRS RF BSC-187	2.9	43	413

7. Cobalt. Only Nusorb™ LP-70-S sorbs cobalt with a triple-digit Kd value, although many other absorbers offer high double-digit Kd values.

Table 11. Cobalt Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
Nusorb™ LP-70-S	44	262	443
NiFC-PAN	29	65	89
Duolite™ CS-100	25	51	85
NM-PAN	20	39	45
Bone char	14	28	40
Tannin	13	29	49
SRS RF BSC-187	5.9	19	41
Nusorb™ Ferrocabon A	2.3	6.1	19
TiFC-PSF	0.8	5.5	14

8. Iron. The high Kd values for sorbing iron on many absorbers from DSSF solution may preclude their use for sorbing other elements of interest.

Table 12. Iron Distribution Data			
Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
ZrP-PAN	>1400	>1800	>1900
MnO-PAN	>1300	>1400	>1400
TiO-PAN	1174	>4900	>5200
NiFC-PAN	586	2621	>4400
SNL/HTO	526	267	253
NM-PAN	524	1353	1592
Tannin	452	721	>1600
Duolite™ CS-100	277	590	1011
MgO-PAN	174	304	403
NATiO-PAN	120	602	1373
TiSbA-PAN	97	308	519
SRS RF BSC-187	72	209	330
TiP-PAN	70	99	131
Ionsiv™ TIE-96	69	215	478
MgAlHT	61	77	96
Ionsiv™ TIE-96 (mod.)	47	234	720
SnSbA-PAN	24	45	71
Nusorb™ Ferrocabon A	18	46	230
TiFC-PAN	13	115	230
ZrO-PAN	13	63	291
CoFC-PSF	5.2	31	145
ZrOP-PAN	4.2	21	134

9. Manganese. Many absorbers offer high Kd values for sorbing manganese from DSSF simulant, which may preclude the use of these absorbers for removing other elements of interest.

Table 13. Manganese Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
ZrP-PAN	1072	>5600	>5900
MnO-PAN	483	>4200	>4600
TiO-PAN	318	658	1483
SNL/HTO	313	353	501
Duolite™ CS-100	204	377	687
Tannin	123	217	362
TiP-PAN	67	129	217
NiFC-PAN	58	235	232
NaTiO-PAN	58	218	622
NM-PAN	46	296	1364
TiSbA-PAN	52	160	372
Ionsiv™ TIE-96	42	115	268
Ionsiv™ TIE-96 (mod.)	31	151	506
MgAlHT	20	40	90
SRS RF BSC-187	20	56	111
TiFC-PSF	12	108	283
ZrO-PAN	12	46	143
Nusorb™ Ferroc carbon A	11	31	189
Durasil™ 230	11	51	418
CoFC-PSF	7.8	39	217
SNL/CST 120	7.2	36	240
ZrOP-PAN	4.8	24	131

10. Nickel. Five absorbers offer at least triple-digit Kd values for sorbing nickel from DSSF simulant.

Table 14. Nickel Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
NiFC-PAN	357	1290	>1800
NM-PAN	150	612	660
Bone char	92	184	109
Duolite™ CS-100	68	140	219
Nusorb™ LP-70-S	63	472	481
LIX™-54	12	27	64
SRS RF BSC-187	6.8	21	50
Amberlite™ IRC-718	6.6	15	28
Tannin	6.6	12	10
ZrP-PAN	6.5	9.5	12
Nusorb™ Ferroc carbon A	3.6	11	33
Chelex™ 100	3.3	8.3	20
TiFC-PSF	3.0	18	33
MgO-PAN	2.3	9.2	34

11. Vanadium. Only Zr-PAN offers even double-digit Kd values for sorbing vanadium from DSSF simulant.

Table 15. Vanadium Distribution Data			
Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
ZrP-PAN	2.3	39	44
ZrO-PAN	1.4	2.2	5.0
ZrOP-PAN	0.8	2.3	3.4

12. Zinc. Seven absorbers offer at least triple-digit Kd values for sorbing zinc from DSSF simulant.

Table 16. Zinc Distribution Data			
Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
NiFC-PAN	309	819	1116
MgO-PAN	251	429	502
TiO-PAN	217	317	365
NM-PAN	163	364	483
SNL/HTO	107	170	207
TiP-PAN	72	228	334
MnO-PAN	68	132	241
ZrP-PAN	18	64	92
MgAlHT	13	19	27
Bone char	10	15	18
Ionsiv™ TIE-96	9.5	9.7	15
Tannin	8.5	13	16
Diphonix™	8.5	9.8	11
ZrO-PAN	5.5	15	30
NaTiO-PAN	5.5	11	23
Ionsiv™ TIE-96	5.5	7.7	13
SnSbA-PAN	4.7	8.5	16
TiSbA-PAN	4.0	8.2	20
ZrOP-PAN	2.0	8.8	22
CoFC-PSF	1.0	5.2	14

13. Zirconium. More than ten absorbers offer at least triple-digit Kd values for sorbing zirconium from DSSF simulant.

Table 17. Zirconium Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
TiO-PAN	2242	4780	4841
ZrP-PAN	2032	>3400	>3600
SNL/HTO	1444	1625	2735
NK 120B	199	169	176
TiP-PAN	108	260	461
Tannin	87	168	260
TiSbA-PAN	79	453	892
MnO-PAN	59	112	171
Ionsiv™ TIE-96	55	191	414
Duolite™ CS-100	48	92	142
Ionsiv™ TIE-96 (mod.)	38	189	527
Bone char	36	72	95
SNL/CST 120	36	31	57
NK 194	32	45	47
Diphonix™	28	52	78
KW-4-40x	18	54	115
SNL/CST 149	16	25	28
MgO-PAN	15	25	41
SRS RF BSC-187	13	37	68
ZrO-PAN	10	44	170
TiFC-PSF	9.1	74	195
Durasil™ 230	7.9	16	35
ZrOP-PAN	3.5	17	102

14. Uranium. Four absorbers, three of which contain titanium, offer at least triple-digit Kd values for sorbing uranium from DSSF simulant.

Table 18. Uranium Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
SNL/HTO	622	1419	>2300
TiO-PAN	574	1707	2671
TiP-PAN	101	369	872
ZrP-PAN	51	296	340
SNL/CST 120	26	25	28
Tannin	20	37	57
Ionsiv™ TIE-96	14	28	71
NaTiO-PAN	12	32	69
Ionsiv™ TIE-96 (mod.)	8.7	20	53
Diphonix™	7.4	6.2	4.9
ZrO-PAN	6.3	23	89
TiSbA-PAN	5.2	15	69
SRS RF BSC-187	3.8	11	23
TiFC-PSF	2.7	19	40
ZrOP-PAN	1.8	10	40

15. Americium. Many absorbers offer at least triple-digit Kd values for sorbing americium from DSSF simulant.

Table 19. Americium Distribution Data

Absorber	Kd Value for Specified Time		
	30 min	2 h	6 h
ZrP-PAN	>580	>590	>590
Bone char	215	>590	>590
MgAlHT	76	163	215
SNL/HTO	66	104	172
KW-4-40x	60	70	75
NiFC-PAN	53	93	170
KW-4-41x	46	59	60
NM-PAN	38	83	132
TiSbA-PAN	28	52	95
MnO-PAN	22	83	473
Nusorb™ Ferrocabon A	22	109	602
TiO-PAN	17	135	647
Duolite™ CS-100	12	22	63
MgO-PAN	11	13	38
TiP-PAN	10	19	31
Durasil™ 230	9.5	28	78
Nusorb™ LP-70-S	9.3	29	41
Ionsiv™ TIE-96 (mod.)	9.0	27	66
Diphonix™	6.2	12	22
NaTiO-PAN	5.9	7.9	19
CoFC-PSF	3.5	6.2	28

B. Individual Absorbers

Tables 20 through 77 present Kd values for sorption of all 15 elements onto each of the 58 absorbers from simulated DSSF solution. The measured Kd values for three different times — 30 min, 2 h, and 6 h — provide some limited information about the sorption kinetics. Moreover, because we measured the sorption of 15 different elements, these tables provide information about which unwanted elements are most likely to interfere with the targeted element by competing for absorber sites. Therefore, Tables 20 through 77 may be used to predict the selectivity of each individual absorber for any of these elements.

Although long-term stability is an essential attribute of any absorber that would be seriously considered for

waste processing, we made no attempt to evaluate the stability of these absorbers in the simulated DSSF solution. All candidate absorbers were included in our tests unless we observed noticeable degradation in the test solution. Although we eliminated those absorbers whose chemical degradation was apparent, we recommend that the remaining absorbers that show promise for HLW tank processing should be evaluated for long-term chemical stability and for radiation resistance if these properties are not already known.

1. Commercially Available Absorbers. The 23 commercially available absorbers listed in Table 4 were included in our study.

a. Amberlite™ DP-1 Cation Exchange Resin. Amberlite™ DP-1, manufactured by Rohm & Haas, Philadelphia, Pennsylvania, is a weak-acid cation exchanger consisting of a crosslinked methacrylic polymer with carboxylic acid functionality. This resin was air-dried before use.

Table 20 shows that Amberlite™ DP-1 sorbs yttrium and strontium from DSSF simulant at useful levels.

Table 20. Amberlite™ DP-1 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	0.4
Cs	6.6	4.8	3.4
Sr	25	32	34
Tc	6.2	4.6	3.2
Y	21	42	76
Cr	6.0	4.4	3.2
Co	0.4	0.6	0.7
Fe	3.1	4.3	5.4
Mn	1.7	1.9	2.1
Ni	0.8	1.6	2.3
V	0.3	<0.1	<0.1
Zn	0.8	1.0	1.1
Zr	2.9	4.3	6.5
U	<0.1	<0.1	0.3
Am	5.2	5.7	7.3

b. Amberlite™ IRC-76 Cation Exchange Resin. Amberlite™ IRC-76, manufactured by Rohm & Haas, Philadelphia, Pennsylvania, is a weak-acid cation exchanger consisting of a crosslinked acrylic acid polymer with carboxylic acid functionality. This resin was air-dried before use.

Only strontium and manganese are sorbed with even double-digit Kd values.

Table 21. Amberlite™ IRC-76 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	1.9	3.7	4.2
Sr	17	37	58
Tc	2.0	3.7	4.2
Y	1.1	2.4	4.1
Cr	1.6	3.2	3.8
Co	0.3	0.6	0.9
Fe	2.9	3.7	3.7
Mn	4.1	9.2	14
Ni	1.0	1.6	1.6
V	<0.1	<0.1	<0.1
Zn	0.5	0.8	0.8
Zr	0.8	1.9	2.6
U	0.2	0.5	0.7
Am	1.0	1.8	2.4

c. Amberlite™ IRC-718 Cation Exchange Resin. Amberlite™ IRC-718, manufactured by Rohm & Haas, Philadelphia, Pennsylvania, is a weak-acid cation exchanger consisting of a styrene/divinylbenzene copolymer with iminodiacetic acid functionality. This resin was air-dried before use.

Amberlite™ IRC-718 sorbs strontium well and yttrium, nickel, and americium at useful, but much lower, Kd values.

Table 22. Amberlite™ IRC-718 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	3.6
Cs	2.2	2.0	2.0
Sr	244	632	969
Tc	5.8	5.6	5.7
Y	9.9	22	34
Cr	1.9	1.7	2.0
Co	0.6	1.0	1.1
Fe	2.1	2.4	2.8
Mn	2.1	3.0	3.4
Ni	6.6	15	28
V	<0.1	<0.1	<0.1
Zn	1.0	1.3	1.4
Zr	0.7	1.4	1.8
U	0.4	0.3	0.7
Am	1.4	4.8	12

d. Bone Char Absorber. Bone char, produced by calcining cattle bones in the absence of air, was obtained from Stauffer Chemical Company, Westport, Connecticut. Bone char, which is predominantly calcium phosphate, was used as received.

Bone char sorbs strontium, cerium, americium, yttrium, and nickel well from DSSF simulant.

Table 23. Bone Char Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	160	>1500	>1600
Cs	<0.1	<0.1	<0.1
Sr	713	2378	4836
Tc	0.7	1.0	1.2
Y	97	529	723
Cr	0.1	0.3	0.7
Co	14	28	40
Fe	13	18	24
Mn	22	38	60
Ni	92	184	109
V	<0.1	<0.1	<0.1
Zn	10	15	18
Zr	36	72	95
U	3.7	5.9	6.0
Am	215	>590	>590

e. Chelex™ 100 Cation Exchange Resin. Chelex™ 100, manufactured by the Dow Chemical Company, Midland, Michigan, is a weak-acid cation exchanger that consists of a styrene/divinylbenzene copolymer with iminodiacetic acid functionality. This resin was air-dried before use.

Chelex™ 100 provides high selectivity for sorbing strontium from DSSF simulant, with nickel the only other element sorbed with even a double-digit Kd value.

Table 24. Chelex™ 100 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	4.2	6.3	4.7
Sr	135	345	358
Tc	5.6	7.9	6.2
Y	1.1	0.4	1.2
Cr	4.2	6.3	4.8
Co	0.7	0.9	1.0
Fe	0.6	0.8	1.1
Mn	0.7	0.7	1.1
Ni	3.3	8.3	20
V	0.4	<0.1	<0.1
Zn	0.3	0.4	0.5
Zr	0.4	0.4	0.6
U	<0.1	0.4	0.4
Am	0.2	2.1	1.9

f. Diphonix™ Cation Exchange Resin. Diphonix™, a polyfunctional resin that contains diphosphonic acid, sulfonic acid, and carboxylic acid functional groups, was obtained from EICRoM Industries, Inc., Darien, Illinois. We air-dried this resin before testing for reasons detailed in Section II.C.

Diphonix™ resin sorbs strontium well and sorbs numerous other elements with double-digit Kd values from DSSF simulant.

Table 25. Diphonix™ Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	12	47
Cs	0.8	0.3	0.3
Sr	1930	4921	7K
Tc	2.6	2.5	2.5
Y	44	66	71
Cr	0.5	0.1	0.2
Co	1.2	0.8	1.0
Fe	18	25	29
Mn	5.6	4.0	4.4
Ni	<0.1	1.5	4.6
V	0.9	0.2	0.2
Zn	8.5	9.8	11
Zr	28	52	78
U	7.4	6.2	4.9
Am	6.2	12	22

g. Duolite™ CS-100 Cation Exchange Resin. Duolite™ CS-100 is a phenol-formaldehyde condensate cation exchange resin manufactured by Rohm & Haas, Philadelphia, Pennsylvania. (However, Rohm & Haas has recently discontinued CS-100 as one of their standard products.) This resin was air-dried before use.

Duolite™ CS-100 resin, the current baseline technology for removing cesium from Hanford waste, sorbs cesium with only a moderate Kd value. However, six other elements, including high-concentration matrix elements iron, manganese, and nickel, are sorbed with at least triple-digit Kd values and could seriously interfere with cesium sorption.

Table 26. Duolite™ CS-100 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	5.0	5.6	19
Cs	46	49	50
Sr	70	106	126
Tc	<0.1	<0.1	0.3
Y	52	123	187
Cr	0.7	1.7	4.7
Co	25	51	85
Fe	277	590	1011
Mn	204	377	687
Ni	68	140	219
V	<0.1	<0.1	<0.1
Zn	2.6	4.0	5.9
Zr	48	92	142
U	6.5	8.0	7.7
Am	12	22	63

h. Duolite™ C-467 Cation Exchange Resin. Duolite™ C-467, a chelating cation exchange resin composed of a polystyrene/divinylbenzene copolymer with aminophosphonic acid functionality, is manufactured by Rohm & Haas, Philadelphia, Pennsylvania. This resin was air-dried before use.

Duolite™ C-467 provides high selectivity for strontium from DSSF simulant, with a Kd 30-fold higher than that for yttrium, the only other element with even a double-digit Kd value. The commercial availability of this resin at moderate cost makes it an attractive candidate for removing strontium from alkaline solution.

Table 27. Duolite™ C-467 Cation Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	1.1
Cs	6.6	4.8	2.2
Sr	324	604	777
Tc	10	9.0	6.4
Y	7.5	17	25
Cr	6.7	5.0	2.4
Co	0.3	0.4	0.8
Fe	0.8	1.0	1.3
Mn	1.9	2.1	2.3
Ni	<0.1	2.8	5.6
V	0.4	0.1	0.1
Zn	0.5	0.6	0.8
Zr	0.3	0.5	0.7
U	0.2	0.2	0.5
Am	6.3	7.4	8.0

i. Durasil™ 190 Resin. Durasil™ 190, a vitreous glass absorber obtained from the Duratek Corporation, Beltsville, Maryland, was used as received.

Durasil™ 190 sorbs none of the 15 elements from DSSF simulant at useful levels.

Table 28. Durasil™ 190 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	1.4
Cs	4.4	1.2	1.0
Sr	4.5	1.7	2.2
Tc	5.0	2.0	1.8
Y	1.5	1.6	5.2
Cr	4.3	1.3	1.1
Co	0.7	0.4	0.6
Fe	1.5	0.9	1.3
Mn	0.8	0.5	1.1
Ni	<0.1	0.3	0.8
V	0.7	0.2	0.2
Zn	0.8	0.5	0.6
Zr	0.4	0.4	0.9
U	0.9	0.5	0.6
Am	2.7	0.9	2.2

j. Durasil™ 230 Resin. Durasil™ 230, an aluminosilicate absorber obtained from the Duratek Corporation, Beltsville, Maryland, was used as received.

Durasil™ 230 sorbs manganese and yttrium with triple-digit Kd values and sorbs six other elements with double-digit Kd values.

Table 29. Durasil™ 230 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	6.1	21	45
Cs	10	13	13
Sr	17	38	69
Tc	0.2	0.3	0.1
Y	16	44	165
Cr	<0.1	<0.1	<0.1
Co	0.7	1.1	1.2
Fe	5.6	13	43
Mn	11	51	418
Ni	2.8	5.5	7.5
V	<0.1	<0.1	<0.1
Zn	2.1	3.2	3.8
Zr	7.9	16	35
U	0.7	1.1	1.2
Am	9.5	28	78

k. Ionac™ SR-3 Anion Exchange Resin. Ionac™ SR-3, a macroporous strong-base anion exchange resin with trimethyl amine as the functional group, was obtained from Sybron Chemicals, Inc., Birmingham, New Jersey. This resin was air-dried before use.

Ionac™ SR-3 sorbs technetium strongly and quite selectively from DSSF simulant.

Table 30. Ionac™ SR-3 Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	3.4	4.4	2.9
Sr	3.5	4.6	3.1
Tc	115	279	312
Y	0.3	1.2	2.2
Cr	3.4	4.5	3.2
Co	0.6	0.9	1.0
Fe	0.6	0.9	1.3
Mn	0.8	1.2	1.4
Ni	0.9	0.9	1.7
V	<0.1	<0.1	<0.1
Zn	0.5	0.7	0.9
Zr	0.4	0.8	1.0
U	0.6	0.7	0.8
Am	3.0	3.6	3.0

l. Ionac™ SR-6 Anion Exchange Resin. Ionac™ SR-6, a macroporous strong-base anion exchange resin with tributyl amine as the functional group, was obtained from Sybron Chemicals, Inc., Birmingham, New Jersey. Ionac™ SR-6 resin has been reported⁸ to offer greatly increased selectivity for sorbing nitrate ion from groundwater. This resin was air-dried before use.

Ionac™ SR-6 sorbs technetium selectively from DSSF simulant, although not as strongly as does Ionac™ SR-3.

Table 31. Ionac™ SR-6 Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	3.6	2.2	3.5
Cs	<0.1	<0.1	<0.1
Sr	0.5	0.5	0.5
Tc	45	105	188
Y	0.2	1.5	2.7
Cr	<0.1	0.2	0.3
Co	0.4	0.6	0.8
Fe	0.9	1.5	1.8
Mn	0.5	0.7	1.2
Ni	0.4	0.8	1.1
V	<0.1	<0.1	<0.1
Zn	0.3	0.5	0.7
Zr	0.4	0.8	1.0
U	<0.1	0.5	0.7
Am	3.3	4.0	5.4

m. Ionsiv™ TIE-96 Absorber. Ionsiv™ TIE-96 is a titanium-loaded zeolite manufactured by UOP Molecular Sieves Division, Moorestown, New Jersey. This absorber was used as received.

Ionsiv™ TIE-96 sorbs strontium, iron, zirconium, and manganese well from DSSF simulant. Several other elements are sorbed at lower, but useful, levels.

**Table 32. Ionsiv™ TIE-96 Absorber:
Distribution of 15 Elements from Simulated
Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	13	28
Cs	9.1	11	12
Sr	235	484	657
Tc	1.4	0.4	0.4
Y	72	133	241
Cr	1.9	1.0	0.9
Co	4.8	1.8	2.0
Fe	69	215	478
Mn	42	115	268
Ni	<0.1	<0.1	1.0
V	4.3	1.0	0.9
Zn	9.5	9.7	15
Zr	55	191	414
U	14	28	71
Am	4.3	16	39

n. Ionsiv™ TIE-96 (Modified) Absorber. Ionsiv™ TIE-96 (modified) is an improved version of the Ionsiv™ TIE-96 titanium-loaded zeolite manufactured by UOP Molecular Sieves Division, Moorestown, New Jersey. This absorber was used as received.

The modified form of Ionsiv™ TIE-96 provides a generally improved version of the sorption pattern of unmodified Ionsiv™ TIE-96.

**Table 33. Ionsiv™ TIE-96 (Modified)
Absorber: Distribution of 15 Elements from
Simulated Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	1.8	14	41
Cs	8.2	11	12
Sr	222	578	1053
Tc	<0.1	<0.1	<0.1
Y	82	221	410
Cr	0.1	0.4	0.2
Co	2.1	1.3	1.4
Fe	47	234	720
Mn	31	151	506
Ni	<0.1	0.7	2.3
V	1.5	0.4	0.4
Zn	5.5	7.7	13
Zr	38	189	527
U	8.7	20	53
Am	9.0	27	66

o. Nusorb™ Ferrocabon A Absorber. Nusorb™ Ferrocabon A is a carbon/iron oxide composite manufactured by Nucon International, Inc., Columbus, Ohio. This material was used as received.

Nusorb™ Ferrocabon A sorbs strontium, cerium, americium, iron, manganese, and yttrium with at least triple-digit Kd values.

**Table 34. Nusorb™ Ferrocabon A Absorber:
Distribution of 15 Elements from Simulated
Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	15	124	920
Cs	1.2	2.1	2.0
Sr	215	723	1753
Tc	3.1	3.7	4.2
Y	11	30	146
Cr	7.3	6.9	2.9
Co	2.3	6.1	19
Fe	18	46	230
Mn	11	31	189
Ni	3.6	11	33
V	<0.1	<0.1	<0.1
Zn	1.5	3.0	5.3
Zr	2.7	6.1	16
U	0.7	1.0	1.0
Am	22	109	602

p. Nusorb™ LP-70-S Absorber. Nusorb™ LP-70-S, an activated carbon whose surface is activated to provide cation exchange functionality, is manufactured by Nucon International, Inc., Columbus, Ohio. This material was used as received.

Nusorb™ LP-70-S strongly sorbs nickel and cobalt, both of which have radioisotopes of environmental concern. Several other elements also are sorbed at useful levels.

**Table 35. Nusorb™ LP-70-S Absorber:
Distribution of 15 Elements from Simulated
Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	1.6	17	124
Cs	1.8	1.8	1.6
Sr	4.9	9.0	15
Tc	15	24	26
Y	5.8	28	93
Cr	<0.1	<0.1	<0.1
Co	44	262	443
Fe	2.0	3.4	5.6
Mn	7.2	16	45
Ni	63	472	481
V	<0.1	<0.1	<0.1
Zn	0.6	0.6	0.9
Zr	1.7	3.6	6.0
U	0.5	0.5	0.5
Am	9.3	29	41

q. Nusorb™ Magnetite Absorber. Nusorb™ Magnetite, a porous low-density single-phase Fe_3O_4 , is manufactured by Nucon International, Inc., Columbus, Ohio. This material was used as received.

Even the elements best sorbed from DSSF simulant by Nusorb™ Magnetite sorb only at low to moderate levels.

**Table 36. Nusorb™ Magnetite Absorber:
Distribution of 15 Elements from Simulated
Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	0.2	<0.1	6.1
Cs	<0.1	<0.1	<0.1
Sr	3.4	7.0	12
Tc	0.8	0.6	0.6
Y	2.8	6.8	12
Cr	<0.1	0.3	0.3
Co	0.3	0.5	0.8
Fe	2.2	4.4	8.7
Mn	1.0	2.3	4.5
Ni	0.9	1.7	2.4
V	<0.1	<0.1	<0.1
Zn	0.4	0.6	0.8
Zr	1.0	1.5	1.8
U	0.7	0.7	1.0
Am	1.4	4.4	9.7

r. Nusorb™ Unitane Absorber. Nusorb™ Unitane, titanium oxide beads with pores in the 1- to 10- μm range, is manufactured by Nucon International, Inc., Columbus, Ohio. This material was used as received.

Nusorb™ Unitane sorbs strontium and cerium with triple-digit Kd values, and several other elements are sorbed with useful, but lower, Kd values.

**Table 37. Nusorb™ Unitane Absorber:
Distribution of 15 Elements from Simulated
Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	1.3	18	112
Cs	0.2	0.2	<0.1
Sr	19	117	504
Tc	0.5	0.8	0.9
Y	6.1	20	75
Cr	0.1	0.3	0.2
Co	0.6	2.0	5.4
Fe	5.1	13	35
Mn	4.4	13	40
Ni	1.9	4.9	13
V	<0.1	<0.1	<0.1
Zn	1.1	1.6	2.0
Zr	2.7	6.2	10
U	0.3	0.9	1.0
Am	3.3	17	55

s. Purolite™ A-520-E Anion Exchange Resin.

Purolite™ A-520-E, a macroporous strong-base anion exchange resin with triethyl amine as the functional group, was obtained from the Purolite Company, Bala Cynwyd, Pennsylvania. This resin was air-dried before use.

Purolite™ A-520-E sorbs technetium strongly and quite selectively from DSSF simulant.

Table 38. Purolite™ A-520-E Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	5.4	6.0	19
Cs	0.2	<0.1	<0.1
Sr	0.4	0.4	0.4
Tc	189	392	527
Y	2.8	3.4	4.3
Cr	<0.1	<0.1	0.1
Co	0.3	0.4	0.7
Fe	0.2	1.0	1.4
Mn	0.5	1.0	1.5
Ni	0.6	0.9	1.5
V	<0.1	<0.1	<0.1
Zn	<0.1	0.2	0.6
Zr	0.6	1.4	1.5
U	<0.1	0.4	0.7
Am	4.9	5.4	8.8

t. Reillex™ HPQ Anion Exchange Resin. Reillex™

HPQ, a strong-base polyvinylpyridine anion exchange resin, was obtained from Reilly Industries, Inc., Indianapolis, Indiana. This resin was converted from the as-received chloride form to the nitrate form and air-dried before use.

Reillex™ HPQ sorbs technetium strongly and quite selectively from DSSF simulant.

Table 39. Reillex™ HPQ Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	1.2	7.4
Cs	2.4	0.5	0.5
Sr	2.8	0.7	0.8
Tc	254	293	332
Y	5.3	11	25
Cr	2.5	0.7	0.8
Co	1.9	1.1	1.6
Fe	2.5	1.8	2.3
Mn	4.1	8.5	12
Ni	<0.1	2.5	10
V	1.4	0.3	0.3
Zn	1.6	0.6	0.9
Zr	1.7	1.4	2.3
U	1.5	0.4	0.9
Am	3.9	5.7	10

u. Resin Tech™ 3972 Resin. Resin Tech™ 3972, a styrene/divinylbenzene copolymer with phosphorous acid functionality, is manufactured by Resin Tech, Inc., Cherry Hill, New Jersey. This resin was air-dried before use.

Resin Tech™ 3972 offers useful Kd values for sorbing strontium, manganese, yttrium, and iron from DSSF simulant.

**Table 40. Resin Tech™ 3972 Resin:
Distribution of 15 Elements from Simulated
Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	5.8	6.7	6.6
Sr	17	51	93
Tc	5.7	6.6	6.6
Y	4.1	12	25
Cr	5.3	6.5	6.4
Co	0.3	0.9	1.7
Fe	2.3	8.7	20
Mn	3.6	14	32
Ni	0.7	3.8	6.6
V	<0.1	<0.1	<0.1
Zn	<0.1	0.4	0.6
Zr	0.3	1.1	2.1
U	<0.1	0.2	0.4
Am	1.2	1.6	2.3

v. SRS Resorcinol/Formaldehyde (BSC-187) Resin.

Jane Bibler of Westinghouse Savannah River Company provided this sample of batch BSC-187 resin and recommended that we convert it from the as-received potassium form to a sodium form. We did this by passing ten volumes of 10% NaOH solution through a column of potassium-form resin, rinsed the column with 15 column volumes of water. The resin was air-dried before use.

SRS resorcinol/formaldehyde resin sorbs chromium, technetium, iron, cesium, strontium, and manganese with triple-digit Kd values. Five other elements are sorbed with double-digit Kd values.

**Table 41. SRS Resorcinol/Formaldehyde
(BSC-187) Resin: Distribution of 15 Elements
from Simulated Hanford DSSF Solution**

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	0.3	<0.1	0.8
Cs	46	140	236
Sr	42	88	124
Tc	3.3	39	374
Y	14	34	54
Cr	2.9	43	413
Co	5.9	19	41
Fe	72	209	330
Mn	20	56	111
Ni	6.8	21	50
V	<0.1	<0.1	<0.1
Zn	0.6	1.4	1.6
Zr	13	37	68
U	3.8	11	23
Am	0.8	2.6	5.1

w. Tannin Absorber. Tannin absorber was obtained from Mitsubishi Nuclear Fuels Corporation, Japan. We air-dried this absorber before testing for reasons detailed in Section II.C.

Tannin sorbs iron, chromium, strontium, manganese, and zirconium with at least triple-digit Kd values. All 15 elements except vanadium are sorbed with at least a double-digit Kd value.

Table 42. Tannin Absorber: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	8.5	48
Cs	12	12	12
Sr	203	476	761
Tc	4.5	14	85
Y	15	25	40
Cr	6.7	59	2213
Co	13	29	49
Fe	452	721	>1600
Mn	123	217	362
Ni	6.6	12	10
V	<0.1	<0.1	<0.1
Zn	8.5	13	16
Zr	87	168	260
U	20	37	57
Am	1.9	7.2	15

2. Experimental Inorganic Materials. Six experimental inorganic materials were included in our study. Five are pillared layered materials and one is a layered hydrotalcite material.

Pillared layered materials are obtained by modifying selected inorganic layered compounds. The modification technique first involves intercalating polar molecules, such as amines, to spread apart the layers before pillaring. Pillaring then replaces the alkylammonium ions that are initially between the layers with large metal oxy-hydroxide cations. Subsequent calcination drives off water and releases protons to create metal oxide pillars, which creates an expanded structure with large channels and cavities of fixed size and a reservoir of exchangeable protons.

a. KW-3-21x. KW-3-21x consists of $\text{HSb}(\text{PO}_4)_2$ pillared with chromium oxide. The d-spacing of this material is 27.8 Å. This pillared layered material, prepared by Karen L. Wade of LANL, was used as received.

KW-3-21x provides high and selective sorption of strontium at the shortest contact time of 30 min; however, the decreasing Kd values for longer contact times may indicate instability of this material in alkaline solution.

Table 43. KW-3-21x: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	0.6	4.3	5.4
Cs	<0.1	0.2	<0.1
Sr	624	169	80
Tc	3.2	4.2	5.0
Y	5.8	2.8	1.9
Cr	1.0	1.8	1.9
Co	<0.1	0.3	0.6
Fe	12	27	21
Mn	15	44	40
Ni	1.0	1.4	1.8
V	<0.1	<0.1	<0.1
Zn	5.2	18	23
Zr	4.3	12	12
U	1.4	4.8	17
Am	2.4	3.8	3.9

b. KW-3-58x. KW-3-58x consists of $\text{HSb}(\text{PO}_4)_2$ pillared with chromium oxide. The d-spacing of this material is 15.0 Å. This pillared layered material, prepared by Karen L. Wade of LANL, was used as received.

KW-3-58x, similar to KW-3-21x, provides high and selective sorption of strontium at the shortest contact time of 30 min, with decreasing Kd values for longer contact times. This material is less selective than KW-3-21x, and the Kd values for iron and zinc also decrease as the contact time increases.

Table 44. KW-3-58x: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	3.1	3.6	25
Cs	<0.1	<0.1	0.1
Sr	840	215	97
Tc	2.3	2.7	3.8
Y	5.2	3.4	2.8
Cr	3.1	3.6	3.9
Co	0.3	0.4	0.7
Fe	64	49	32
Mn	118	131	109
Ni	2.1	2.7	3.7
V	<0.1	<0.1	<0.1
Zn	40	35	22
Zr	17	22	16
U	3.8	6.0	16
Am	2.5	2.3	8.7

c. KW-4-40x. KW-4-40x consists of HTaWO_6 pillared with chromium oxide. The d-spacing of this material is 19.6 Å. This pillared layered material, prepared by Karen L. Wade of LANL, was used as received.

The Kd values for strontium sorption offered by KW-4-40x were too high to measure accurately and did not decrease with increased contact time. However, many other elements also are sorbed with at least triple-digit Kd values from the DSSF simulant.

Table 45. KW-4-40x: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	186	339	299
Cs	0.3	<0.1	<0.1
Sr	>26K	>25K	>26K
Tc	0.1	0.3	0.3
Y	77	154	283
Cr	<0.1	<0.1	0.1
Co	0.4	0.8	1.1
Fe	939	>2800	>2900
Mn	384	1189	2373
Ni	2.7	5.6	9.9
V	<0.1	<0.1	<0.1
Zn	126	386	752
Zr	18	54	115
U	1.4	3.1	4.5
Am	60	70	75

d. KW-4-41x. KW-4-41x consists of HTaWO₆ pillared with chromium oxide. The d-spacing of this material is 19.3 Å. This pillared layered material, prepared by Karen L. Wade of LANL, was used as received.

The K_d values for strontium sorption offered by KW-4-41x were too high to measure accurately and did not decrease with increased contact time. However, many other elements also are sorbed with at least triple-digit K_d values from the DSSF simulant.

Table 46. KW-4-41x: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	K _d Value for Specified Time		
	30 min	2 h	6 h
Ce	121	214	233
Cs	0.1	<0.1	<0.1
Sr	11K	>26K	>25K
Tc	0.5	0.2	0.4
Y	77	164	260
Cr	<0.1	<0.1	0.2
Co	0.6	0.9	1.0
Fe	752	>2800	>2800
Mn	364	983	2444
Ni	2.6	4.4	8.7
V	<0.1	<0.1	<0.1
Zn	121	361	755
Zr	18	51	102
U	2.2	3.7	7.2
Am	46	59	60

e. KW-4-42x. KW-4-42x consists of H₃Sb₃O₆(PO₄)₂ pillared with chromium oxide. The d-spacing of this material is 20.1 Å. This pillared layered material, prepared by Karen L. Wade of LANL, was used as received.

KW-4-42x provides high sorption of strontium at the shortest measured contact time of 30 min; however, the decreasing K_d values for longer contact times may indicate instability of this material in alkaline solution. The selectivity for strontium decreases at the longer contact times.

Table 47. KW-4-42x: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	K _d Value for Specified Time		
	30 min	2 h	6 h
Ce	8.0	13	23
Cs	2.0	1.9	1.9
Sr	3109	1023	297
Tc	11	10	10
Y	21	13	10
Cr	5.9	8.6	9.7
Co	0.5	0.8	1.0
Fe	192	429	334
Mn	129	328	542
Ni	1.3	2.8	4.5
V	<0.1	<0.1	<0.1
Zn	37	102	130
Zr	14	48	81
U	2.7	6.3	12
Am	6.5	6.3	9.7

f. MgAlHT. MgAlHT, a hydrotalcite, is an inorganic layered double-hydroxide compound, that could have an affinity for multivalent anions from high pH solution. This material, provided by Jim Amonette of PNL, was hydrated overnight with 0.1 M NaCl solution (per Amonette's instructions) before use.

MgAlHT sorbs strontium, cerium, yttrium, and americium from DSSF simulant with triple-digit Kd values.

Table 48. MgAlHT: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	378	664	673
Cs	0.5	0.5	0.4
Sr	301	513	710
Tc	1.0	1.0	0.8
Y	121	258	332
Cr	1.8	1.9	2.2
Co	0.4	0.6	0.4
Fe	61	77	96
Mn	20	40	90
Ni	2.6	4.9	8.2
V	0.8	0.6	0.5
Zn	13	19	27
Zr	8.0	11	15
U	1.2	1.1	1.4
Am	76	163	215

3. Experimental Resins. Four experimental resins were included in our study. Two of these were prepared at New Mexico State University and two were prepared by Sybron Chemicals, Inc.

a. NK 120B Resin. NK 120B, a derivative of polyvinylbenzylamine with two hydroxamic acid groups attached to the nitrogen, was prepared by Professor Amudhu Gopalan of the Department of Chemistry and Biochemistry, New Mexico State University. This resin was air-dried before use.

NK 120B sorbs iron, strontium, manganese, and zirconium from DSSF simulant with triple-digit Kd values.

Table 49. NK 120B Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	3.9	1.7
Cs	0.8	0.3	0.2
Sr	211	251	273
Tc	3.0	3.0	2.4
Y	16	23	30
Cr	1.0	0.5	0.3
Co	0.4	1.5	2.9
Fe	616	591	511
Mn	148	218	251
Ni	38	55	73
V	<0.1	<0.1	<0.1
Zn	0.5	0.9	1.1
Zr	199	169	176
U	4.0	4.9	3.8
Am	6.0	7.3	9.8

b. NK 194 Resin. NK 194, a derivative of polyallylamine containing two amidoxime groups attached to the amine nitrogen, was prepared by Professor Amudhu Gopalan of the Department of Chemistry and Biochemistry, New Mexico State University. This resin was air-dried before use.

NK 194 sorbs six elements at moderate K_d values from DSSF simulant.

Table 50. NK 194 Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	K _d Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	0.7
Cs	6.3	5.1	3.4
Sr	15	13	10
Tc	13	9.6	7.5
Y	24	31	27
Cr	6.9	6.1	4.2
Co	0.5	1.9	3.7
Fe	11	19	39
Mn	21	31	35
Ni	21	20	20
V	<0.1	1.2	3.6
Zn	4.6	3.8	3.8
Zr	32	45	47
U	0.4	<0.1	<0.1
Am	3.6	6.3	9.0

c. Sybron (Et)₃N Anion Exchange Resin. This experimental, macroporous strong-base anion exchange resin with triethyl amine as the functional group was obtained from Sybron Chemicals, Inc., Birmingham, New Jersey. A previous study⁹ reported that this resin offers a significant increase over (Me)₃N resin for sorbing Pu(IV) from dilute nitric acid. This resin was air-dried before use.

The behavior of this experimental resin in DSSF simulant is fairly similar to that of Purolite™ A-520-E resin (its commercial equivalent).

Table 51. Sybron (Et)₃N Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	K _d Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	4.1	5.0	2.2
Sr	11	12	8.0
Tc	167	401	471
Y	3.0	6.0	10
Cr	4.2	5.2	2.4
Co	0.4	0.6	0.7
Fe	1.1	2.6	3.2
Mn	1.7	2.6	3.1
Ni	1.0	2.1	2.9
V	<0.1	<0.1	<0.1
Zn	<0.1	0.5	0.5
Zr	0.2	0.6	0.8
U	0.1	0.3	0.5
Am	5.5	6.0	6.3

d. Sybron (Pr)₃N Anion Exchange Resin. This experimental, macroporous strong-base anion exchange resin with tripropyl amine as the functional group was obtained from Sybron Chemicals, Inc., Birmingham, New Jersey. This resin was air-dried before use.

This resin sorbs technetium well with high selectivity, similar to most other anion exchange resins.

Table 52. Sybron (Pr)₃N Anion Exchange Resin: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	4.3	5.9	4.1
Sr	4.9	6.7	5.0
Tc	96	257	390
Y	0.8	1.9	3.0
Cr	4.2	5.9	4.2
Co	0.2	0.7	0.8
Fe	0.8	1.0	1.7
Ni	<0.1	0.8	1.2
V	<0.1	<0.1	<0.1
Mn	0.7	1.1	1.5
Zn	0.2	0.6	0.7
Zr	0.2	0.5	0.8
U	<0.1	0.3	0.6
Am	4.0	5.6	5.2

4. Polyacrylonitrile (PAN) Composite Absorbers.

Although inorganic ion exchangers are known to offer high selectivity, high capacity, and rapid kinetics, their granular and mechanical properties often make them unsuitable for column applications. One way to circumvent these limitations is to incorporate the inorganic exchange materials in beads of a suitable porous polymer.¹⁰

The 16 composite absorbers prepared by Dr. Ferdinand Sebesta of the Czech Technical University in Prague consist of various inorganic exchange materials dispersed in modified-binding-polymer beads of PAN.¹¹

Although Dr. Sebesta asked that these PAN composites be kept wet because their performance would be seriously degraded if they were dried, we chose to air-dry them to put them on an equivalent basis with the other absorbers. We therefore note that the excellent performance obtained with many PAN composites might be even better had we followed Dr. Sebesta's instructions. In particular, the frequently observed slow sorption kinetics might be faster.

a. AMP-PAN Ammonium Molybdophosphate

Composite. The ammonium molybdophosphate content of the dry composite was 81%. We air-dried this composite before testing for reasons detailed in Section II.C.

The AMP-PAN composite sorbs strontium and yttrium moderately from DSSF simulant.

Table 53. AMP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	3.7	7.0
Cs	0.4	0.4	0.4
Sr	18	26	33
Tc	1.7	1.8	2.2
Y	7.2	17	32
Cr	0.2	0.3	0.4
Co	0.5	0.4	0.7
Fe	2.4	2.8	4.5
Mn	2.0	3.4	7.0
Ni	0.8	1.3	4.5
V	0.3	<0.1	<0.1
Zn	0.6	0.6	0.9
Zr	1.9	2.7	3.7
U	0.6	0.4	1.1
Am	2.9	8.6	11

b. Ba(Ca)SO₄-PAN Barium/Calcium Sulfate Composite. The barium/calcium sulfate content of the dry Ba(Ca)SO₄-PAN composite was 85%. We air-dried this composite before testing for reasons detailed in Section II.C.

The Ba(Ca)SO₄-PAN composite sorbs yttrium well and several other elements moderately from DSSF simulant. The observed slow kinetics for sorbing yttrium may be a consequence of air-drying this composite.

Table 54. Ba(Ca)SO₄-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	2.3
Cs	1.1	0.4	0.3
Sr	17	22	25
Tc	1.6	1.0	1.1
Y	28	74	197
Cr	7.7	11	14
Co	<0.1	<0.1	0.1
Fe	2.5	3.0	3.9
Mn	2.6	3.5	5.6
Ni	<0.1	0.6	2.7
V	0.3	<0.1	<0.1
Zn	0.3	0.3	0.3
Zr	5.7	9.1	13
U	0.6	1.0	2.8
Am	7.3	10	15

c. CSbA-PAN Crystalline Polyantimonic Acid Composite. The polyantimonic acid content of the dry composite was 86%. We air-dried this composite before testing for reasons detailed in Section II.C.

The CSbA-PAN composite offers very high sorption and selectivity for strontium from DSSF simulant.

Table 55. CSbA-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	1.7	4.1	6.1
Cs	<0.1	<0.1	<0.1
Sr	5K	18K	19K
Tc	1.3	1.6	1.8
Y	14	25	43
Cr	0.1	0.3	0.3
Co	<0.1	0.3	0.6
Fe	6.3	9.5	14
Mn	2.7	5.3	9.6
Ni	0.6	2.9	13
V	<0.1	<0.1	<0.1
Zn	0.3	0.5	0.8
Zr	6.1	10	13
U	5.7	11	17
Am	5.6	9.2	10

d. M315-PAN Synthetic Mordenite Composite. The synthetic mordenite content of the dry M315-PAN composite was 93%. We air-dried this composite before testing for reasons detailed in Section II.C.

The M315-PAN composite offers low to moderate sorption of several elements from DSSF simulant.

Table 56. M315-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	—
Cs	29	30	29
Sr	5.7	8.7	15
Tc	1.0	0.6	0.7
Y	12	23	33
Cr	0.5	0.2	0.1
Co	0.3	0.5	0.6
Fe	0.9	1.3	1.6
Mn	0.6	1.4	1.7
Ni	0.7	1.3	4.4
V	<0.1	<0.1	<0.1
Zn	0.4	0.7	0.8
Zr	1.7	2.1	2.3
U	<0.1	0.4	0.3
Am	3.8	6.1	13

e. MgO-PAN Magnesium Oxide Composite. The magnesium oxide content of the dry MgO-PAN composite was 80%. We air-dried this composite before testing for reasons detailed in Section II.C.

The MgO-PAN composite sorbs strontium, zinc, iron, and yttrium from DSSF simulant with at least triple-digit Kd values.

Table 57. MgO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	—
Cs	2.2	1.1	0.7
Sr	751	1214	1690
Tc	3.8	2.6	2.4
Y	83	164	394
Cr	2.0	0.9	0.6
Co	0.4	0.6	0.9
Fe	174	304	403
Mn	41	57	70
Ni	2.3	9.2	34
V	<0.1	<0.1	<0.1
Zn	251	429	502
Zr	15	25	41
U	0.6	2.0	4.2
Am	11	13	38

f. MnO-PAN Manganese Dioxide Composite. The manganese dioxide content of the dry MnO-PAN composite was 85%. We air-dried this composite before testing for reasons detailed in Section II.C.

The MnO-PAN composite sorbs strontium, manganese, and iron with four-digit Kd values and yttrium, americium, zinc, cerium, and zirconium with triple-digit Kd values.

Table 58. MnO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	4.1	26	193
Cs	0.3	<0.1	<0.1
Sr	8K	>27K	>27K
Tc	1.3	0.9	1.0
Y	60	336	665
Cr	<0.1	<0.1	<0.1
Co	0.5	1.8	3.8
Fe	>1300	>1400	>1400
Mn	483	>4200	>4600
Ni	2.2	4.4	5.3
V	<0.1	<0.1	<0.1
Zn	68	132	241
Zr	59	112	171
U	2.6	4.0	4.8
Am	22	83	473

g. NaTiO-PAN Sodium Titanate Composite. The sodium titanate content of the dry NaTiO-PAN composite was 92%. We air-dried this composite before testing for reasons detailed in Section II.C.

The NaTiO-PAN composite sorbs strontium, iron, zirconium, manganese, and yttrium well from DSSF simulant. Uranium, zinc, and americium sorb at moderate levels.

Table 59. NaTiO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	—
Cs	2.3	1.6	1.0
Sr	2415	9K	25K
Tc	2.1	1.7	1.3
Y	52	135	389
Cr	1.6	1.1	0.6
Co	0.3	0.4	0.6
Fe	120	602	1373
Mn	58	218	622
Ni	0.6	1.4	5.7
V	<0.1	<0.1	<0.1
Zn	5.5	11	23
Zr	68	460	981
U	12	32	69
Am	5.9	7.9	19

h. NiFC-PAN Nickel Hexacyanoferrate Composite.

The nickel hexacyanoferrate content of the dry NiFC-PAN composite was 85%. We air-dried this composite before testing for reasons detailed in Section II.C.

The NiFC-PAN composite sorbs strontium, iron, nickel, and zinc with four-digit Kd values. Yttrium, manganese, cobalt, and americium also sorb well.

Table 60. NiFC-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	7.6	9.3	19
Cs	16	2.6	2.4
Sr	1750	5K	12K
Tc	0.1	0.2	2.6
Y	174	379	940
Cr	1.1	1.1	3.9
Co	29	65	89
Fe	586	2621	>4400
Mn	58	235	232
Ni	357	1290	>1800
V	1.8	1.6	1.3
Zn	309	819	1116
Zr	10	11	13
U	0.9	1.1	1.0
Am	53	93	170

i. NM-PAN Nickel Hexacyanoferrate/Manganese Dioxide Composite.

The nickel hexacyanoferrate content and the manganese dioxide content of the dry composite were each 42.8%. We air-dried this composite before testing for reasons detailed in Section II.C.

The NM-PAN composite sorbs seven elements with at least triple-digit Kd values. Strontium sorbs especially well.

Table 61. NM-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	8.5	18	29
Cs	8.7	1.6	1.6
Sr	5K	27K	>28K
Tc	1.2	2.1	2.8
Y	128	316	635
Cr	1.0	2.1	2.6
Co	20	39	45
Fe	524	1353	1592
Mn	46	296	1364
Ni	150	612	660
V	0.9	0.5	0.3
Zn	163	364	483
Zr	10	14	19
U	1.0	1.2	1.2
Am	38	83	132

j. SnSbA-PAN Stannic Antimonate Composite. The stannic antimonate content of the dry composite was 86%. We air-dried this composite before testing for reasons detailed in Section II.C.

The SnSbA-PAN composite sorbs strontium strongly, whereas the Kd values for other sorbed elements are at least 100-fold lower.

Table 62. SnSbA-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	1.3	2.4	1.4
Cs	<0.1	<0.1	<0.1
Sr	1105	4911	9K
Tc	0.7	1.1	1.2
Y	9.6	23	57
Cr	0.2	0.4	0.5
Co	<0.1	0.4	0.6
Fe	24	45	71
Mn	9.5	16	29
Ni	2.3	5.6	18
V	<0.1	<0.1	<0.1
Zn	4.7	8.5	16
Zr	8.4	14	17
U	1.4	1.6	2.1
Am	5.5	8.8	8.5

k. TiO-PAN Titanium Dioxide Composite. The titanium dioxide content of the dry TiO-PAN composite was 85%. We air-dried this composite before testing for reasons detailed in Section II.C.

The TiO-PAN composite sorbs five elements with at least four-digit Kd values. Strontium sorbs especially well.

Table 63. TiO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	0.6	34	>100
Cs	<0.1	<0.1	<0.1
Sr	6K	24K	>29K
Tc	0.4	0.7	0.9
Y	108	429	622
Cr	0.3	0.5	0.6
Co	0.1	0.3	0.9
Fe	1174	>4900	>5K
Mn	318	658	1483
Ni	3.7	4.3	11
V	<0.1	<0.1	<0.1
Zn	217	317	365
Zr	2242	4780	4841
U	574	1707	2671
Am	17	135	647

l. TiP-PAN Titanium Phosphate Composite. The titanium phosphate content of the dry composite was 92%. We air-dried this composite before testing for reasons detailed in Section II.C.

The TiP-PAN composite sorbs strontium with at least a four-digit Kd value and sorbs five other elements with triple-digit Kd values.

Table 64. TiP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	10	34	65
Cs	<0.1	<0.1	<0.1
Sr	2708	6K	9K
Tc	0.6	0.6	0.7
Y	19	37	66
Cr	0.3	0.4	0.5
Co	0.5	0.8	0.6
Fe	70	99	131
Mn	67	129	217
Ni	1.1	2.4	4.0
V	0.2	<0.1	—
Zn	72	228	334
Zr	108	260	461
U	101	369	872
Am	10	19	31

m. TiSbA-PAN Titanium Antimonate Composite. The titanium antimonate content of the dry composite was 86%. We air-dried this composite before testing for reasons detailed in Section II.C.

The TiSbA-PAN composite sorbs strontium with a four-digit Kd value and sorbs five other elements with triple-digit Kd values.

Table 65. TiSbA-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	65	212	376
Cs	<0.1	0.1	<0.1
Sr	935	1671	3644
Tc	0.6	0.7	0.9
Y	51	167	413
Cr	<0.1	0.2	0.3
Co	<0.1	0.3	0.7
Fe	97	308	519
Mn	52	160	372
Ni	1.4	2.7	8.9
V	<0.1	<0.1	<0.1
Zn	4.0	8.2	20
Zr	79	453	892
U	5.2	15	69
Am	28	52	95

n. ZrO-PAN Zirconium Oxide Composite. The zirconium oxide content of the dry composite was 75%. We air-dried this composite before testing for reasons detailed in Section II.C.

The ZrO-PAN composite sorbs strontium with a four-digit Kd value, whereas three other elements sorb with triple-digit Kd values.

Table 66. ZrO-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	5.5	3.3	2.0
Sr	43	398	2077
Tc	6.9	5.3	4.0
Y	3.1	7.8	13
Cr	5.8	3.9	2.5
Co	0.5	1.0	2.0
Fe	13	63	291
Mn	12	46	143
Ni	1.9	3.9	12
V	1.4	2.2	5.0
Zn	5.5	15	30
Zr	10	44	170
U	6.3	23	89
Am	1.3	2.9	3.8

o. ZrOP-PAN Zirconium Oxide/Zirconium Phosphate Composite. The zirconium oxide content and the zirconium phosphate content of the dry composite were 60% and 15%, respectively. We air-dried this composite before testing for reasons detailed in Section II.C.

The ZrOP-PAN composite sorbs strontium, iron, zirconium, and manganese quite well at the longer contact times. The noticeably slow kinetics may be a consequence of air-drying this composite.

Table 67. ZrOP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	0.6	2.4	1.6
Cs	<0.1	<0.1	<0.1
Sr	15	113	1031
Tc	1.1	1.7	2.3
Y	3.0	13	55
Cr	0.4	0.4	0.6
Co	<0.1	0.9	1.7
Fe	4.2	21	134
Mn	4.8	24	131
Ni	0.9	2.5	8.6
V	0.8	2.3	3.4
Zn	2.0	8.8	22
Zr	3.5	17	102
U	1.3	10	40
Am	0.3	3.8	6.4

p. ZrP-PAN Zirconium Phosphate Composite. The zirconium phosphate content of the dry composite was 92%. We air-dried this composite before testing for reasons detailed in Section II.C.

The ZrP-PAN composite sorbs six elements with at least four-digit Kd values from DSSF simulant.

Table 68. ZrP-PAN Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	>1500	>1500	>1500
Cs	<0.1	<0.1	0.1
Sr	6K	>26K	>27K
Tc	0.8	0.9	1.1
Y	456	644	1340
Cr	0.4	0.6	0.7
Co	1.3	0.7	0.8
Fe	>1400	>1800	>1900
Mn	1072	>5K	>5K
Ni	6.5	9.5	12
V	2.3	39	44
Zn	18	64	92
Zr	2032	>3400	>3600
U	51	296	340
Am	>580	>590	>590

5. Phenolsulfonic-Formaldehyde (PSF) Composite Absorbers. These two composites were prepared and provided to us by Dr. Jerzy Narbutt, Head of the Department of Radiochemistry, Institute of Nuclear Chemistry and Technology, Warsaw, Poland. In these two composite resins, the inorganic exchange material is dispersed in a phenolsulfonic-formaldehyde matrix.¹² These dry composites were used as received.

a. CoFC-PSF Cobalt Hexacyanoferrate Composite. The cobalt hexacyanoferrate content of the CoFC-PSF composite was approximately 20%.

Of the four elements sorbed by this composite from DSSF simulant with at least triple-digit Kd values, strontium sorbs most strongly.

Table 69. CoFC-PSF Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	7.0	46
Cs	55	213	354
Sr	34	140	1222
Tc	5.9	1.2	1.3
Y	1.8	4.4	20
Cr	5.8	1.3	1.5
Co	1.3	4.6	9.7
Fe	5.2	31	145
Mn	7.8	39	217
Ni	1.7	5.2	9.3
V	<0.1	<0.1	<0.1
Zn	1.0	5.2	14
Zr	0.9	4.5	11
U	0.6	3.2	6.1
Am	3.5	6.2	28

b. TiFC-PSF Titanium Hexacyanoferrate Composite.

The titanium hexacyanoferrate content of the TiFC-PSF composite was approximately 17%.

Of the four elements sorbed by this composite from DSSF simulant with at least triple-digit Kd values, strontium sorbs most strongly.

Table 70. TiFC-PSF Composite: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	7.7
Cs	14	20	23
Sr	147	1076	1716
Tc	6.1	1.6	1.4
Y	8.7	31	68
Cr	5.3	1.2	1.6
Co	0.8	5.5	14
Fe	13	115	230
Mn	12	108	283
Ni	3.0	18	33
V	<0.1	<0.1	<0.1
Zn	1.5	9.8	19
Zr	9.1	74	195
U	2.7	19	40
Am	6.5	4.1	9.1

6. Liquid Extractants. We prepared and evaluated porous beads impregnated with three different liquid extractants.

a. Aliquat™ 336. We diluted 5 g of Aliquat™ 336 (methyltricaprylammonium chloride), obtained from Aldrich Chemical Co., Milwaukee, Wisconsin, with 10 mL of hexane and added 17.32 g of Amborsorb™ 563 porous carbon beads, obtained from Rohm & Haas, Philadelphia, Pennsylvania, to absorb the liquid. The cyclohexane evaporated to yield 26.2 g of the loaded Amborsorb™ beads.

This extractant sorbs technetium strongly and selectively from DSSF simulant. Its very low sorption of technetium from acidic solution, determined in a previous study,¹ indicates that technetium could be stripped by nitric acid.

Table 71. Aliquat™ 336: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	3.1	4.8	6.6
Cs	<0.1	<0.1	<0.1
Sr	0.4	0.7	0.9
Tc	177	464	524
Y	2.7	3.9	4.2
Cr	0.1	0.3	0.1
Co	0.5	0.9	1.0
Fe	1.1	1.6	2.0
Mn	0.7	1.3	1.5
Ni	0.1	1.0	1.1
V	<0.1	<0.1	<0.1
Zn	0.4	0.6	0.8
Zr	0.9	1.1	1.4
U	0.5	0.9	1.1
Am	2.2	4.2	5.4

b. Cyanex™ 923. We diluted 10 mL of Cyanex™ 923 (trialkylphosphine oxide), obtained from the American Cyanamid Company, Wayne, New Jersey, with 20 mL of cyclohexane and added 26.83 g of Ambersorb™ 563 porous carbon beads, obtained from Rohm & Haas, Philadelphia, Pennsylvania, to absorb the liquid. The cyclohexane evaporated to yield 36.8 g of the loaded Ambersorb™ beads.

This extractant strongly and selectively sorbs technetium from DSSF simulant.

Table 72. Cyanex™ 923: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	<0.1
Cs	1.4	4.6	3.8
Sr	1.9	5.5	5.6
Tc	121	244	230
Y	2.1	1.4	1.8
Cr	1.2	4.4	3.8
Co	1.3	0.7	1.0
Fe	1.7	1.3	1.4
Mn	1.6	0.9	1.5
Ni	<0.1	0.6	0.7
V	1.0	0.2	0.2
Zn	1.2	0.5	0.9
Zr	1.3	0.7	1.1
U	1.4	0.7	1.2
Am	<0.1	1.3	2.1

c. LIX™-54. We diluted 10 mL of LIX™-54 (a beta diketone), obtained from the Henkel Corporation, Tucson, Arizona, with 20 mL of cyclohexane and added 26.80 g of Ambersorb™ 563 porous carbon beads, obtained from Rohm & Haas, Philadelphia, Pennsylvania, to absorb the liquid. The cyclohexane evaporated to yield 34.6 g of the loaded Ambersorb™ beads.

This extractant sorbs strontium, nickel, and yttrium at useful levels from DSSF simulant.

Table 73. LIX™-54: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	<0.1	1.8
Cs	3.5	2.3	1.2
Sr	32	108	185
Tc	3.2	2.6	1.6
Y	13	25	59
Cr	3.4	2.3	1.2
Co	1.0	1.4	2.1
Fe	1.7	2.5	4.2
Mn	1.3	2.2	3.4
Ni	12	27	64
V	0.1	<0.1	<0.1
Zn	<0.1	0.3	0.6
Zr	0.8	1.5	2.4
U	0.2	0.6	0.6
Am	3.3	4.1	9.5

7. Sandia/NM Absorbers. Materials designated as SNL/CST are a new class of inorganic ion exchangers called crystalline silico-titanates (CSTs). These materials, jointly invented by Sandia National Laboratories/New Mexico (SNL) and Texas A&M University (a patent application has been filed), show a significant potential for removing cesium from defense wastes that contain more than 5 M Na⁺ and more than 1 M OH⁻. CST materials are very fine powders composed of cuboidal crystals with particle sizes of several hundred angstroms. Different numerical values in the absorber designations represent different synthesis procedures.

Because the composition of the various CST materials we evaluated is proprietary, we can provide only general information. As the development effort progressed, however, a baseline composition was selected for larger-scale synthesis, characterization, and evaluation of properties. SNL/CST 141 and 149 are baseline materials that are being developed for the removal of cesium and other radionuclides from a wide range of waste solutions.

SNL/CST 141 powder has already been prepared in commercial quantities by the UOP Corporation, Des Plaines, Illinois, Sandia/NM's partner in a cooperative research and development agreement (CRADA). An engineered form of CST suitable for use in ion exchange columns is scheduled to be commercially available in 1995.

a. SNL/CST 120 Crystalline Silico-Titanate. SNL/CST 120 strongly and selectively sorbs strontium from DSSF simulant. The K_d value for manganese, the next most strongly extracted element, is more than 100-fold lower.

Table 74. SNL/CST 120: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	1.1	0.3	0.3
Cs	20	26	27
Sr	13K	>32K	>32K
Tc	<0.1	0.4	0.1
Y	32	67	93
Cr	0.4	0.9	0.7
Co	0.2	0.3	0.5
Fe	8.4	12	19
Mn	7.2	36	240
Ni	1.2	1.8	2.6
V	<0.1	<0.1	<0.1
Zn	1.1	1.0	1.1
Zr	36	31	57
U	26	25	28
Am	6.6	6.1	10

b. SNL/CST 141 Crystalline Silico-Titanate.

SNL/CST 141 strongly sorbs both strontium and cesium from DSSF simulant. None of the other 13 elements sorb with Kd values higher than 20.

Table 75. SNL/CST 141: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	6.5	9.6	17
Cs	530	649	736
Sr	1319	1839	2343
Tc	<0.1	<0.1	<0.1
Y	17	16	17
Cr	<0.1	0.2	0.3
Co	0.4	0.5	0.7
Fe	4.5	6.7	9.7
Mn	2.5	4.0	6.4
Ni	1.4	1.8	1.9
V	<0.1	<0.1	<0.1
Zn	0.6	0.6	0.9
Zr	13	20	17
U	5.2	8.0	11
Am	6.0	8.3	12

c. SNL/CST 149 Crystalline Silico-Titanate.

SNL/CST 149 strongly sorbs both strontium and cesium from DSSF simulant. None of the other 13 elements sorb with Kd values higher than 28.

Table 76. SNL/CST 149: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	<0.1	3.3	9.9
Cs	436	570	612
Sr	2047	3808	4692
Tc	0.4	0.1	0.1
Y	19	23	27
Cr	0.5	0.5	0.5
Co	0.3	0.5	0.7
Fe	4.2	6.2	8.2
Mn	2.2	3.5	5.8
Ni	0.9	1.6	1.7
V	<0.1	<0.1	<0.1
Zn	0.6	0.8	1.0
Zr	16	25	28
U	5.4	8.7	12
Am	2.2	5.6	8.7

d. SNL/HTO Amorphous Hydrous Titanium Dioxide.

As expected, the behavior of hydrous titanium dioxide is very different from that of the crystalline silico-titanates. Many elements sorb strongly from DSSF simulant.

Table 77. SNL/HTO: Distribution of 15 Elements from Simulated Hanford DSSF Solution

Element	Kd Value for Specified Time		
	30 min	2 h	6 h
Ce	282	416	542
Cs	0.5	0.3	0.3
Sr	23K	10K	>24K
Tc	<0.1	<0.1	<0.1
Y	245	288	465
Cr	0.6	0.7	0.7
Co	0.6	1.5	2.7
Fe	526	267	253
Mn	313	353	501
Ni	2.1	4.6	10
V	<0.1	<0.1	<0.1
Zn	107	170	207
Zr	1444	1625	2735
U	622	1419	>2300
Am	66	104	172

IV. FUTURE STUDIES

This screening study met its objective of identifying specific absorbers that seem capable of partitioning targeted elements from Hanford DSSF solution. The best absorbers and promising new materials identified in our screening studies will be evaluated with realistic simulant compositions that represent other Hanford tanks, especially those scheduled to be processed first. We will continue to use radiotracers, which provide a rapid, reliable, and inexpensive way to obtain large quantities of distribution data.

Because even the best simulant solutions cannot accurately represent the contents of any HLW storage tank, we are anxious to obtain and test actual samples from the Hanford waste tanks. Only by testing genuine waste solutions can we obtain sorption data that are sufficiently reliable to permit the design of full-scale partitioning processes to begin. We recognize that even tests with actual wastes will not be conclusive because

the compositions of the Hanford tanks vary greatly and that individual tanks exhibit large heterogeneities in their horizontal and vertical compositions. However, as we obtain sorption data for the most promising absorbers with samples from various HLW tanks, we hope to identify absorbers that sorb the target elements well from a wide variety of waste compositions.

Finally, chemical and radiation stabilities are important factors to consider when selecting materials for processing radioactive waste solutions. The long-term chemical stability and the effect of radiation on the most promising absorbers from our screening studies should be determined (if such information is not already available) before absorbers are selected for use in large-scale recovery processes.

V. CONCLUSIONS

Our screening study of many absorbers from a realistic simulant for Hanford DSSF has met the initial objective of identifying many promising absorbers. Moreover, because we measured the sorption of so many different elements, our study provides important selectivity information about which unwanted elements are most likely to compete for absorber sites. Based on our experimental data, it appears that many of the separations required for processing HLW from Hanford DSSF solution, and perhaps from other underground storage tanks as well, can be achieved using available absorbers and existing, proven technology.

A. Experimental Procedure

Radiotracers, as used in our study, provide a fast, reliable, and cost-effective way to obtain large quantities of distribution data. Follow-on studies should measure the distribution of key elements from other Hanford waste tank compositions onto the most promising absorbers identified by completed screening studies.

B. Individual Elements

All elements studied except vanadium sorb from DSSF simulant with good to excellent Kd values on at least one of the absorbers tested.

C. Individual Absorbers

- The performance of the 58 absorbers tested with this PNL-prepared DSSF simulant solution is often much different from the performance reported for similar absorbers tested in solutions of more simple chemical composition.
- Low-cost partitioning agents such as Aliquat^{TM} 336, Cyanex^{TM} 923, and Reillex^{TM} HPQ often outperform other materials whose cost is many times higher.
- The silico-titanate absorbers from Sandia show high sorption of cesium and strontium from simulated Hanford DSSF solution. Because the sorption of cesium on silico-titanates appears to be irreversible, this material should be considered for use in the interim storage of radioactive waste, for incorporation into HLW glass, or for use as a final waste form.

ACKNOWLEDGMENTS

This study was supported by the Tank Waste Remediation System (TWRS) of DOE/Richland Operations Office; the TWRS Technology Development Program Office (TDPO) of Westinghouse Hanford Company; and the Hanford Program Office, EM-36, of the Office of Environmental Restoration and Waste Management, U.S. Department of Energy.

Clifford Mills of the Nuclear Materials Process Technology Group at Los Alamos designed the tip-filter system that allowed disposable hypodermic syringes to be successfully used as container-dispensers during our many hundreds of dynamic contact experiments.

Frank McGarvey of Sybron Chemicals, Inc., provided samples of macroporous anion exchange resins with trimethyl, triethyl, tripropyl, and tributyl amine functional groups.

Jane Bibler of Westinghouse Savannah River Company provided the sample of SRS resorcinol/formaldehyde resin (batch BSC-187).

Dennis Fennelly of UOP Molecular Sieves Division provided samples of Ionsiv^{TM} TIE-96 for evaluation.

Elmer Klavetter and Norman Brown of Sandia National Laboratories/New Mexico provided samples of crystalline silico-titanate (SNL/CST) absorbers and hydrous titanium oxide (SNL/HTO) absorber.

Ferdinand Sebesta, Department of Nuclear Chemistry, Czech Technical University, Prague, Czech Republic, prepared and provided samples of 16 PAN-matrix composite absorbers for our evaluation.

Jerzy Narbutt, Department of Radiochemistry, Institute of Nuclear Chemistry and Technology, Warsaw, Poland, prepared and provided samples of two PSF-matrix composite absorbers for our evaluation.

Leonard Mausner and Katherine Kolsky of the Medical Isotopes Program, Brookhaven National Laboratory, provided the ⁵⁶Ni and ⁴⁸V radiotracers.

The simulated DSSF solution was prepared and provided by Garrett Brown of Battelle Pacific Northwest Laboratory.

Stephen Yarbrow and Gordon Jarvinen of the Nuclear Materials Process Technology Group at Los Alamos provided valuable advice and suggestions during numerous technical discussions.

Norman Brown of Sandia/NM provided valuable advice and suggestions during numerous technical discussions and also peer-reviewed this manuscript.

We especially appreciate the assistance and cooperation of many members of the Separations and Radiochemistry Group, the Nuclear Chemistry and Analysis Group, and the Medical Radioisotopes and Reactor Applications Group at Los Alamos.

REFERENCES

1. S. F. Marsh, Z. V. Svitla, and S. M. Bowen, "Distributions of 14 Elements on 63 Absorbers from Three Simulant Solutions (Acid-Dissolved Sludge, Acidified Supernate, and Alkaline Supernate) for Hanford HLW Tank 102-SY," Los Alamos National Laboratory report LA-12654, Rev. (August 1994).
2. J. L. Ryan and E. J. Wheelwright, "Recovery and Purification of Plutonium by Anion Exchange," *Ind. Eng. Chem.* 51(1), 60-65 (1959).
3. W. L. Poe, A. W. Joyce, and R. I. Martens, "Np-237 and Pu-238 Separation at the Savannah River Plant," *I&EC Proc. Design Devel.* 3(4), 314-322 (1964).
4. J. A. Kelly, "Ion Exchange Process for Separating Americium and Curium from Irradiated Plutonium," Savannah River Laboratory report DP-1308 (1972).
5. J. Korkisch, *Handbook of Ion Exchange Resins; Their Application to Inorganic Analytical Chemistry, Vol. 1* (CRC Press, Boca Raton, Florida, 1989), p. 33.
6. R. Gunnink and J. B. Niday, "Computerized Quantitative Analysis by Gamma-Ray Spectrometry. Vol. 1. Description of the Gamanal Program," Lawrence Livermore Laboratory report UCRL-51061, Vol. 1 (March 1972).

7. T. M. Benjamin, Nuclear Chemistry and Analysis Group, Los Alamos National Laboratory, personal communication, April 1994.
8. F. X. McGarvey and R. Gonzales, "Ion Exchange Studies on Strongly Basic Anion Exchange Resins Prepared with Tertiary Amines of Varying Molecular Weight," in *Ion Exchange Advances, Proceedings of IEX '92*, M. J. Slater, Ed. (Elsevier Science Publishing Ltd., Essex, England, 1992), pp. 97-103.
9. S. F. Marsh, "The Effect of Triethyl, Trimethyl, Tripropyl, and Tributyl Amine Functional Groups in Strong-Base Anion Exchange Resin on the Sorption of Pu(IV) from Nitric Acid," in *Ion Exchange Processes: Advances and Applications*, A. Dyer, M. J. Hudson, and P. A. Williams, Eds. (Royal Society of Chemistry, Cambridge, England, 1993), pp. 81-89.
10. F. Sebesta, A. Motl, J. John, M. Prazsky, and J. Binka, "Composite Ion-Exchangers and Their Possible Use in Treatment of Low/Intermediate Level Liquid Radioactive Wastes," in *Proc. 1993 International Conference on Nuclear Waste Management and Environmental Remediation*, R. Baschwitz, R. Kohout, J. Marek, P. I. Richter, and S. C. Slate, Eds. (American Society of Mechanical Engineers, New York, 1993), Vol. 3, pp. 871-878.
11. F. Sebesta and J. John, "An Overview of the Development, Testing, and Application of Composite Absorbers," Los Alamos National Laboratory report LA-12875-MS (in press).
12. J. Narbutt, A. Bilewicz, and B. Bartos, "Composite Ion Exchangers for Radiocaesium Removal from Nuclear Reactor Wastes," in *Proc. Management of Low and Intermediate Level Radioactive Wastes* (International Atomic Energy Agency, Vienna, Austria, 1989), IAEA-SM-303/152P, Vol. 2, pp. 266-268.