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SODIUM NONATITANATE: A HIGHLY SELECTIVE INORGANIC ION EXCHANGER FOR STRONTIUM

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SODIUM NONATITANATE: A HIGHLY SELECTIVE INORGANIC ION EXCHANGER FOR STRONTIUM

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ABSTRACT

Sodium nonatitanate ($Na_4Ti_9O_{20}$), which is a highly selective inorganic ion exchanger for strontium, is regenerable, is radiation resistant, and has a high cation exchange capacity. This paper summarizes the test results with a variety of simulants for tank waste and groundwater streams that demonstrate the potential of this unique material. Sodium nonatitanate is most effective in an alkaline environment and tolerates high concentrations of competing ions. It retains substantial effectiveness in the presence of organic complexants. Sodium nonatitanate is available either in powder or pellet form: both materials are stable in an alkaline tank waste environment.

INTRODUCTION

Sodium nonatitanate was developed by a team from AlliedSignal, Inc., (now Honeywell International) and Texas A&M University as a very selective ion exchanger tailored to remove strontium from the extremely alkaline, high-

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sodium-content streams found in high-level tank wastes at sites such as Hanford and Savannah River. After its development, many samples from various batches of this material were supplied to national laboratories and potential user sites for evaluation. The researchers measured the distribution coefficient and other properties of the material in both simulants of the streams of interest and the streams themselves. Since each of these sites used whatever sample was available to them at the time and the published reports appeared over several years from multiple sites, it has been very difficult to actually compare one material with another. No study reported thus far has brought together all of the published information about this exchanger. The purpose of this article is to fill this gap and to provide a coherent picture of the performance of sodium nonatitanate in a variety of streams.

EXPERIMENTAL METHODS

Four simulants were prepared according to the instructions provided by Pacific Northwest National Laboratory (PNNL) (1) (N-Springs, NCAW); BNFL, Inc. (107-AN); and a published report (2) (Savannah River simulant). The 107-AN simulant was diluted to 5 M in Na^+ using 0.1 M NaOH before K_d determinations to mimic proposed processing conditions. The compositions of these simulants are provided in Appendix A. Each simulant was spiked with sufficient ^{89}Sr tracer, obtained from Isotope Products Laboratories (as $SrCl_2$ in 0.1 M HCl, 0.142 Ci/g Sr), to provide an initial ^{89}Sr activity of approximately 250,000 counts per minute (cpm)/mL. This equated to the addition of a total of 0.7 mg strontium per liter.

Distribution coefficients (K_d values) for strontium were determined for each ion- exchange material according to the following procedure. A total of 0.05 g of exchanger was weighed directly into a scintillation vial, and 10 mL of waste simulant, spiked with ^{89}Sr, was added. Unless otherwise stated, all exchangers were in the form of fine powders. The vials were capped and placed on a rotary shaker for 24 h. The mixtures were then filtered through a 0.20-μm syringe filter, and the aqueous phase was counted on a Wallac 1410 liquid scintillation counter. The K_d values were then calculated according to the following equation:

$$K_d = [(A_i\ (A_f)/A_f\ ][v/m],$$

where

A_i = initial activity of solution (cpm/mL),
A_f = final activity of solution (cpm/mL),
v = volume of solution (mL),
m = mass of exchanger (g).

The above procedure was followed for K_d measurements for the 107-AN, NCAW, and Savannah River simulants. For the N-Springs groundwater simulant, the volume/mass (V:M) ratio was increased to 1000, which necessitated the use of 0.01 g of ion-exchange material per 10 mL of simulant. The pH of this simulant, as provided by PNNL, is approximately 11, but conversations with DOE personnel indicated that a pH of around 7 was more typical of a Hanford groundwater. Consequently, the pH of the simulant was carefully adjusted using dilute hydrochloric acid to decrease it to a more realistic value. This resulted in a change in the anion concentrations but did not affect the concentrations of the metals (Mg, Ca, Ba, and Na) that would compete with the strontium for the ion- exchange sites. The pH was also measured after contact with the exchange materials.

Blank K_d determinations were performed to evaluate the removal of strontium due to absorption onto the vial for each simulant. Absorption of strontium onto the syringe filters used to separate the liquid from the solid ion-exchange material was also investigated. All K_d determinations were performed in duplicate and the K_d and percentage strontium removed are the mean of a minimum of two duplicates.

RESULTS AND DISCUSSION

Sodium nonatitanate is a layered inorganic ion exchanger prepared by gelation of an appropriate titanium-containing precursor, followed by hydrothermal treatment of this gel (3). As such, it belongs to a family of related exchangers, which include the monosodium titanate originally prepared by Dosch (4) and earlier nonatitanates prepared by Clearfield and Lehto (5). It differs from monosodium titanate both in stoichiometry and performance, and from the Clearfield/Lehto material primarily with regards to performance. In an earlier publication (3), we discussed how changes in the hydrothermal preparation step can adjust both the morphology of the material and its performance as an ion exchanger for strontium. Figure 1 shows the highly porous morphology characteristic of our current material, and Table 1 provides some typical physical properties.

The selectivity of sodium nonatitanate for strontium, as measured by its K_d is strongly affected by pH (Fig. 2). This pH effect is highly useful since it allows the strontium to be absorbed by the exchanger at the neutral to alkaline pH levels characteristic of groundwater or tank waste streams and then to be regenerated using dilute acid. As expected for inorganic ion-exchangers, sodium nonatitanate is also tolerant to ionizing radiation. With the assistance of D. Wester of PNNL, we measured the K_d values of sodium nonatitanate samples that had been irradiated using a ^{60}Co source. As Table 2 shows, little degradation in performance occurred.

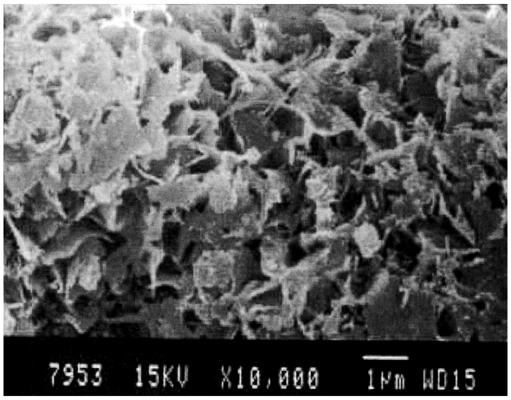

Figure 1. SEM photograph of sodium nonatitanate, showing porous structure.

Table 1. Typical Physical Properties of Sodium Nonatitanate

BET surface area: 40 m^2/g
Langmuir surface area: 80 m^2/g
Pore volume: 0.15 cm^3/g

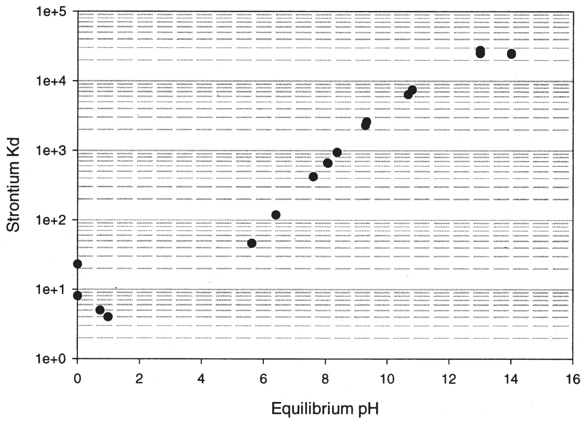

Figure 2. Effect of pH on strontium distribution coefficient (sample 7976-201:5 M Na, 0.0005 M Sr' 5°C; 72-h contact time; measured by Lane Bray PNNL).

Table 2. Effect of Irradiation by ^{60}Co Radiation on Strontium Uptake by Sodium Nonatitanate Powder (5 M Na, 0.0005 M Sr, 25°C, 72-h Contact Time)

Treatment (or Mrads)	Sr Remaining Solution (ppm)	24-h K_d (mL/g)
0 (untreated)	0.17	40,300
250	0.36	19,000
500	0.14	48,900
750	0.14	48,900
1000	0.15	45,600

Tank Waste Trials

We originally developed sodium nonatitanate for the removal of ^{90}Sr from the high- level waste stored at DOE sites such as Hanford and Savannah River. These waste streams are highly alkaline and contain high concentrations of sodium and other competing ions. To be effective in these streams, an ion exchanger must be highly selective for strontium, especially at alkaline pH, and be tolerant of the alkalinity and radioactivity of the environment. Since practical difficulties are experienced in obtaining reproducible samples of wastes from these sites and the samples are difficult to handle, it has become customary to use various standard simulants to evaluate ion- exchange materials. We used neutralized current acid waste (NCAW), a simulant that has been widely used to represent a Hanford tank waste, a simulant for Savannah River waste developed by McCabe (2), and two simulants for Hanford waste containing chemical complexants. Table 3 shows K_d results we obtained using the NCAW and Savannah River simulants, along with published results (6, 7, 8, 9) (using samples we provided), for simulants for the Hanford 101-AW double-shell tanks, and a Melton Valley Storage Tank (MVST) simulant. It should be noted that for each experiment, the V/M ratio has been specified, as well as the simulant used. Since K_d values are simply the results of a defined experiment, rather than any absolute quantity, they should be directly compared only for the materials run with the same simulant, using the same V/M ratio and the same equilibration time. We believe, however, that the selectivity order is likely to be consistent from feed to feed.

The NCAW results show that sodium nonatitanate generally outperforms other ion exchangers in removing strontium. The K_d of 120,500 mL/g corresponds to the removal of 99.8% of the strontium present in the feed. The best of the sodium nonatitanate samples is a factor of 2 better than the nearest competitor, and most remaining materials are significantly less effective. The sodium nonatitanate

Table 3. Strontium K_ds for Sodium Nonatitanate and Competitive Ion-Exchange Materials, Measured in Simulants and Waste Streams for High-Level Tank Waste (24-h Contact Time)

Waste Stream		NCAW Simulant			70% 101-AW DSSF Simulant	Actual 70% 101-AW DSSF	MVST W-29 Simulant	Savannah River Simulant
Source		Ref. 6	a	a	Ref. 7	Ref. 7	Ref. 8	
V:m		24	200	1,000	149	149	200	200
AlliedSignal/Texas A&M Sodium Titanates								
Sodium nonatitanate	AS8212-154 (pelletized, then ground to <80 μm)		120,500					
Sodium nonatitanate	AS8104-154 (powder)		318,550					>1,200,000
Sodium nonatitanate	AS8212-115 (pelletized)						12,600	
Sodium nonatitanate	SE		13,430					245,500
Sodium nonatitanate	AS8104-170 (powder)				>5,880,000	1,200		
Sodium nonatitanate	GMG-I-1	>36,000	235,000	39,600				
Other AlliedSignal/Texas A&M Materials								
Pharmacosiderite	AS8341-167		4,658					7,773
Pharmacosiderite	KTS-Ph		20,200	5,000				
Pharmacosiderite	HTS-Ph		44,800	3,700				
Manganese dioxide	SE		13,260					26,450
Other Ion-Exchange Materials								
TIE-96		1,696			4,270	200		
IE-910					>5,930,000	570		
IE-911			29,300	20,600		1,100	2,400	
Sr- Treat	Selion		121,400					
Superlig-644	IBC Technologies				85	20		
Monosodium titanate	Boulder Scientific		82,380					138,200
K CoHex	3M	>35,000						

[a] Some values were previously reported in Ref. 9.

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samples vary among themselves, largely based on the source of the material and whether or not it has been pelletized. After the sodium nonatitanates, the next best material in this simulant was Sr-Treat, followed by some of the pharmacosiderites and IE-911.

In the Savannah River simulant, no detectable quantity of strontium remained after contact with sodium nonatitanate powder, leading us to express the K_d as a lower limit. The improvement in performance in this simulant relative to the NCAW simulant presumably reflects the fact that the former contains fewer competing ions, such as potassium, which compete, however poorly, with strontium for available exchange sites. The other sodium titanate sample also gave a high K_d, followed by monosodium titanate. Since McCabe and Walker (2) have previously reported that sodium nonatitanate meets all of the other criteria for use in the Savannah River In-Tank Precipitation (ITP) process, these results suggest that sodium nonatitanate should be considered as an alternative to monosodium titanate in this application.

In the 101-AW simulant used by Brown et al. (7), the K_d for strontium was also unmeasurably high for sodium nonatitanate, as was also the case for IE-911. However, when Brown used actual 101-AW tank water as his feed, the K_d was substantially lower. The K_d for Sr was also lower in the simulant used by Collins and Anderson, et al. (8) for Melton Valley tank waste. In all of these feeds, however, sodium nonatitanate showed either the highest or one of the highest K_d values.

In the waste at Hanford, the tanks that contain chemical complexants have aroused the greatest concern with respect to strontium removal. While it has been suggested that the highly alkaline pH present in many of the tanks may have led to the precipitation of strontium, the tanks containing chemical complexants have the highest concentrations of dissolved strontium in the supernatant. Of course, these waste streams also present the greatest challenge to ion exchange material, since the ion-exchangers must compete for strontium with the dissolved chelating agents, such as EDTA.

We have explored two simulants for these streams: a 101-SY simulant that has been the basis for several other studies, and a new 107-AN simulant obtained from BNFL, Inc. (1). The data are shown in Table 4, along with the results of a previous study by Marsh et al. (10) using many of the same materials.

The distribution coefficients observed in our study are far lower than those in feeds without the complexants but remain in a useful range (a K_d of 89 mL/g corresponds to removal of 30.9% of the strontium). The selectivity order observed in the other tank waste simulants is roughly preserved in these simulants, with the sodium nonatitanate materials retaining their lead. Sodium titanium silicate, an experimental material developed at Texas A&M, is also effective in this stream, while IE-911 is somewhat less effective. More traditional ion-exchange materials, like clinoptilolite, are not effective in this challenging stream.

Table 4. Strontium Distribution Coefficients Obtained Using Chemical Complexant Simulants (24-h Contact Time)

Waste Stream		101SY Simulant		107-AN Simulant
Source		a	Ref. 10	
V/m ratio		200	24.0	200
AlliedSignal/Texas A&M Sodium Titanates				
Sodium nonatitanate	AS8225-127 (pelletized, then ground)		107.0	
Sodium nonatitanate	AS8212-154 (pelletized, then ground to $<80\ \mu m$)			89
Sodium nonatitanate	SE			67
Sodium nonatitanate	AS8104-170 (powder)		43.0	
Sodium nonatitanate	GMG-I-1	295		
Other AlliedSignal/Texas A&M Materials				
Pharmacosiderite	AS8341-167			30
Pharmacosiderite	KTS-Ph	31		
Pharmacosiderite	HTS-Ph	164		
Manganese dioxide	SE			23
Na titanium silicate		231		34
Other Ion-Exchange Materials				
TIE-96			2.0	
IE-96			<0.1	
IE-910			1.5	
IE-911		210		
Clinoptilolite	Natural (obtained BNFL)		0.3	
Superlig-644	IBC Technologies		<0.1	
Monosodium titanate	Boulder Scientific			55
K CoHex	3M		45.0	

[a] Some values previously reported in Ref. 7.

Groundwater Treatment

While sodium nonatitanate is best suited, because of the shape of its K_d-pH profile, for use in the highly alkaline tank waste streams, treatment of groundwater streams has also been of interest. In these neutral-pH streams, ^{90}Sr concentrations are lower, the total concentration of strontium is similar, and the overall ion content is orders of magnitude lower. In groundwaters the challenge is not as much selectivity for Sr against a very high background of univalent cations, as it is selectivity for Sr over other chemically similar divalent cations particularly Ca^{2+} and Mg^{2+}, which are present at concentration of one or two orders of magnitude greater.

To evaluate our materials for this application, we used a simulant recipe (11) obtained from PNNL for groundwater from the N-Springs site at Hanford. This simulant contains calcium, magnesium, and barium as competing divalent cations. The results of the study are shown in Table 5. Since hydrolysis of some ion exchangers may cause an increase in pH and precipitation of the divalent salts might confound our results, we ran the experiments using a V/M ratio of 1000. At this ratio, we observed that in no case did the pH after contact exceed 10.85.

Our results show that, in this stream, both the sodium nonatitanate and the monosodium titanate were highly effective Sr sequestrants. Next best were some of the developmental pharmacosiderite materials, followed by other commercial products. Since the monosodium titanate is an extremely fine material, sold as an aqueous suspension, sodium nonatitanate is clearly the preferred option for treating such streams. Some plans for treating groundwater contamination have

Table 5. Strontium K_ds Measured Using an N-Springs Simulant (24 h. Contact Time)

V/m Ratio		1000[a]	1000
AlliedSignal/Texas A&M Sodium Titanates			
Sodium nonatitanate	AS8212-154 (pelletized, then ground to <80 μm)		1,104,000
Sodium nonatitanate	SE		520,300
Sodium nonatitanate	GMG-I-1	322,400	
Other AlliedSignal/Texas A&M Materials			
Pharmacosiderite	AS8341-167	646,900	219,800
Pharmacosiderite	AS8341-176	600,400	
Na zirconium silicate	AS8341-147	2,130	
Na zirconium silicate	AS8341-155	1,770	
Manganese dioxide	SE		120,400
Other Ion-Exchange Materials			
IE-96		265,500	
IE-911		73,600	
AW-500 (Chabazite)		26,700	
Clinoptilolite	Natural (obtained from BNFL)	7,700	3161
Sr- Treat	Selion	91,600	
Monosodium titanate	Boulder Scientific		1,161,000

[a] Previously published in Ref. 11.

Table 6. Strontium K_d Results Using Actual 105-KE Basin and N-Area Well Water Samples (12, 13)

Waste stream		105-KE Basin		N-Area Well Water-Low Sr	
V/M ratio		*10,000*	*100,000*	*2,000*	*2,000*
AlliedSignal/Texas A&M Sodium Titanates					
Sodium nonatitanate	AS8212-152 (pellets)	48,000	297,000	7,720	14,000
Sodium nonatitanate	GMG-I-1	1,830,000	369,000		
Other AlliedSignal/Texas A&M Materials					
Pharmacosiderite	AIB-TS255	4,770,000			
Pharmacosiderite	KTS-Ph	644,000	287,000		
Na Mica	AS8212-15d	69,600	225,000		
Other Ion-Exchange Materials					
TIE-96				9,110	12,300
IE-911		97,200	363,000	74,800	90,100
Clinoptilolite	Natural (obtained from BNFL)	90,300	316,000		
Sr- Treat	Selion	91,000	296,000	15,700	22,100
Superlig-644	IBC Technologies			93	90
K CoHex	3M	23,500	261,000		

involved burying containers of ion-exchange material to act as an active barrier, thereby removing harmful cations as they diffuse past. This option would require relatively larger quantities of a less expensive ion-exchange material. The relatively high K_d observed for Honeywell's manganese dioxide suggests that it may be considered for such an application.

We can compare these simulant results with those from two of trials with actual Hanford streams. Table 6 shows the results of the two trials run by Brown et al. (12, 13) — one with pond water from the Hanford 105-KE basin and the other with well water from the N-area. In the KE-basin trial, at a V/M ratio of 10,000, sodium nonatitanate and one of the pharmacosiderite developmental materials had K_ds above 1.5 million. When the experiment was repeated with a V/m ratio of 100,000, however, all of the exchangers included in the test appeared to behave similarly. At this extremely high ratio, mass transfer or other issues may have intervened. In the trial using actual well water from N-area, the best material tested was an IE-911 sample. However, it is worth noting that the sodium titanate sample used in this test had compared poorly with other sodium titanate samples in other trials.

Pelletized Sodium Nonatitanate

Inorganic ion exchangers have typically been used to process nuclear waste in two contacting modes: addition to stirred tanks as a "precipitant" and as fill material in packed columns. AlliedSignal's sodium nonatitanate powders have also been used as the active component in 3M's membrane adsorbents (14). Ion-exchange materials that are to be used in these modes must have different physical forms. Fine powders are generally preferred when the exchangers are to be used as in-tank adsorbents or precipitants, while pellet-form materials are required to obtain low pressure drops in packed columns. Since the binder used to form pelletized ion-exchange material must be as tolerant of the alkaline, high radiation environment as the material itself, special pelletization techniques were required (15). Table 7 shows typical physical properties for the pelletized ion-exchange materials we have prepared.

In packed-column operation, it is quite important to ensure good mass transfer between the fluid and solid phases. This leads to good dynamic capacities, sharp-breakthrough curve shapes, and effective use of the ion-exchanger. In order to evaluate our materials effectively for packed- column operation, we ran packed column breakthrough experiments using two of the tank waste simulants discussed earlier in this article. Figures 3 and 4 show comparisons of the breakthrough behavior of some commercial and developmental ion exchangers using the NCAW and 101-SY simulants.

From these studies we observed two clear trends. First, the sodium nonatitanate pellets tended to break through last. This simply reflects the higher capacity of the material for strontium, which is largely due to its high selectivity—which in turn prevents loading of the available sites by extraneous ions. Second, the effects of the pelletization procedure were apparent in the comparison of

Table 7. Typical Physical Properties for Sodium Nonatitanate Pellets

Property	Value
Dimensions	2.3 (d) x 3 mm
Piece density	1.85-2.1 g/mL
K_d for Sr* (5 M Na/0.1 OH)	21,419 mL/g
Theor. Capacity for Sr^{2+}	2.37 meq/g
Dynamic Capacity for Sr^{2+} (5 M Na/0.1 OH)	0.81 meq/g
Radial Crush Strength	518 psi
BET Surface Area	52.6 m^2/g
Total Porc Volume	0.108 mL/g

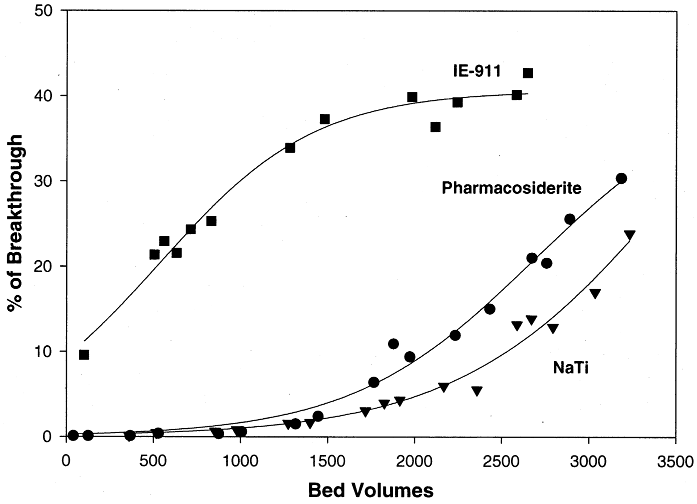

Figure 3. Breakthrough curves for column absorption of strontium from NCAW simulant (flow rate: 20 bed volumes/h).

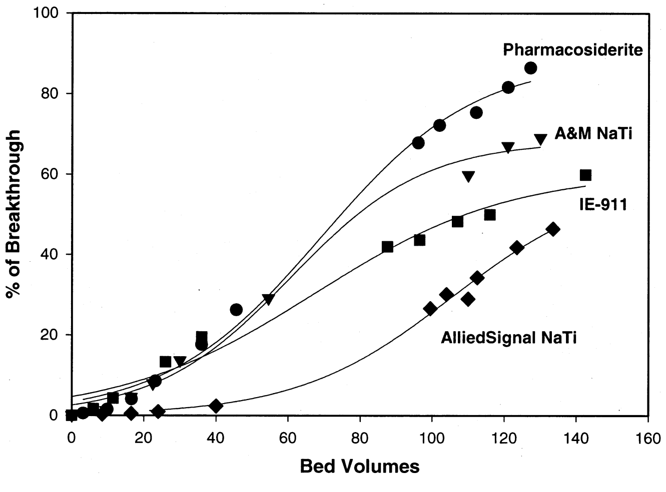

Figure 4. Breakthrough curves or column absorption of strontium from 101-SY simulant (flow rate: 5 bed volumes/h).

AlliedSignal's sodium titanate pellets with the pellets generated by a similar procedure at Texas A&M. The more rapid mass transfer into the former material led it to demonstrate a higher effective capacity, even though a comparison of the parent powders indicated that the A&M powder had a marginally higher K_d.

SUMMARY

Current data, along with published results, are presented for sodium nonatitanate, an inorganic ion-exchanger designed to be used for strontium removal from alkaline tank waste streams. This ion-exchange material is highly selective, has a high capacity, is radiation resistant, and is regenerable. In several simulant trials vs. realistic feeds, it has been shown to have superior selectivity for strontium in comparison with other ion-exchangers. Results of several studies by different researchers using different feeds (both simulants and real feeds) have confirmed that sodium nonatitanate is superior in effectiveness to the other commercially available ion-exchangers, as well as some of the frequently mentioned developmental materials. The current results also reconfirm our earlier report that sodium nonatitanate is capable of removing significant quantities of strontium from streams that approximate the composition of the "chemical complexant" tanks at Hanford. Even in groundwater applications, where the pH- K_d relationship for sodium makes it less effective, sodium nonatitanate shows selectivity results that outmatch competitive materials.

Pellet-form sodium nonatitanate has also been developed. This mechanically strong material has good mass transfer properties and provides high dynamic capacities and sharp breakthrough curve shapes. Such properties make it well suited for use in conventional packed-column ion-exchange systems. The availability of this material allows potential users the flexibility to choose between packed column and in-tank precipitation processes.

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Appendix A. Compositions of Simulants and Streams

Waste Stream	N-Springs Simulant	Actual 105-KE Basin Water	Actual N-Area Well Water-Low Sr	NCAW Simulant	NCAW Simulant	70% 101-AW DSSF Simulant	Actual 70% 101-AW DSSF	101SY Simulant	MVST W-29 Simulant	River Simulant	Savannah Simulant
Source		Ref. 12	Ref. 13	Ref. 6		Ref. 7	Ref. 7		Ref. 10	Ref. 8	
pH	6.6				14.5			14.4	13.7		
Sr	1.48E-06	1.54E-06	2.67E-09	3.42E-08	2.70E-07	7.14E-08	1.31E-05	2.90E-07	3.10E-06	1.10E-05	7.99E-06
Na	2.61E-04		2.52E-07	4.99E+00	4.99E+00	5.00E+00	4.75E+00	5.10E+00	3.45E+00	5.14E+00	5.15
K			5.12E-08	1.20E-01	1.20E-01	4.75E-01	4.40E-01	3.40E-02	3.50E-02	2.50E-01	
Rb			1.64E-11	5.00E-05	5.00E-05			4.20E-06	5.00E-07		
Cs			5.27E-12	5.00E-04	5.00E-04			4.19E-05	9.00E-05		
Mg	2.16E-04		3.61E-07								
Ca	7.27E-04		1.16E-06			2.41E-04	8.00E-04	4.20E-03	1.00E-03	1.00E-04	
Ba	1.12E-07		2.83E-10			5.91E-07					
Zn						9.00E-05		5.00E-04			
Al				4.30E-01	4.30E-01	4.97E-01	4.60E-01	4.20E-01	3.70E-01		0.31
Fe						7.00E-05		1.96E-04	2.70E-04		
CO_3	1.25E-04			2.30E-01	2.30E-01			3.80E-02	1.64E+00	1.40E-01	0.17
F	1.05E-05			8.90E-02	9.00E-02			9.20E-02			0.015
OH	1.22E-03			3.40E+00	3.40E+00	1.40E-01	1.30E-01	3.78E+00		1.00E+00	2.66
NO_3	1.94E-04			1.67E+00	1.67E+00	1.49E+00	1.34E+00	1.29E+00	6.70E-01	4.15E+00	2
NO_2				4.30E-01	4.30E-01	9.40E-01	8.10E-01	1.09E+00	8.90E-01		0.73
SO_4	2.16E-04			1.50E-01	1.50E-01	1.26E-02	1.00E-02	4.75E-03	1.60E-02		0.14
PO_4				2.50E-02	2.50E-02	1.75E-02	1.60E-02	2.00E-02	2.70E-02		8.30E-03
Citric								5.00E-03	a		
EDTA								5.00E-03	a		
Iminodiacetic Acid								3.10E-02	a		
Na_3NTA								2.50E-04	a		
Na gluconate								1.30E-02	a		
Na oxalate									a		0.014

[a]***Not specified: total organic carbon = 0.71%.**

Appendix B. Composition of 107-AN Simulant

Compound	Concentration (mol/L
Aluminum nitrate	1.43×10^{-2}
Boric acid	3.24×10^{-3}
Calcium nitrate	1.47×10^{-2}
Cerium nitrate	3.77×10^{-4}
Cesium nitrate	1.40×10^{-4}
Copper nitrate	4.74×10^{-4}
Na_2EDTA	1.95×10^{-2}
Iron(III) nitrate	3.03×10^{-2}
HEDTA	7.78×10^{-3}
Lanthanum nitrate	3.28×10^{-4}
Lead nitrate	1.87×10^{-3}
Magnesium nitrate	1.03×10^{-3}
Manganous chloride	1.02×10^{-2}
Neodymium nitrate	6.65×10^{-4}
Nickel nitrate	9.03×10^{-3}
Potassium nitrate	4.55×10^{-2}
Strontium nitrate	7.54×10^{-5}
Zinc nitrate	6.93×10^{-4}
Zirconyl nitrate	7.67×10^{-4}
Glycolic acid	2.48×10^{-1}
Sodium gluconate	6.00×10^{-2}
Citric acid	4.49×10^{-2}
Nitrilotriacetic acid	2.98×10^{-3}
Iminodiacetic acid	4.54×10^{-2}
Sodium chloride	3.11×10^{-2}
Sodium fluoride	7.00×10^{-3}
Sodium chromate	3.38×10^{-3}
Sodium carbonate	1.4
Sodium hydroxide	8.32×10^{-1}
Sodium nitrite	1.33
Sodium phosphate	1.17×10^{-2}
Potassium molybdate	3.73×10^{-4}
Sodium sulfate	8.59×10^{-2}
Sodium formate	2.31×10^{-1}
Sodium acetate	1.74×10^{-2}
Sodium oxalate	9.38×10^{-3}
Sodium nitrate	3.5

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