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SCALE-UP AND TESTING OF A NOVEL ION EXCHANGER FOR STRONTIUM

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ABSTRACT

The preparation of sodium nonatitanate was successfully scaled up to the 10 kg scale. The resulting material is highly selective for strontium, especially in alkaline solutions, giving a distribution coefficient (K_d) of 21,000 mL/g for strontium in a solution of 55 ppm Sr, 5 M $NaNO_3$, and 0.1 M NaOH. Column studies with pelletized sodium titanate show that this form has good mass transfer kinetics, and a high dynamic capacity for strontium (2.0 meq/g from a solution of 47 ppm Sr, 5 M $NaNO_3$, and 0.1 M NaOH). One of the highlights of this work is that our exchanger maintains its high selectivity for strontium in the presence of a variety of complexants.

INTRODUCTION

In the era since nuclear weapons first began to be produced at the end of World War II, large volumes of nuclear waste have been generated at various government-owned facilities. This waste, which consists largely of the by-products of uranium and plutonium production and purification, was disposed of in ways which at the time were deemed suitable, but which in retrospect were inadequate to deal with materials of this kind. Over 60% of the nation's high-level radioactive waste from weapons production, equal to 65 million gallons, is now stored at the Hanford Site in southeastern Washington (1, 2). Most of this waste is stored in 149 single shell tanks and 28 double shell tanks, of which some of the single shell tanks are known to have leaked over the intervening years (2). Treatment of this waste so that it cannot enter the environment is an urgent problem which has become the focus of public attention.

While the waste in the tanks at Hanford varies from tank to tank, it is generally alkaline (pH 14), and contains large amounts of sodium nitrate (much of it in the form of a salt cake). The tanks also contain various complexing agents, fission products, transuranic elements and other materials. Of the radionuclides present, cesium and strontium contribute most to the total radioactivity.

The sodium nonatitanate material ($Na_4Ti_9O_{20}$), first described by Lehto and Clearfield (3, 4), has an extremely high selectivity for strontium (5). This material has additional advantages which make it particularly well-suited for removing strontium from the nation's high-level radioactive waste. Unlike organic ion exchangers, sodium titanate, can withstand a high degree of gamma radiation, and can be ceramized to a solid final waste product (6). This paper will describe the studies leading to the scale-up development and production of sodium nonatitanate, as well as the characterization of our material.

EXPERIMENTAL

Preparations

Ten kilograms of sodium titanate were made by hydrothermally treating a sol-gel as previously described (7). All of the sol-gel was made in one batch. The final product was made by hydrothermally treating the sol-gel in four batches. The material was subsequently ground and sieved through 100 mesh. A portion of the material was pelletized with an inorganic binder using an AlliedSignal proprietary technique.

Determination of Distribution Coefficients

The distribution coefficient (K_d) was determined using the following equation

$$K_d = \frac{(C_i - C_f)}{C_f}\frac{V}{W} \qquad (1)$$

Where C_i and C_f are the initial and final concentrations of strontium, V is the volume of equilibrium solution, and W is the weight of the exchanger tested. K_d is reported in mL/g. The K_d values were measured using 200 mg of sample placed into 20 mL of various solutions. The samples were shaken in polyethylene vials for 24 hours in a water bath shaker set at 30 °C.

NCAW Simulant

Table 1 gives the composition of the Neutralized Current Acid Waste (NCAW) simulant (as developed by Battelle Pacific Northwest Laboratory). The reagents were added to the water in the order shown. The solution was mixed overnight with a pneumatic mixer, before being filtered through a 1 micron polypropylene bag filter.

Determination of Batch Capacity

To obtain the capacity, we suspended 200 mg of exchanger in 200 mL of a solution containing 55.4 ppm Sr, 5 M $NaNO_3$, and 0.1 M NaOH. Each day the exchangers were recovered from the solution by filtration, and then the solids resuspended in fresh solution. The process was repeated until the final concentration of strontium in the equilibrium solution was constant (which took about 6 days). The solid exchanger was then analyzed for strontium content.

Column Experiments

Figure 1 shows the experimental set-up. Due to the high alkalinity of the feed solutions, glass could not be used anywhere in the system. The columns,

TABLE 1. PREPARATION OF 25 GALLONS (95 LITERS) OF NCAW

Component	Formula Weight g/mol	Molarity	Concentration g/L	Weight for 25 Gallons
Water	18.02	---	---	75.97 kg
$NaNO_3$	85.00	0.258	21.93	2.08 kg
KNO_3	101.11	0.120	12.13	1.15 kg
$RbNO_3$	147.47	5.0×10^{-5}	7.4×10^{-3}	700 mg
$CsNO_3$	194.92	5.0×10^{-4}	9.8×10^{-2}	9.275 g
Na_2SO_4	142.05	0.150	21.31	2.08 kg
$Na_2HPO_4\ 7H_2O$	268.07	0.025	6.70	634.1 g
NaOH	40.00	3.40	136.0	12.87 kg
$Al(NO_3)_3\ 9H_2O$	375.15	0.430	161.31	15.27 kg
Na_2CO_3	105.99	0.23	24.38	2.31 kg
NaF	41.99	0.089	3.74	354.0 g
$NaNO_2$	69.00	0.43	29.67	2.81 kg

made of polycarbonate pipe, were 1 inch ID by 8 to 12 inches long. The ends of the columns have PVC slip fittings with 1 inch pipe thread. The end caps of the columns were drilled for 1/4 inch T-fittings. The ends of the columns were packed with either stainless steel saddles, polypropylene pellets, or Teflon beads. Polypropylene wool was placed at the interfaces of the packing and the exchanger. The columns contained 20-40 mesh bound sodium nonatitanate.

The tubing was 1/4 inch polypropylene, except at the peristaltic pump heads (Masterflex pumps, model 7523-10 with 7518 Easy-Load heads), where the tubing was 1/4 inch Tygon. The feed was contained in 30 gal polyethylene drums; the effluent was collected in a 30 gal drum. All drums were surrounded by another drum as secondary containment.

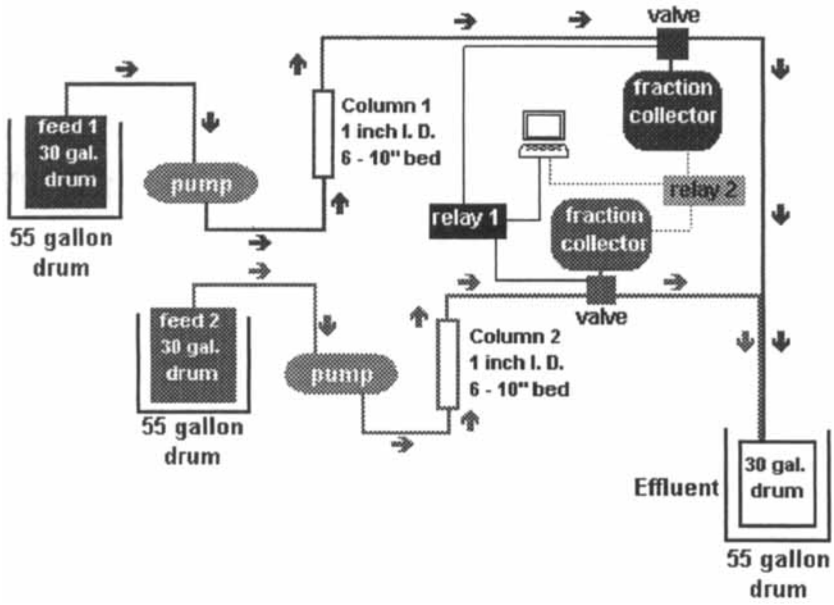

FIGURE 1. Ion exchange column experiments process flow scheme.

Samples were taken using Viewdac (Keithley, Cleveland, OH) data acquisition software to control the 3-way solenoid valves (Burkert 3-way solenoid valves) and the fraction collectors (Eldex, model 1243). Viewdac also monitored the time when the samples were taken, as well as the voltage of a pressure drop transducer. Ten milliliter samples were taken every 5 to 20 minutes. The strontium content was measured using an ICP.

Twenty gallons (76 L) of feed was made by adding 21.9 g of $Sr(NO_3)_2$, 64.3 kg $NaNO_3$, and 122.8 kg of NaOH to 122.8 kg of water for a final concentration of 47.2 ppm Sr, 5.1 M Na, and 0.1 M OH. After mixing, the feed was used directly without filtration.

RESULTS AND DISCUSSION

Characterization of Sodium Nonatitanate

Our new sodium titanate material resulted from a concerted effort to improve the strontium selectivity and preparation method of the Lehto/Clearfield (3, 4) material by a university/industry team. The new material has the same empirical formula, but differs in the degree of crystallinity, d-spacing, and affinity for strontium from alkaline waste solutions. Figure 2 shows the XRD pattern of the improved material. The new material's method of preparation was readily scaled up, and is easily made at the 10 kg batch scale.

Since the intended use of the new material is as an ion exchanger for removal of radioactive strontium from nuclear waste at such sites as Hanford, Savannah River or Idaho National Energy Laboratory, our testing has been focused on qualification of the material for this application. To perform well, a strontium exchanger must be selective for strontium against a high sodium background under alkaline conditions, and in the presence of complexants. It must resist degradation by nuclear radiation. It should also be readily used in a conventional column operation, exhibiting good mass transfer into the exchanger, and a high capacity.

Selectivities of our new sodium nonatitanate are extremely high. Lane Bray (Battelle Pacific Northwest Laboratory) measured K_d as a function of pH at 5M sodium and 0.0005M strontium and obtained the data shown in Figure 3. Note that the distribution coefficient is a strong function of pH, with a maximum at the alkaline end, as needed for the alkaline waste. At this high end, the K_d is over 20,000 mL/g. Distribution coefficients also appear to vary with sodium and strontium concentration. For sodium, we observe a steep decrease with increasing sodium concentration, while for strontium concentration, lower concentrations produce higher K_d values (Figure 4).

Effect of Organic Complexants

One frequent concern is that the strontium in the Hanford supernatant is complexed by various organic contaminants and that these might successfully

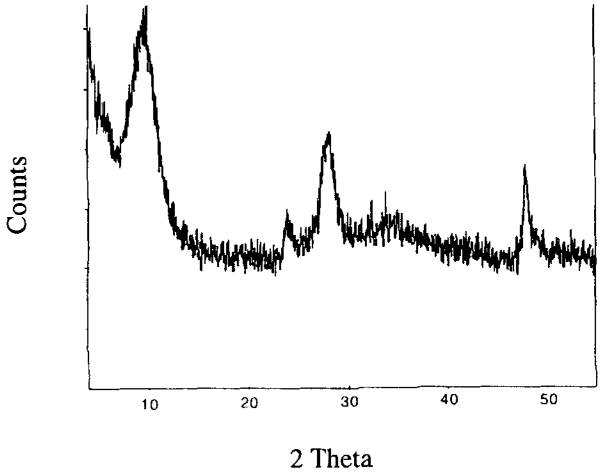

FIGURE 2. X-ray diffraction pattern of sodium nonatitanate (Sample RC-3-67B). The d-spacing of the 001 reflection is 9.4 Angstroms. Figure provided by R. Cahill and A. Clearfield of Texas A&M University.

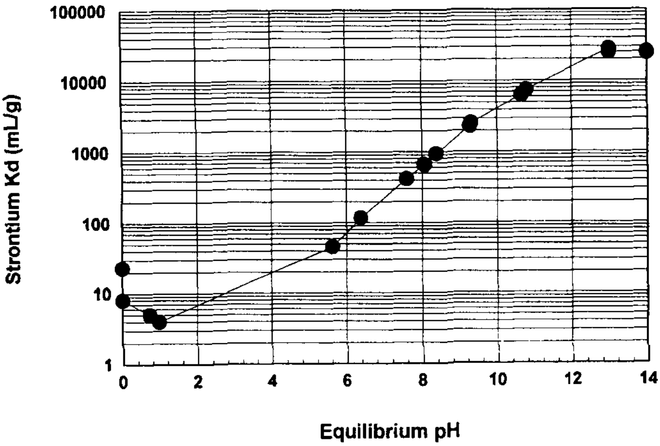

FIGURE 3. Effect of pH on strontium distribution coefficient. Sample 7926-201, 5 M Na, 0.0005M Sr, 25 °C, 72 hr contact time. Measured by Lane Bray (PNL).

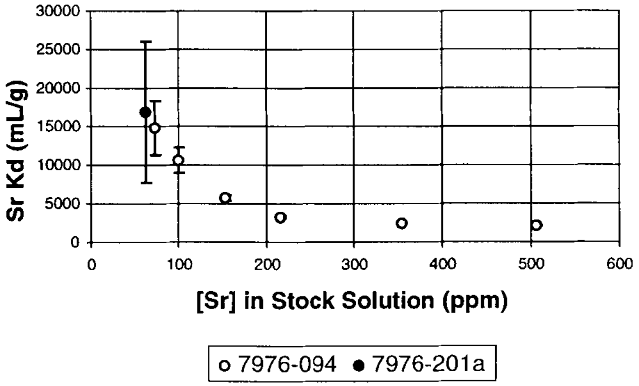

FIGURE 4. The effect of strontium concentration on sodium titanate K_d. 5M $NaNO_3$/0.1M NaOH.

compete with an ion exchanger for strontium. We studied the effect of complexants on K_d by preparing a series of solutions containing complexants which are believed to be significant components in the supernatant. All solutions were prepared using NCAW (see Experimental section) to which 60 ppm strontium nitrate had been added. These solutions were then spiked with citric acid, oxalic acid or ethylenediaminetetraacetic acid (EDTA) and shaken either with or without sodium titanate according to the standard procedure for distribution constant measurements. It is important to note that both the titanate-exposed samples and the blanks were filtered. Omitting the filtration step for the blanks led to false high Sr concentrations due to the presence of precipitated strontium hydroxide. The sodium titanate used was the bound form ground to 20-40 mesh.

Table 2 shows the results of this experiment. First, we observe that in no case was the final strontium concentration equal to the initial concentration, even in the blank sample where no organic complexant or sodium titanate had been added. Precipitation was therefore one of the processes removing strontium in all of the samples. Secondly, we observe that adding a complexant increased the

TABLE 2. EFFECT ON SODIUM NONATITANATE K_d OF ORGANIC COMPLEXANTS

a) The strontium distribution coefficient (K_d, mL/g)[a].

Conc. of complexant (ppm)	Strontium Distribution Coefficient (K_d, mL/g)[a] Citric Acid	Oxalic Acid	EDTA
0	751	751	751
200	5113	267	5123
2000	2897	149	2831

b) Strontium concentration after filtration in the presence or absence of sodium nonatitanate.

Conc. of complexant (ppm)	Exchanger Added	Strontium Concentration (ppm) Citric Acid	Oxalic Acid	EDTA
0	N	0.6	0.6	0.6
	Y	0.069	0.069	0.069
200	N	4.9	1.4	8.4
	Y	0.094	0.38	0.15
2000	N	3.1	6.0	25.4
	Y	0.1	2.4	0.86

[a] NCAW with 60 ppm added strontium. K_d calculated using the actual initial concentrations from part b (not 60 ppm).

concentration of strontium in solution. The three complexants differed in their ability to hold strontium in solution, with EDTA being most effective, and citric acid and oxalic acid being roughly comparable. In general, higher concentrations of complexant led to higher strontium concentrations.

The most significant result however was the reduction in strontium concentrations observed when sodium titanate was added to the complexant-containing samples. Contrary to previous wisdom, we observe that sodium titanate is able to remove strontium from these complexant-containing solutions with high effectiveness. K_d values range from 149 to 5123 mL/g. If the initial concentration had been calculated from the amount added, thus summing the effects of ion exchange and precipitation, these K_d values would increase to ca. 60,000 mL/g. Recently, S.F. Marsh, et al. (8) confirmed these results with an independent set of experiments using a different alkaline feed and samples supplied by our team. These remarkable results confirm the utility of sodium titanate in this application.

Radiation Stability

We also measured radiation stability of sodium nonatitanate with the help of Dennis Wester (Battelle Pacific Northwest Laboratory). The samples were exposed to doses between 250 and 1000 Mrad of ^{60}Co radiation. Radiation, even at the highest doses, did not affect the strontium uptake of sodium titanate (see Table 3). The slightly higher values listed in Table 3 are within experimental error of the analytical technique.

Analysis of Scaled-Up Sodium Titanate

In order to supply samples of our exchanger and to facilitate column studies, we scaled up our sodium titanate preparation method to the 10 kg scale. The final step involved a hydrothermal treatment which was done in four batches. The sodium titanate from all four scale-up batches have high strontium K_d and batch equilibrium capacities (see Table 4). The Sr K_d for the batches that were hydrothermally treated for a short time are about two times higher than for the batches treated for longer times (20,500 vs. 11,500 mL/g). This difference may be correlated with the degree of crystallinity of the samples. Sodium nonatitanate is a layered material with a d-spacing of 8-10 Angstroms (4, and see Figure 2). The degree of crystallinity can be quantified from the x-ray diffraction patterns by measuring the full width at half the maximum peak height (FWHM) of the 001 reflection (see Figure 2). Figure 5 plots the Sr K_d of the batches as a function of FWHM. The larger the FWHM, the less crystalline the material. The materials

TABLE 3. STRONTIUM UPTAKE BY IRRADIATED SODIUM NONATITANATE

Treatment (Megarads)	Sr Remaining in Solution (ppm)	24 hr Kd (mL/g)
0 (untreated)	0.17	40,253
250	0.36	18,956
500	0.14	48,900
750	0.14	48,900
1000	0.15	45,633

TABLE 4. SUMMARY OF THE PILOT PLANT HYDROTHERMAL TREATMENTS

Batch	Time at temp[a]	Mixer	Crystallinity FWHM[b] deg	Sr K_d[c] mL/g	Batch equilibrium capacity[d] meq/g
1	long	off	1.13	12,100 ±2,100	0.897
2	long	on	1.92	10,800 ± 420	1.06
3	short	on	2.67	19,800 ± 410	1.12
4	short	on	2.23	21,100 ±2,300	1.19

[a] At temp. = at temperature between 160-200 °C

[b] FWHM = full width at half maximum of largest peak on X-ray pattern

[c] 5M NaNO3/0.1M NaOH/68.6 ppm Sr

[d] 55.4 ppm Sr, 5.1 M Na, 0.1 M OH

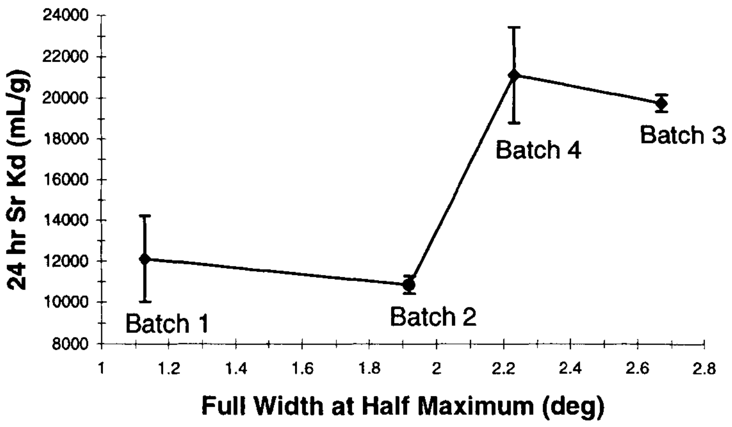

FIGURE 5. Strontium uptake of pilot plant sodium nonatitanate as a function of full width at half maximum (FWHM) peak height of the 001 x-ray reflection. The higher the FWHM, the lower the crystallinity. 69 ppm Sr, 5.1 M Na, 0.1 M OH.

with the higher crystallinity (batches 1 and 2) have the lower K_d's. High crystallinity may hinder the interlayer diffusion, thereby lowering the Sr uptake.

Clearfield and Lehto (4) describe the gross morphology of their sodium nonatitanate as needle-shaped (0.5-2 μm by 0.05-2 μm). Scanning electron micrographs (SEM) of each of the pilot plant batches show batches 1-3 consist of fibers compacted into nuggets, while batch 4 consists of elongated bundles of fibers (see Figure 6). While mixing does not affect the resulting K_d (see results of batch 3-4 in Table 1), it does influence the gross morphology of the exchanger. Mixing the gel during hydrothermal treatment causes shear stresses on the newly forming sodium titanate, which in turn results in a higher number of loose fibers and elongated bundles.

Although batch 2 is more crystalline than batch 3, the SEMs show that these samples look very similar in that they have masses of short fibers (see Figure 6). Unlike any of the other batches, batch 1 has a coral-like appearance made up mostly of plates and few fibers. Although their gross structures are different, both

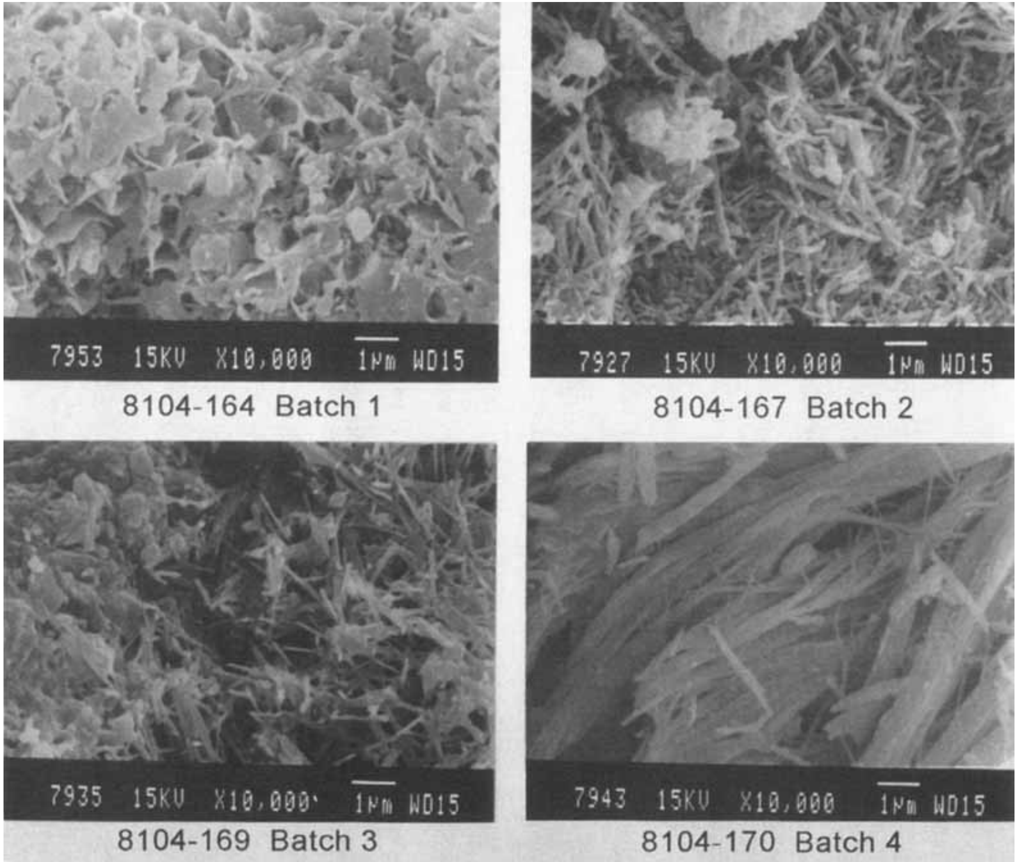

FIGURE 6. Electron micrographs of each of the pilot plant hydrothermal treatment batches at 10,000 times magnification.

batches 1 and 2 have similar K_d values. Batch 1 has the slowest heat up profile during the hydrothermal treatment (6 hours longer than batch 3). The slow heating rate may have allowed the fibers to fuse and develop the unique structure of batch 1.

Column Studies

Column experiments simulate the actual process of using the exchangers in their final form. Unlike batch experiments, column experiments give us kinetic data, and therefore allow us to determine the rate-controlling step of the process. Information such as whether film diffusion or particle diffusion controls the exchange is important in developing both the exchanger and the process. From the breakthrough data obtained under each set of conditions, we have calculated the ion exchange capacity, the degree of bed saturation, the liquid mass transfer coefficient, and the distribution coefficient. These parameters will allow us to conduct a theoretical plate analysis to optimize the process.

Analysis of breakthrough curves. Doulah and Jafar (9) developed a method characterizing breakthrough curves with three parameters by describing the curve with a probability function. These parameters can be used to calculate mass transfer quantities and other breakthrough characteristics. The linearized breakthrough curves are expressed as:

$$\log\,\ln\left(\frac{1}{1-\frac{C}{C_o}}\right) = \beta\log(\Theta-\Theta_o) - \beta\log\Theta_m \qquad (2)$$

and

$$\Theta = t - \frac{\alpha\ H}{v} \qquad (3)$$

where C_0 = feed concentration of target ion (ppm)

C = concentration of target ion at outlet (ppm)

t = time (hr)

α = bed voidage

H = bed height (cm)

v = superficial velocity of feed (cm/hr)

Θ_0 is taken as the value of Θ at $C/C_0 = 5\%$. A plot of the left side of equation (2) versus $\log(\Theta - \Theta_0)$ is a straight line with β as the slope and $-\beta \log \Theta_m$ as the intercept.

Doulah and Jafar (9) derived the following parameters as a function of Θ_0, Θ_m, and β. The saturation capacity of the target ion (Sr) is:

$$q_o = \frac{vC_o(\Theta_o + \Theta_m)}{H\rho_b} \tag{4}$$

q_0 = target ion saturation capacity (meq/g)

ρ_b = solid phase bulk density (g/cc)

The distribution coefficient of a column (K_d) is found by dividing Equation 4 by the initial target ion concentration (C_0):

$$K_d^l = \frac{q_o}{C_o} \tag{5}$$

The degree of bed saturation (D_{bs}) at the time of breakthrough (defined at $C/C_0 = 5\%$) is:

$$D_{bs} = \frac{\Theta_o}{\Theta_o - \Theta_m} \tag{6}$$

The deviation from equilibrium between the liquid and the exchanger along the bed can be accounted for by using the concept of "theoretical plates." With this method, the actual continuous column is represented as a series of finite stages (or plates) within which equilibrium has been attained. As the number of plates increases (and the plate height decreases) for a given bed height, the separation becomes more efficient. The height of a theoretical plate, h (or mass transfer zone), can be calculated by:

$$h = \frac{H\Theta_m}{\Theta_o + \Theta_m} \tag{7}$$

The number (N) of theoretical plates is simply the total bed height divided by the height of one theoretical plate:

$$N = \frac{H}{h} \tag{8}$$

The liquid phase mass transfer coefficient ($K_l a$) can be expressed as:

$$K_l a = \frac{\beta}{\Theta_m} \tag{9}$$

Results with bound sodium nonatitanate. Table 5 summarizes the experimental conditions under which the strontium breakthrough tests were conducted, and the parameters calculated from the breakthrough curves via the method of Doulah and Jafar (9). Two experiments were conducted at different feed rates (S1a and S2a).

The strontium capacity of bound sodium nonatitanate is very high, about 42% of the theoretical capacity for the unbound sodium titanate (2 vs. 4.74 meq/g). Surprisingly, the column capacity is about twice the value obtained from batch equilibrium tests (2 vs. 1 meq/g). The batch tests were conducted with 55.4 ppm Sr, while the column tests had 47.2 ppm Sr. Past results have shown that the uptake of strontium increases as the amount of Sr in the feed decreases. The higher amount of strontium in the batch measurements may account for the lower value of capacity obtained.

The high capacity that bound sodium nonatitanate has for strontium is evident from the high number of column volumes which can be treated before breakthrough (see Figure 7). As the flowrate decreases from 13.9 to 7.2 column volumes (CV) per hour, the 5% breakthrough value increases from 470 to 600 CV.

Theoretical Plate Analysis. As the number of theoretical plate increases, the efficiency of the ion exchange process in a column increases. Helfferich (10) has derived an equation to calculate the height of a theoretical plate in terms of different mass transfer limitations. Basically, h (the plate height) is the sum of contributions from the finite particle size (h_s), slow particle diffusion (h_p), slow film diffusion (h_f), and longitudinal diffusion (h_l) along the column. Therefore,

$$h = h_s + h_p + h_f + h_l \tag{10}$$

TABLE 5. CONDITIONS AND RESULTS OF THE STRONTIUM BREAKTHROUGH EXPERIMENTS WITH BOUND SODIUM NONATITANATE[a]

	Exp. S1a	Exp. S2a
Bed Volume (mL)	54.7	53.7
Bed Height (cm)	10.8	10.6
Bed Height to Diameter	4.3	4.2
Superficial Velocity (cm/min)	2.5	1.26
Sr Saturation Capacity (meq/g)	2.01	2.14
Distribution Coef. (mL/g)	1870	1990
Degree of Bed Saturation (%)	43.1	50.4
Height of a Theoretical Plate (cm)	6.14	5.26
No. of Theoretical Mass Transfer Plates	1.8	2.0
Liq. Mass Transfer Coef., K_la (1/hr)	0.0263	0.0154

[a] Feed: 47.2 ppm Sr, 5 M $NaNO_3$, and 0.1 M NaOH

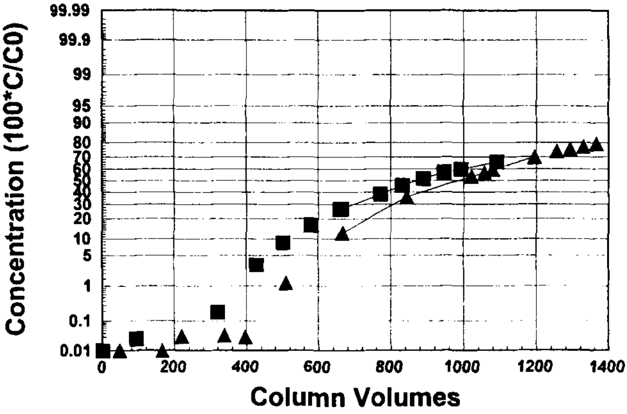

FIGURE 7. Breakthrough curve of bound sodium nonatitanate. Feed: 47.2 ppm Sr, 5.1 M Na, and 0.1 M OH; 1 inch columns. ▲ = 7.2 CV/hr; ■ = 13.9 CV/hr; line shows which data points were used to calculate the Doulah & Jafar parameters.

The contribution by the finite particle size is

$$h_s = 1.64r_o \tag{11}$$

where r_0 = the average particle radius (cm).

The contribution by slow particle diffusion is

$$h_p = \frac{\lambda}{(\lambda+\alpha)^2}\frac{0.14r_o{}^2v}{D_p} \tag{12}$$

where

$$\lambda = \frac{X_i}{C_i} \tag{13}$$

and λ = column distribution ratio

X_i = equilibrium amount of Sr in the exchanger per unit bed volume (meq/L)

C_i = concentration of Sr in the interstitial solution at equilibrium with the exchanger (meq/L)

α = bed voidage

v = superficial velocity (cm/s)

D_p = diffusion coefficient of Sr within the exchanger (cm^2/s)

The contribution to the theoretical plate height by slow film diffusion is

$$h_f = \left(\frac{\lambda}{\lambda+\alpha}\right)^2 \frac{0.266r_o{}^2v}{D(1+70r_ov)} \tag{14}$$

where D = diffusion coefficient of Sr in the free liquid (cm^2/s)

The longitudinal diffusion contribution is expressed as

$$h_l = \frac{D\alpha\sqrt{2}}{v} \tag{15}$$

Helfferich (10) has plotted the effective plate height as a function of the operating conditions (see Figure 8). Such figures are a function of the values for D and D_p. The values used for the plot are very close to our estimate of the diffusivities (our calculated values of D = $1.18\text{x}10^{-5}$ cm^2/min and D_p = $1.42\text{x}10^{-7}$ cm^2/min). From Figure 8, we see that the strontium uptake for both bound sodium nonatitanate (as 2.5 cm/min feed rate) falls in the particle-diffusion limited regime. This is mainly the result of a high feed velocity with respect to the capacity of the exchanger.

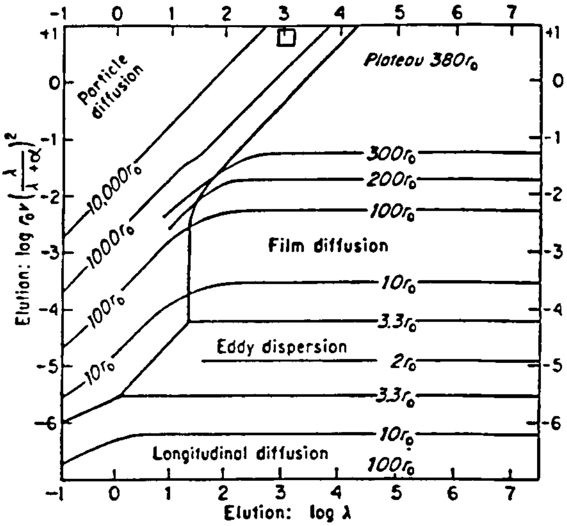

FIGURE 8. Theoretical plate height as a function of operating conditions. D=10^{-5} cm^2/s and $D_p=3x10^{-7}$ cm^2/s. = Bound sodium nonatitanate (S1a, 2.5 cm/min feed). Figure based on Helfferich (10).

The best operating conditions occur when neither film or particle diffusion dominates. At the minimum plate height, the optimal set of conditions in Figure 8 is near the "triple point," where the particle diffusion, film diffusion, and eddy dispersion lines meet. To move towards the triple point, we need to decrease either the feed velocity or the particle size for the exchanger. Furthermore, for bound sodium nonatitanate, we need to decrease the column distribution ratio (λ). The column distribution ratio is determined by the pH and the initial ion concentrations of the system, as well as the capacity of the exchanger.

CONCLUSIONS

The sodium nonatitanate powder is highly selective for strontium over sodium; we have reproducibly measured distribution constants of ca. 20,000 mL/g for strontium in feed containing 64 ppm Sr 5M sodium and 1M hydroxide. Its selectivity improves as the sodium concentration decreases, or as the strontium concentration decreases, and it is at its most effective under alkaline conditions. The exchanger has a theoretical capacity of 4.74 meq/g, of which 2.2 meq/g is used for strontium under the standard (5M Na, 1M OH) conditions and column experiments have shown that it has excellent ion exchange kinetics even after binding into pellets. Bound sodium nonatitanate can treat 600 column volumes of Sr feed (5.1 M Na, 0.1M OH, and 47.2 ppm Sr) at a feed rate of 7.2 CV/hr. Our material is stable to the alkaline conditions of the feed, and to exposure to radiation up to 1000 Mrad. In tests not reported here, we have also found that the exchanger is regenerable with dilute acid, and retains its selectivity after regeneration.

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