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Evaluation of Potential Eluants for Non-Acid Elution of Cesium From Spherical Resorcinol-Formaldehyde Resin

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ABSTRACT

Ion Exchange column loading and elution of cesium from spherical resorcinol-formaldehyde resin have been conducted for two potential non-acid eluants – $(NH_4)_2CO_3$ and CH_3COONH_4. The results revealed encouraging cesium elution performance. 100% elution was achieved in at most 22 hours (~28 bed volumes) of elution. Elution performance was fairly high at 6 hours (~8 bed volumes) of elution for some of the eluants and also practically comparable to the benchmark acid eluant (HNO_3). Hence, it is quite possible 100% percent elution will be closer to the 6th hour than the 22nd hour. Elution is generally enhanced by increasing the concentration and pH of the eluants, and combining the eluants.

Keywords: spherical resorcinol-formaldehyde resin, ion exchange; cesium; column; non-acid elution; loading; $(NH_4)_2CO_3$; CH_3COONH_4.

INTRODUCTION

Plans are underway to use small-column ion exchange (SCIX) units installed in high-level waste tanks to remove Cs-137 from highly alkaline salt solutions in the United States Department of Energy (DOE) Complex. Spherical resorcinol-formaldehyde (sRF) ion exchange resin, known for its high selectivity for cesium in highly alkaline radioactive wastes, is the baseline material under consideration for the DOE's Hanford site (1). It is a weak acid cation exchange resin and as a result has a high affinity for hydrogen ions. Therefore, it is easily eluted with acid solutions. Nitric acid is used most frequently (2-11).

Tanks containing highly alkaline radioactive waste are made of carbon steel. Use of an acid eluant may pose a hazard to the tank integrity (corrosion and associated structural damage) in the event of a spill, leak, etc. A non-acid eluant may be a viable alternative. It will eliminate the need for special acid handling requirements within the tank farms.

This work is a continuation of the non-acid elution of sRF resin study. The earlier work screened 36 potential non-acid eluants via batch contact sorption (or loading) tests followed by confirmation of the leading candidates by batch contact sorption and quasi column caustic wash/water rinse/elution tests (12,13).

As mentioned in the detailed literature review that preceded the non-acid elution work, there seems to be no work on non-acid elution of RF resin (14). The parallels on non-acid elution in the literature are with other cation exchange resins e.g., Linde AW-500, Zeolon-900, and Duolite

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ARC-359, Duolite CS-100, and Duolite S-761, Lewatit DN, and clinoptilolite (natural zeolite). The details of the review regarding the above resins are given elsewhere (14). The gist of the review was that ammonium compounds, particularly $(NH_4)_2CO_3$, have been successful in eluting cesium from various cation exchange resins.

The objectives of this study was to further evaluate two potential non-acid eluants [$(NH_4)_2CO_3$ and CH_3COONH_4] using the typical sRF-cesium ion exchange column process (i.e., loading, caustic wash, water rinse, and elution) with the goal of optimizing the elution process in terms of concentration, pH, and eluant combinations.

EXPERIMENTAL

Ion Exchange Material

The resin used was the sRF ion exchange resin. The resin was manufactured by Microbeads AS in Skedsmokorset, Norway. It was received in hydrogen form (H-form) in deionized (DI) water.

The resin was preconditioned using a protocol developed at Savannah River National Laboratory (SRNL) in 2004 (15). Resin preconditioning involves taking the resin through DI water, NaOH (1 M), DI water, HNO_3 (0.5 M), and DI water steps at room temperature. The preconditioned resin was stored in a polypropylene bottle filled to the brim with DI water to virtually eliminate the air headspace.

Preparation of Eluant/Other Relevant Solutions

Desired concentrations of the solution of each eluant [$(NH_4)_2CO_3$ and CH_3COONH_4] and other relevant compounds (e.g., NaOH and HNO_3) were prepared. Each preparation involved weighing a predetermined amount of the compound(s) and adding it/them to a required volume of DI water followed by stirring at room temperature.

A few particles (though negligible) were observed in the $(NH_4)_2CO_3$ solutions. Hence, as a precautionary measure, they were filtered under vacuum using 0.45 µm nylon Nalgene (Rochester, New York) filter units to avoid any potential clogging in the tubings of the ion exchange column apparatus.

The preparation of one eluant mixture [2 M CH_3COONH_4/2 M $(NH_4)_2CO_3$] resulted in incomplete dissolution of the compound(s). Therefore they were filtered as mentioned earlier. An approximate symbol precedes the concentration of the compounds in the eluant (see Table 4).

The simulant solution used for this study was DOE's Savannah River Site (SRS) Tank 241-2F supernate simulant. For brevity, it will be referred to as Tank 2F simulant. Table 1 gives the target and measured concentrations of the constituents in the Tank 2F supernate simulant (10,12). The simulant was not specifically prepared for this work but was obtained from another study (10). The concentration of cesium in the as-received simulant was increased [by adding non-radioactive $CsNO_3$ (Acros Organics, Pittsburgh, Pennsylvania)] to match the cesium concentration (500 mg/L nominal) in the Tank 2F simulant used in the earlier screening study (12,13). Again, the simulant was filtered under vacuum using 0.45 µm nylon Nalgene filter units

after the addition of the $CsNO_3$ to avoid any potential clogging in the tubings of the ion exchange column apparatus as was done for the $(NH_4)_2CO_3$ solutions.

$(NH_4)_2CO_3$ (Fisher Scientific, Pittsburgh, Pennsylvania), CH_3COONH_4 (GFS Chemicals, Inc., Powell, Ohio), and NH_4OH (LabChem Inc., Pittsburgh, Pennsylvania) were used to prepare the various eluants. HNO_3 (Fisher Scientific, Pittsburgh, Pennsylvania) and NaOH (Fisher Scientific, Pittsburgh, Pennsylvania) were used to prepare 0.5 M HNO_3, 0.1 M NaOH, 0.5 M NaOH, and 1 M NaOH solutions. The chemicals used were all reagent grade.

Ion Exchange Column Setup

Each ion exchange column setup consisted of a jacketed glass column, a glass column top unit, thermocouple probe, two pumps, tubings, feed bottles, and effluent bottles/vials. Each pump was dedicated to one of the two flow rates (see Table 2). All the columns (a maximum of three) shared a constant-temperature water circulating bath. The column setup was in a chemical hood.

The **in-house** glass columns had an inside diameter of 1.565 $\pm$ 0.005 cm (i.e., 1.92 mL/cm of height) and graduations (0.1 cm divisions) on the walls to facilitate measurement of resin bed height and height of liquid or solution above the resin bed.

The top of each column was connected (via screwing) to a glass unit with four openings. One opening served as the feed solution inlet via connection to the pump outlet tubing. One opening served as port for the type T thermocouple probe used to measure or monitor the temperature of the liquid above the resin bed in the column. The thermocouple probes were connected to a thermometer (Digi-Sense® 12 Channel Scanning Thermometer, Model # 92000-00, Cole-Parmer Instrument Company, Vernon Hills, Illinois). One of the two remaining openings was capped while the other was opened to the atmosphere as a safety precaution to alleviate any (unexpected) pressure buildup in the system.

The glass columns were equipped with 200 mesh stainless steel screens at the bottom. The screens were used as supports for the resins. O-rings held the screens securely in place. The space beneath each 200 mesh stainless steel screen was filled with 3 mm glass beads (Cat. # 11-312A, Fisher Scientific, Pittsburgh, Pennsylvania) to minimize the system dead volume.

Temperature regulation in the columns was achieved with a constant-temperature circulating water bath (Model # DC10/P3, Thermo Haake, Newington, New Hampshire) looped with the column glass jackets with quick-disconnect fittings.

Solutions were introduced down flow through the columns using Fluid Metering, Inc. (Syosset, New York) positive displacement pumps (Pump drive module: Model # QG20; Pump head module: Model # RH00-CKC-LF). The piston pump head was made of ceramic.

All the individual units (i.e., from the feed solution polyethylene bottles, pumps, column to the effluent polypropylene bottles/vials) were connected with tetrafluoroethylene tubings (1/16-in ID X 1/8-in OD). The portions of the pump inlet tubings that were inserted into the feed solution

bottles were made of stainless steel to ensure they were at the bottom of the feed bottles. The pump inlet tubings were manually transferred between the various process solutions.

The setup essentially had no valves. The columns operated on a manometric equilibrium principle basis in that while the pumps introduced feed solutions into the columns, solutions exited the columns by gravity. The column exit tubings were bent in a quasi U-shape fashion with the tips slightly turned downwards to allow effluents to be collected beneath the tips. Once a manometric equilibrium height is reached through adjustment of the tip up or down, any liquid the pumps introduce into the columns leave the columns by gravity to maintain the equilibrium.

Column Tests

A known volume (3.35 mL) of preconditioned settled H-form sRF resin in DI water was converted to Na-form prior to transferring to the column. The 3.35 mL of settled H-form resin in DI water is equivalent to 4.2 mL of Na-form resin in the simulant solution. The conversion was done by adding five H-form resin volumes (about 17 mL) of 1 M NaOH solution to the H-form resin for about 30 minutes with brief stirring every 10 minutes at room temperature per SRNL protocol (15).

This was followed by pouring all the Na-form resin slurry (i.e., Na-form resin/1 M NaOH solution mixture) into the column while simultaneously gently tapping the glass column walls to ensure uniform resin bed packing. To prevent flow out of the column, a glass stopcock (valve) was connected to the column outlet tubing during pouring of the resin to the column.

To determine the dry resin mass, another 3.35 mL of preconditioned settled H-form sRF resin in DI water was placed in a vacuum oven (IsoTemp Vacuum oven, model # 280A, Fisher Scientific, Pittsburgh, Pennsylvania) at 50 $\pm$ 2 ^{o}C and < 90 torrs (90 mm Hg) absolute pressure and dried to a constant mass. The dry resin mass for the 3.35 mL of settled preconditioned H-form sRF resin in DI water was 1.1971 grams (or 0.36 g/mL). This agrees with the value 0.36 g/mL obtained by others in the past for the sRF resin (4,5).

The temperature for all the column operations was 25 $\pm$ 2 ^{o}C. The height of the resin bed, the height of the liquid above the resin bed, and temperature of the liquid above the resin bed were measured periodically. Table 2 gives details of the experimental conditions. The conditions are basically the typical used for the sRF-cesium ion exchange process in the DOE complex. Note that each column run begun with an in-column resin pretreatment per a protocol developed at SRNL (15). Also, the flow rate of all the process steps was 3 BV/hr except the elution step which was 1.4 BV/hr.

Effluents from the columns for each process step outlined in Table 2 were collected manually with polypropylene bottles or vials either in bulk or in fractions (elution step only) for cesium analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS); and pH and flow rate measurements (via mass and density measurements). The overall error for all the analyses was within $\pm$ 20%.

RESULTS AND DISCUSSION

Resin Cesium Loading Duration

To allow comparison and for consistency with the earlier screening study (12,13), it was important to use the same resin cesium loading as the previous study. In the earlier screening study, cesium loading was achieved by batch contact sorption method using Tank 2F simulant containing 500 mg/L cesium. Since the column cesium loading was used for this study, the time required to attain approximately the same loading had to be determined. The resin cesium loading in the previous study was 10,017 mg/kg Na-form resin. This is equivalent to 12,822 mg/kg H-form resin based on the ratio of dry Na-form/dry H-form resin of 1.28 obtained in the previous work (12,13).

Table 3 provides data for the column cesium loading duration tests. The data indicate a loading duration of 2.5 hours was enough to attain the target duration. Hence, 2.5/2.67 hours (150/160 minutes) was used for all subsequent column cesium loading steps. Note that all the process steps up to the cesium loading step given in Table 2 were performed in the loading duration tests. The predicted or target resin loading values were obtained using a sRF resin breakthrough curve for Tank 2F simulant containing 2.25 mg/L cesium and a cesium-sRF isotherm generated with DOE's Hanford site Tank AP-101 simulant as guides (10,16). Even though the actual and predicted values are fairly close, the prediction was largely based on intuition or was an informed guess at best.

The cesium loading value (13,233 mg/kg H-form resin) for the 2.5-hour duration obtained here was consistent with the 2.5/2.67-hour cesium loading values for all the subsequent column runs. In fact, the average for all ten values is 12,729 mg/kg H-form resin with a percent relative standard deviation (%RSD) of 7.3 (see Table 4). This indicates good reproducibility.

Elution with $(NH_4)_2CO_3$ Solutions

Figure 1 shows plots of percent cesium eluted (i.e., percent of cesium loaded on resin that is eluted) at various bed volumes (BV) of eluant processed for several $(NH_4)_2CO_3$ solutions – plain (no pH adjustment) 1 M and 2 M solutions, and 2 M solution whose pH has been adjusted with 2.5 M NH_4OH. The duration of the elution runs was about 22 hours. As expected for the plain $(NH_4)_2CO_3$ solutions, cesium elution is enhanced as the eluant concentration is increased from 1 to 2 M. Similarly, for the 2 M solutions, elution increases as the pH increases. Note that NH_4OH barely contributes to the elution performance because the fraction (<0.003) that ionizes is small (17).

At the end of 22 hours (about 25-31 BV) of elution, each of the eluants regardless of concentration and pH had attained virtually 100% cesium elution. The percent elution at the end of 6 hours (about 6-7 BV) of elution, at least for the top two plots or eluants, are relatively high to infer that 100% elution will probably occur closer to the 6th hour than the 22nd hour. Note that the 6th to the 22nd hour occurred during off-hours (overnight). Schedule acceleration necessitated running several (three) columns simultaneously. It prevented the use of automatic fraction collectors because of limited space in the chemical hood.

Figure 2 is an attempt to ascertain the effect of a further increase in the concentration of $(NH_4)_2CO_3$. The elution performance of 3 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution and its 2 M counterpart are roughly the same. Note that for the 3 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution, the pH (9.63) was not intentionally adjusted. It seems the effect from the increase in elution from the higher ammonium concentration of the 3 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution may have been offset by the higher pH (9.98) of the 2 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution.

It is not clear why the percent elution value (94%) of the last data point for the 3 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution is a little lower than the others. However, it could be considered close to 100% for all practical purposes. It is more likely due to the relatively large change in concentration (feed minus effluent) that was obtained which, in turn, may be due to the relatively high feed concentration obtained from the feed analysis for the run. The deductions made earlier regarding the 6th and 22nd hour also hold here.

Elution with CH_3COONH_4 Solutions

Figure 3are plots for various CH_3COONH_4 solutions – plain (no pH adjustment) 1 M and 2 M solutions, and 2 M solutions whose pHs have been adjusted with 0.06 M and ~2 M $(NH_4)_2CO_3$. The duration of the elution runs was also about 22 hours. Again, increasing the eluant (CH_3COONH_4) concentration from 1 to 2 M results in an increase in elution performance. Contrary to expectation, the performance of 2 M CH_3COONH_4 solution whose pH has been adjusted with 0.06 M $(NH_4)_2CO_3$ and plain 2 M CH_3COONH_4 solution are roughly the same. If anything at all, the ammonium from the $(NH_4)_2CO_3$, though small, increased the overall ammonium concentration which typically should have resulted in an increase in elution.

The elution performance of the ~2 M CH_3COONH_4 solution whose pH has been adjusted with ~2 M $(NH_4)_2CO_3$ is fairly high. The enhancement in elution cannot be attributed to only the pH increase but also to the increase in the total concentration of ammonium ions. In fact, the $(NH_4)_2CO_3$ contributes two times more ammonium ions than the CH_3COONH_4.

Again, the deductions made earlier regarding the 6th and 22nd hour also apply here. Note that even though the percent elution (26%) at the end of the 6th hour for the plain 1 M CH_3COONH_4 is comparatively low, it still attains 100% elution by the end of the 22nd hour. This means it takes relatively longer to reach the critical amount of ammonium ions needed to make an impact at the exchange sites.

In view of the fact that the elution performance of 2 M CH_3COONH_4/0.06 M $(NH_4)_2CO_3$ solution and plain 2 M CH_3COONH_4 solution are roughly identical and relatively low compared to the $(NH_4)_2CO_3$ solutions (see Table 4), and also the requirement that the pH of solutions or streams going to the tank farm should be a minimum of 8 (18); a test run was done with 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ solution (pH=8.61). Note that the pH of plain 4 M and 6 M CH_3COONH_4 solutions are both <8. They are 7.46 and 7.63 respectively.

Figure 4 is a comparison of the percent elution of 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ solution and 2 M CH_3COONH_4/0.06 M $(NH_4)_2CO_3$ solution. Expectedly, the performance of 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ solution is higher. This is because aside from the higher pH,

more importantly, it has two times more ammonium ions. The explanation given for the less than expected percent elution value for the last data point for 3 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution in Figure 2 also holds here for the 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ solution. In fact, the two test runs were done at the same time and used the same feed concentration analysis data.

Comparison of the Performance of the Tested Eluants with the Benchmark Eluant

Figure 5 gives the plots discussed so far plus the elution plot for 0.5 M HNO_3, the benchmark eluant. The performance of the top candidate eluants compare reasonably well with that of 0.5 M HNO_3. On an equi-molar concentration basis [e.g., 2 M $(NH_4)_2CO_3$ and 2 M CH_3COONH_4], $(NH_4)_2CO_3$ performs better than CH_3COONH_4. It is not surprising since $(NH_4)_2CO_3$ has twice the moles of ammonium ions than its CH_3COONH_4 counterpart. Note that for the plain 2M CH_3COONH_4 and the plain 1 M $(NH_4)_2CO_3$ solutions the performance at the end of the 6th hour is roughly close.

Table 4 is a complement to Figure 5. It is a ranking of the eluants based on the percent elution at the end of the 6th hour of elution. Percent elution data at the end of the 22nd hour of elution are also provided. The results are generally consistent with other non-acid elution work with other cation exchange resins (19-26).

Even though the percent elution at the end of the 6th hour of elution for ~2 M CH_3COONH_4/~2 M $(NH_4)_2CO_3$ solution is higher than the corresponding value for 2 M $(NH_4)_2CO_3$/2.5 M NH_4OH solution (88.1 versus 82.5%), a closer look as depicted in Figure 6 indicates their performance, at least up to the 6th hour, is roughly the same. Along the same lines, the percent elution at the end of the 6th hour of elution for 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ solution is slightly higher (or roughly the same) than that for plain 2 M $(NH_4)_2CO_3$ solution. Figure 7 shows the latter performs better, at least, up to the 6th hour. Collection of effluent or eluate fractions between the 6th and 22nd hour will help elucidate the performance differences between the eluants and make the elution profiles more complete.

On the whole, all the eluants hold promise if one considers the fact that the resin cesium loading used is on the high side. Virtually most of the resin cesium loadings for the waste streams planned to be treated are much lower because the cesium concentrations in the waste streams are fairly low (27).

CONCLUSIONS

The column elution tests on the alternative non-acid eluants [$(NH_4)_2CO_3$ and CH_3COONH_4] for spherical resorcinol-formaldehyde resin indicated the following.

The eluants are promising cesium eluants especially when the high resin cesium loadings are taken into consideration.

At the end of 22 hours (~28 bed volumes) of elution, each of the eluants regardless of concentration, pH, and eluant combination had attained virtually 100% cesium elution. The percent elution at the end of 6 hours (~8 bed volumes) of elution for some of the eluants are relatively high to infer that 100% elution will occur closer to the 6th hour than the 22nd hour.

The performance of some of the eluants compare favorably with the HNO_3, the benchmark acid eluant.

Increasing concentration and pH of the eluants as well as combining the eluants largely improve cesium elution.

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Table 1. Concentration of the onstituents in SRS Tank 2F supernate simulant**.**

Constituent	Target Concentration, mg/L (M)	Measured Concentration, mg/L (M)
Free OH^-	12,920 (0.76)	13,600 (0.80)
CO_3^{2-}	7,800 (0.13)	nm
NO_2^-	6,854 (0.149)	7,850 (0.171)
NO_3^-	259,800 (4.19)	306,800 (4.95)
PO_4^{3-}	475 (0.005)	< 1,000 (< 0.011)
SO_4^{2-}	3,070 (0.032)	3,170 (0.033)
Cl^-	106 (0.003)	< 250 (< 0.007)
F^-	55 (0.003)	< 250 (< 0.013)
Al	6,980 (0.26)	8,600 (0.32)
Cs	2.26 (1.70×10^{-5})	2.25 (1.69×10^{-5})
K	274 (0.007)	296 (0.0076)
Na	137,900 (6.00)	144,000 (6.26)
P	384 (0.012)	164 (0.005)
Rb	0.535 (6.30×10^{-6})	0.0098 (1.0×10^{-7})
S	1,023 (0.032)	1,170 (0.036)
pH	14	14

nm = not measured

Table 2. Experimental conditions for the column tests.

Process Step	Solution	Bed Volume (BV) of Solution Processed	Flow Rate, BV/hr	Time per Process Step, hr
Na-Form Resin Transfer into Column	A slurry of Na-form sRF resin and 1 M NaOH solution	n/a	n/a	n/a
In-Column Resin Pretreatment: 1st Water Rinse	Deionized water	6	3	2
In-Column Resin Pretreatment: Acid Wash	0.5 M HNO_3	8	3	2.67
In-Column Resin Pretreatment: 2nd Water Rinse	Deionized water	6	3	2
In-Column Resin Pretreatment: Regeneration	0.5 M NaOH	6	3	2
Cesium Loading	Tank 2F simulant	8	3	2.67
Caustic Wash	0.1 M NaOH	6	3	2
Water Rinse	Deionized water	6	3	2
Elution	Various eluants	~30.8	1.4	~22

n/a = not applicable
Temperature of each process step = 25 $\pm$ 2 ^{o}C
Resin bed volume (BV) = 4.2 mL (in simulant solution)

Table 3. Column resin cesium loading duration tests at 25 ^{o}C.

Cs Loading Duration	Cs Conc. in Loading Effluent Solution	Actual Resin Cs Loading	Predicted Resin Cs Loading	Ratio of Predicted/Actual
Units	mg/L	mg/kg H-form resin	mg/kg H-form resin	
2.5 Hours	<0.020	13,233	13,549	1.02
3 Hours	0.0252	16,260	16,259	1.00
4 Hours	<0.020	21,513	21,679	1.01

Loading feed solution = Tank 2F simulant
Loading feed cesium concentration = 513 mg/L
Loading flow rate (nominal) = 3 BV/hr
Resin bed volume = 4.2 mL (in simulant solution)
Resin dry mass = 1.1971g H-form resin

Table 4. Ranking of eluants based on 6-hour elution performance at 25 °C.

		At the End of the 6th Hour		At the End of the 22nd Hour	
Eluant	**Resin Cs Loading**	**Percent Cs Eluted**	**Bed Volume**	**Percent Cs Eluted**	**Bed Volume**
Units	mg/kg H-form resin	%	BV	%	BV
0.5 M HNO_3	13,394	94.2	8.2	99.1	29.6
3 M $(NH_4)_2CO_3$/2.5 M NH_4OH	14,157	89.8	9.1	93.8	30.2
~2 M CH_3COONH_4/~2 M $(NH_4)_2CO_3$	12,289	88.1	7.7	107	27.1
2 M $(NH_4)_2CO_3$/2.5 M NH_4OH	12,220	82.5	7.2	102	24.6
4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$	14,313	78.5	8.4	90.9	28.3
2 M $(NH_4)_2CO_3$	12,206	77.1	7.4	102	26.0
2 M CH_3COONH_4	11,709	64.7	8.1	106	29.2
1 M $(NH_4)_2CO_3$	12,825	61.4	8.5	101	30.9
2 M CH_3COONH_4/0.06 M $(NH_4)_2CO_3$	11,712	53.0	7.0	105	25.8
1 M CH_3COONH_4	12,466	26.1	7.4	107	25.6
Average	12,729	n/a	7.9	n/a	27.7
% RSD	7.3	n/a	8.5	n/a	7.9

n/a = not applicable

Figure Captions

Figure 1 Cesium elution from sRF resin for various $(NH_4)_2CO_3$ solutions at 25 ^oC.

Figure 2 Cesium elution performance of 3 M $(NH_4)_2CO_3$/2.5 M NH_4OH and 2 M $(NH_4)_2CO_3$/2.5 M NH_4OH solutions at 25 ^oC.

Figure 3 Cesium elution from sRF resin for various CH_3COONH_4 solutions at 25 ^oC.

Figure 4 Cesium elution performance of 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ and 4 M CH_3COONH_4/0.06 M $(NH_4)_2CO_3$ solutions at 25 ^oC.

Figure 5 Cesium elution performance of various $(NH_4)_2CO_3$ and CH_3COONH_4 solutions as well as the benchmark eluant (0.5 M HNO_3) at 25 ^oC.

Figure 6 Cesium elution performance of ~2 M CH_3COONH_4/~2 M $(NH_4)_2CO_3$ and 2 M $(NH_4)_2CO_3$/2.5 M NH_4OH at 25 ^oC.

Figure 7 Cesium elution performance of 4 M CH_3COONH_4/0.5 M $(NH_4)_2CO_3$ and 2 M $(NH_4)_2CO_3$ solutions at 25 ^oC.

Figure 1

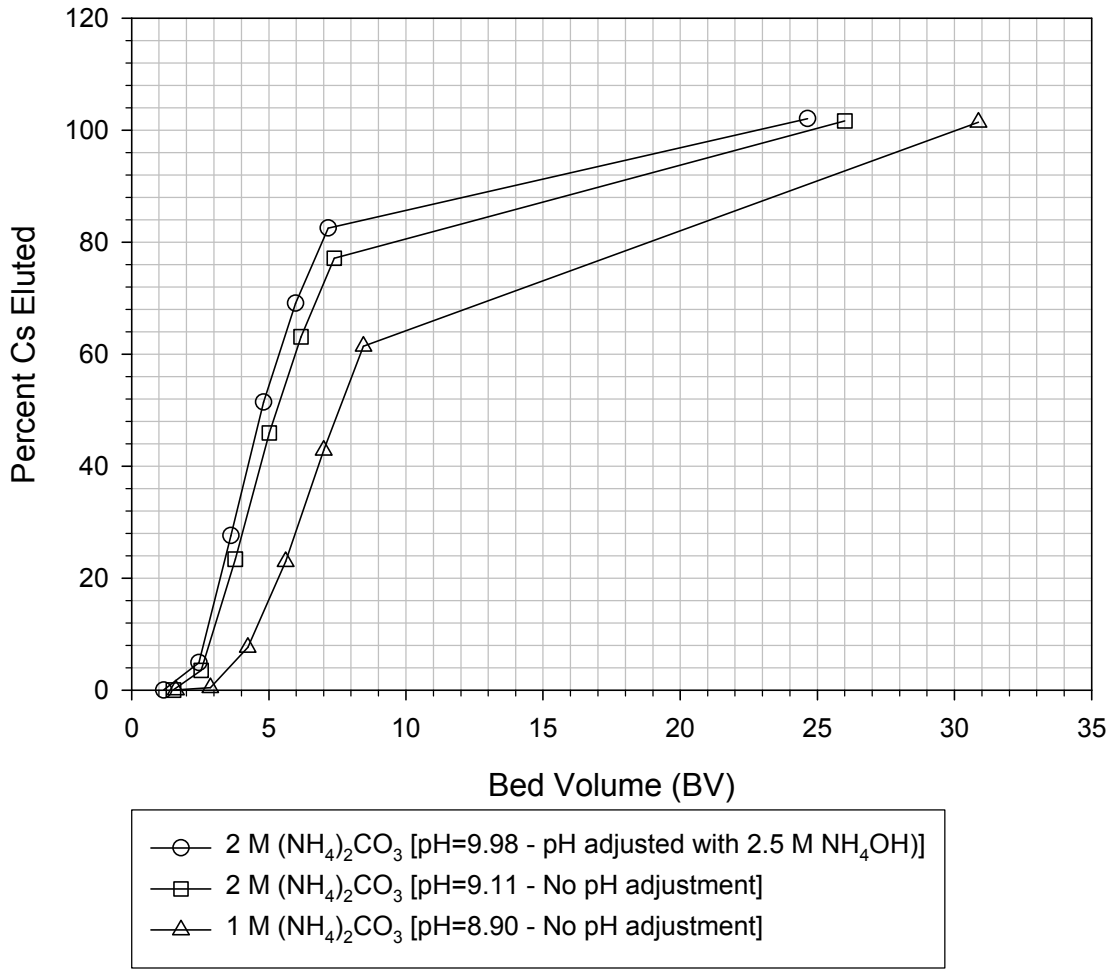

120
100
80
60
40
20
0
Percent Cs Eluted
0
5
10
15
20
25
30
35
Bed Volume (BV)
2 M $(NH_4)_2CO_3$ [pH=9.98 - pH adjusted with 2.5 M NH_4OH)]
2 M $(NH_4)_2CO_3$ [pH=9.11 - No pH adjustment]
1 M $(NH_4)_2CO_3$ [pH=8.90 - No pH adjustment]

Figure 2

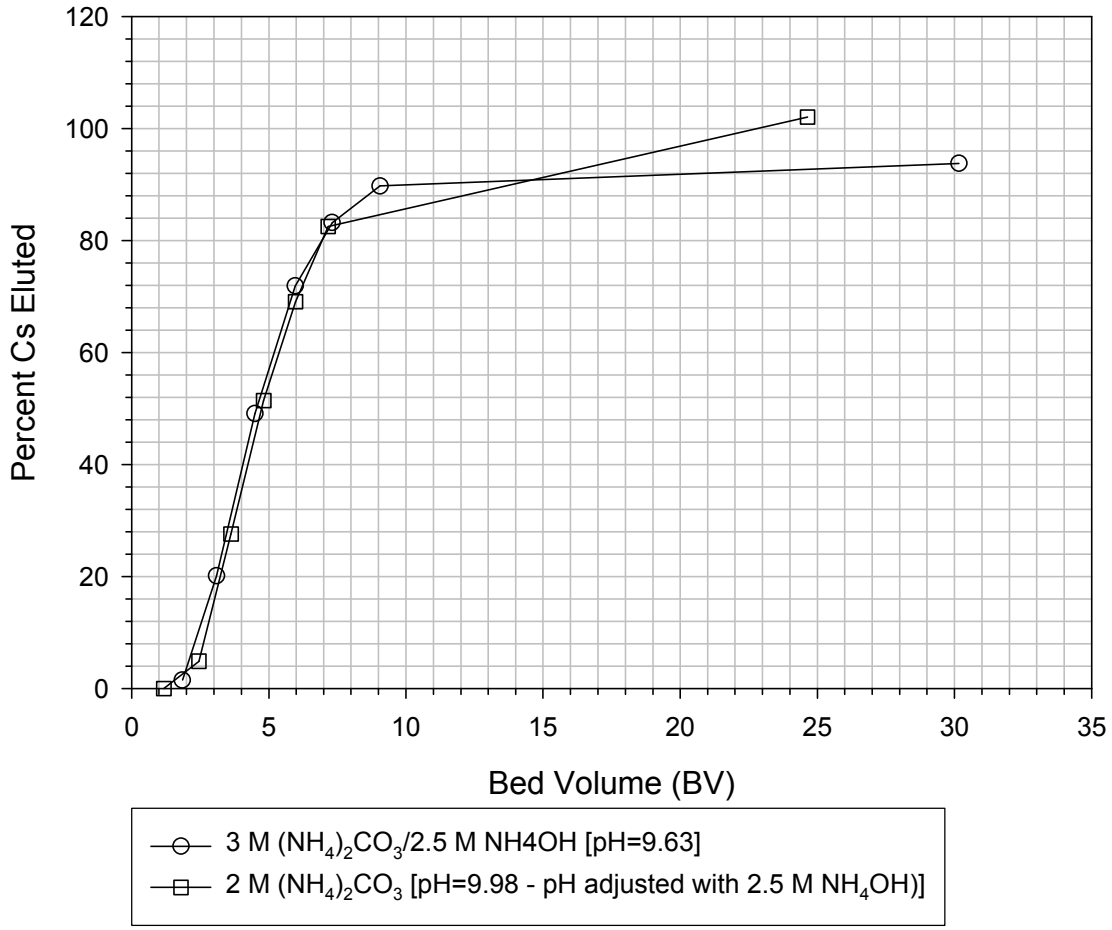

120
100
80
60
40
20
0
Percent Cs Eluted
0
5
10
15
20
25
30
35
Bed Volume (BV)
3 M $(NH_4)_2CO_3$/2.5 M NH4OH [pH=9.63]
2 M $(NH_4)_2CO_3$ [pH=9.98 - pH adjusted with 2.5 M NH_4OH)]

Figure 3

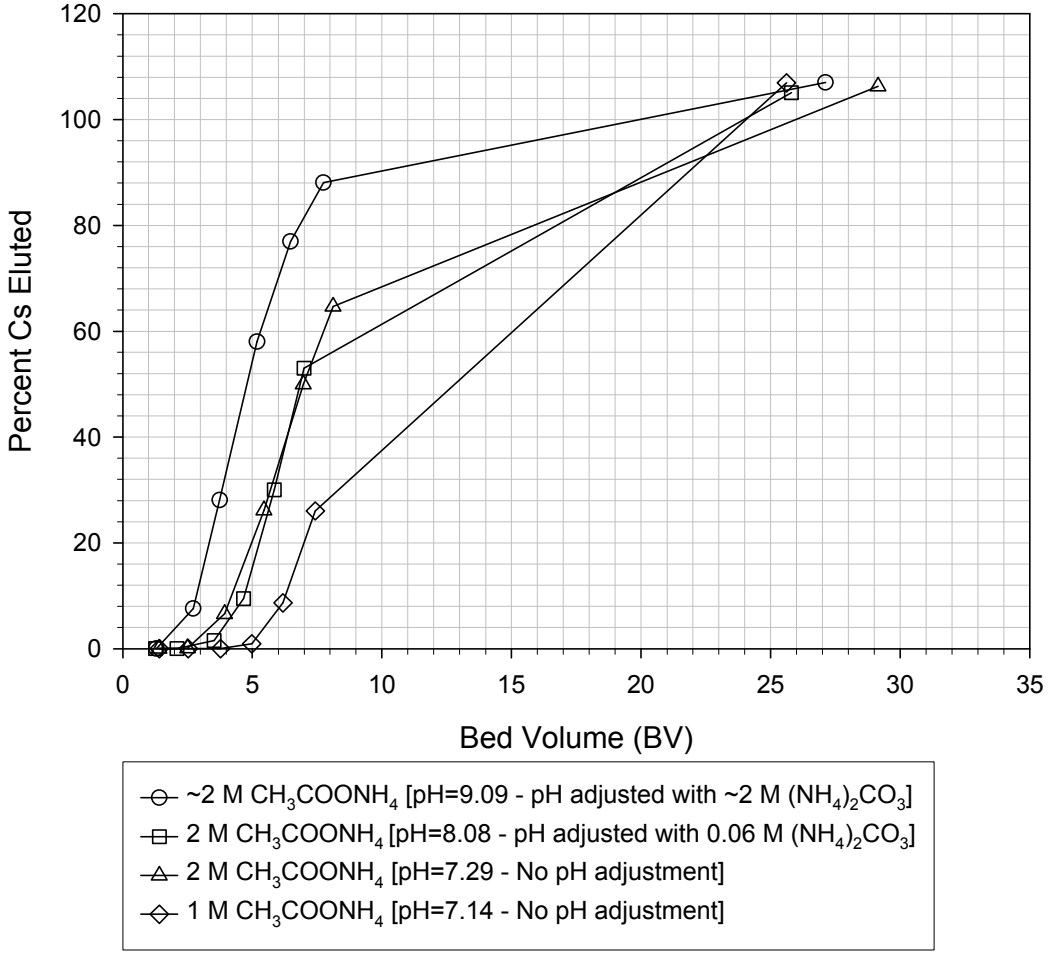

120
100
80
60
40
20
0
Percent Cs Eluted
0
5
10
15
20
25
30
35
Bed Volume (BV)
~2 M CH3COONH4 [pH=9.09 - pH adjusted with ~2 M (NH4)2CO3]
2 M CH3COONH4 [pH=8.08 - pH adjusted with 0.06 M (NH4)2CO3]
2 M CH3COONH4 [pH=7.29 - No pH adjustment]
1 M CH3COONH4 [pH=7.14 - No pH adjustment]

Figure 4

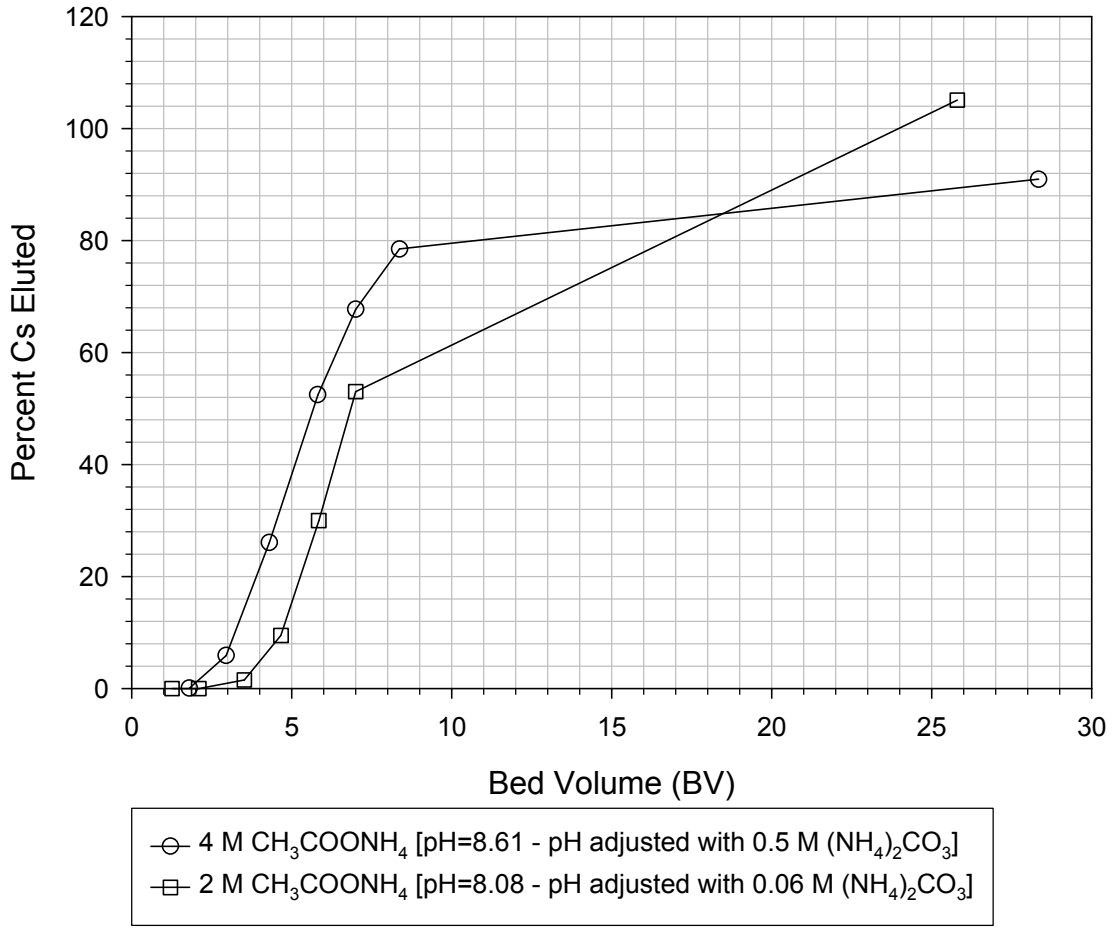

120
100
80
60
40
20
0
Percent Cs Eluted
0
5
10
15
20
25
30
Bed Volume (BV)
4 M CH3COONH4 [pH=8.61 - pH adjusted with 0.5 M (NH4)2CO3]
2 M CH3COONH4 [pH=8.08 - pH adjusted with 0.06 M (NH4)2CO3]

Figure 5

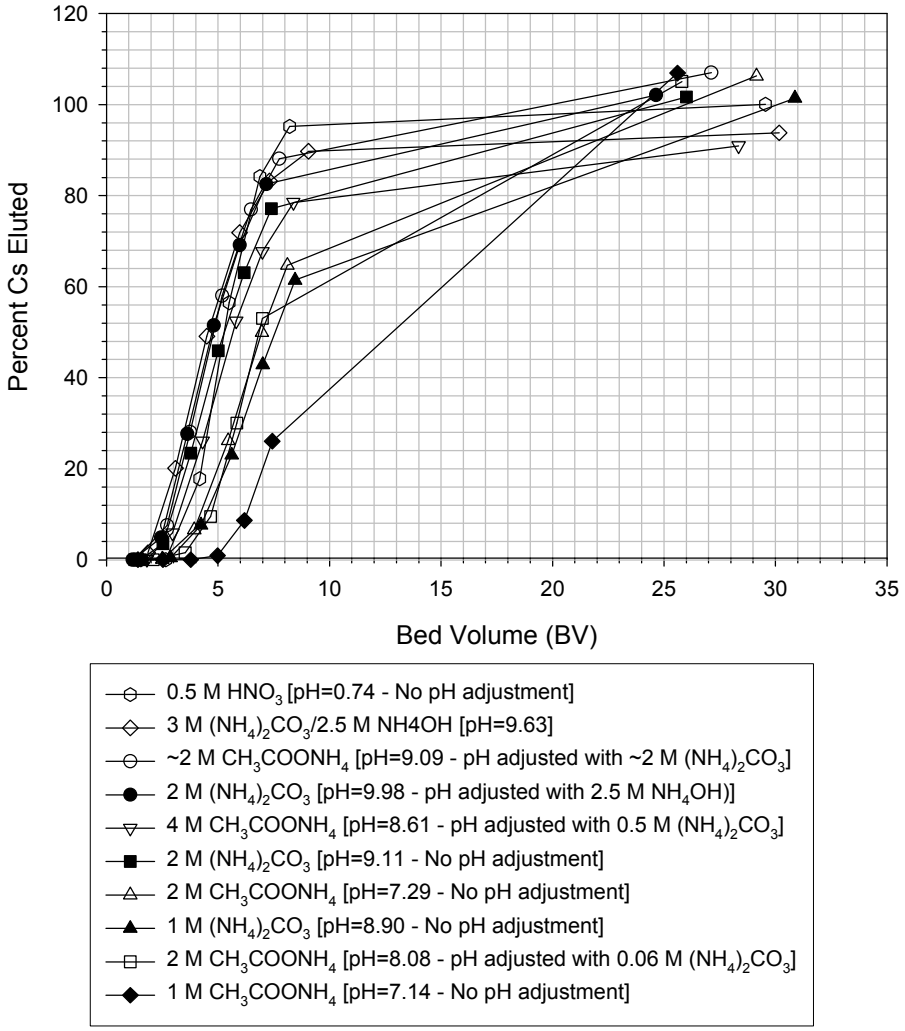

Percent Cs Eluted
Bed Volume (BV)
0
20
40
60
80
100
120
0
5
10
15
20
25
30
35
0.5 M HNO3 [pH=0.74 - No pH adjustment]
3 M (NH4)2CO3/2.5 M NH4OH [pH=9.63]
~2 M CH3COONH4 [pH=9.09 - pH adjusted with ~2 M (NH4)2CO3]
2 M (NH4)2CO3 [pH=9.98 - pH adjusted with 2.5 M NH4OH)]
4 M CH3COONH4 [pH=8.61 - pH adjusted with 0.5 M (NH4)2CO3]
2 M (NH4)2CO3 [pH=9.11 - No pH adjustment]
2 M CH3COONH4 [pH=7.29 - No pH adjustment]
1 M (NH4)2CO3 [pH=8.90 - No pH adjustment]
2 M CH3COONH4 [pH=8.08 - pH adjusted with 0.06 M (NH4)2CO3]
1 M CH3COONH4 [pH=7.14 - No pH adjustment]

Figure 6

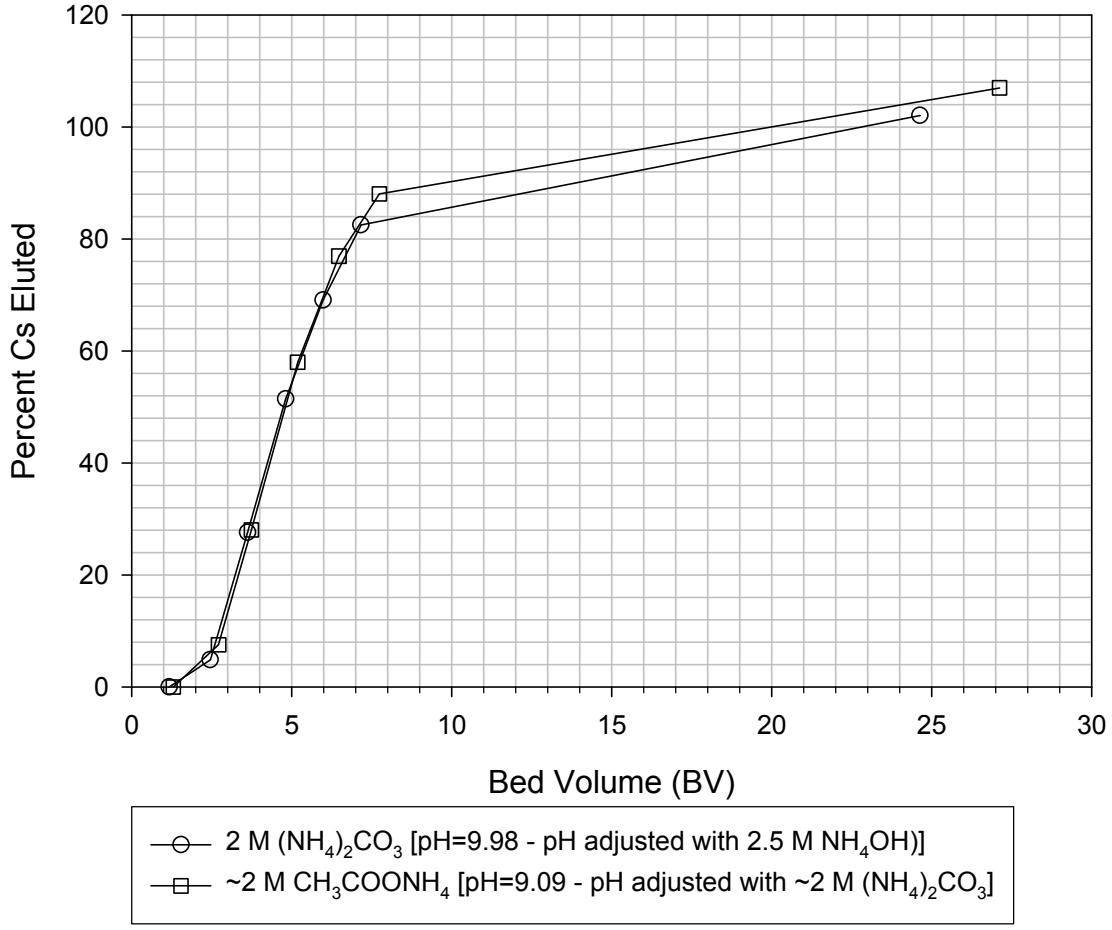
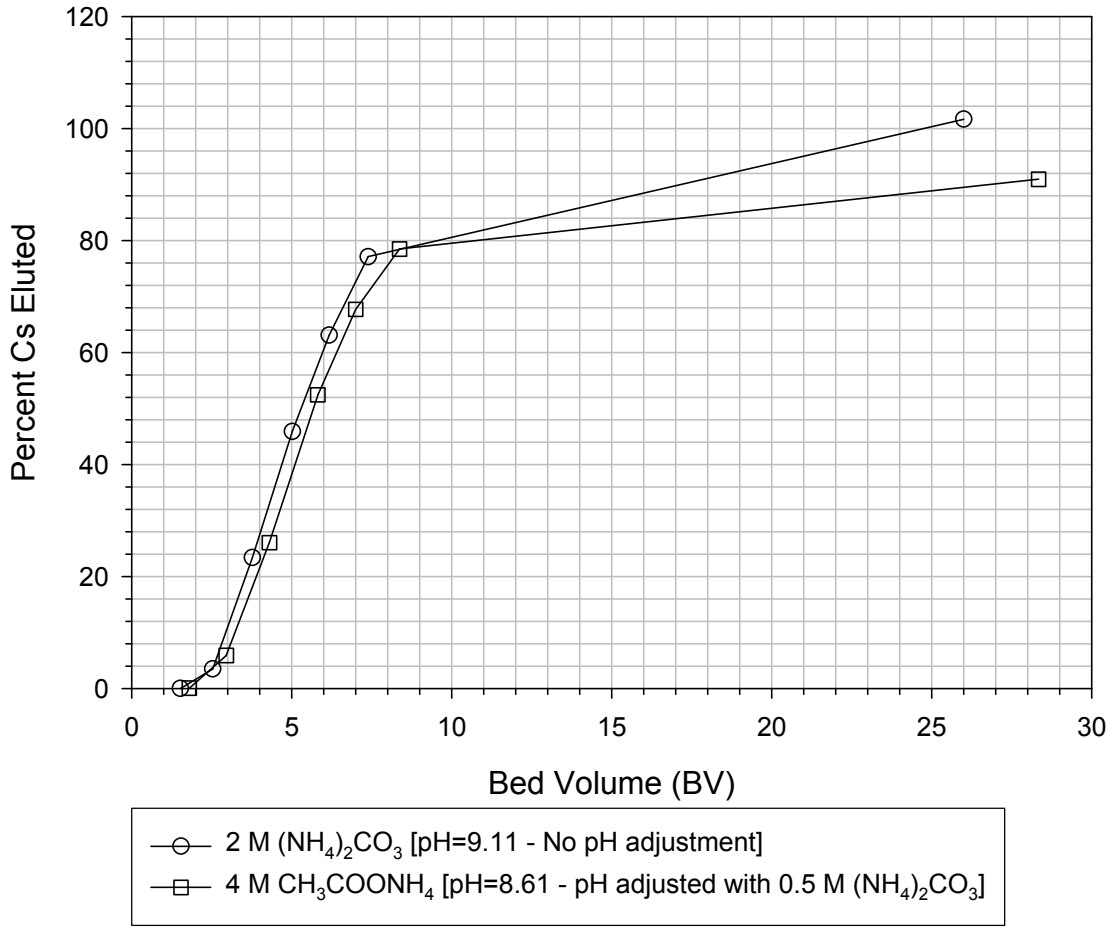

120
100
80
60
40
20
0
Percent Cs Eluted
0
5
10
15
20
25
30
Bed Volume (BV)
2 M $(NH_4)_2CO_3$ [pH=9.98 - pH adjusted with 2.5 M NH_4OH)]
~2 M CH_3COONH_4 [pH=9.09 - pH adjusted with ~2 M $(NH_4)_2CO_3$]

Figure 7


120
100
80
60
40
20
0
Percent Cs Eluted
0
5
10
15
20
25
30
Bed Volume (BV)
2 M $(NH_4)_2CO_3$ [pH=9.11 - No pH adjustment]
4 M CH_3COONH_4 [pH=8.61 - pH adjusted with 0.5 M $(NH_4)_2CO_3$]