Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Fiskum, S. K. , Blanchard Jr., D. L. , Arm, S. T. and Peterson, R. A.(2005) 'Cesium Removal from Simulated and Actual Hanford Tank Waste Using Ion Exchange', Separation Science and Technology, 40: 1, 51 — 67
To link to this Article: DOI: 10.1081/SS-200041760
URL: http://dx.doi.org/10.1081/SS-200041760

Separation Science and Technology, 40: 51–67, 2005
ISSN 0149-6395 print/1520-5754 online
DOI: 10.1081/SS-200041760

Cesium Removal from Simulated and Actual Hanford Tank Waste Using Ion Exchange

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Abstract: Effective cesium removal from Hanford tank wastes is presented using SuperLig® 644, an elutable, organic ion exchanger. Test materials included simulant 241-AW-101, actual wastes from tanks 241-AP-101, 241-AN-102 combined with wash and leachate solutions from 241-C-104 solids, concentrated 241-AZ-102, 241-AZ-101, and 241-AP-104. Multiple process cycle testing was conducted using dual, small columns in series. Cesium (Cs) load and elution profiles were developed. In all cases, high Cs decontamination factors from the Hanford tank waste were obtained. The Cs was efficiently eluted from the resin with 0.5 M HNO_3, and the resin was regenerated with 0.25 M NaOH, allowing for repeated resin reuse.

INTRODUCTION

The U.S. Department of Energy (DOE) is tasked with disposing of high-level radioactive waste stored at the Hanford site. The waste is to be vitrified following specific pretreatment processing, separating the waste into a

This work was supported by Bechtel National Inc. under Contract No. 24590-101-TSA-W0000-0004. The authors thank Michael Mann, Vaughn Hoopes, Francisca Steen, Jeff Chenault, and Clay O'Laughlin for their hot cell support and Kathie Thomas and Truc Trang-Le for gamma spectrometry analysis support.

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relatively small-volume high-activity waste fraction, and a large-volume low-activity waste fraction. The ^{137}Cs must be removed from the large-volume liquid waste fraction to produce the low-activity waste form for vitrification. The final ^{137}Cs concentration in the low-activity glass is targeted to be at or below $0.3\,\mathrm{Ci/m^3}$. The current pretreatment flow sheet includes the use of SuperLig® 644 (SL-644) (IBC Advanced Technologies, Inc., American Fork, UT) for ^{137}Cs removal from the aqueous waste fraction. SL-644 is a proprietary, organic, Cs-selective ion exchanger and has been shown to be effective in removing Cs from a variety of Hanford tank wastes (1–5).

The work presented in this paper summarizes small-scale testing of the SL-644 in a dual small-column system with processing steps mimicking plant-scale, multicycle operations. The test matrices were Hanford tank waste 241-AW-101 simulant, actual wastes from tanks 241-AP-101 diluted to 5 M Na (AP-101), 241-AN-102 (combined with flow-sheet quantities of leach and wash solutions from pretreatment of sludge from 241-C-104) (AN-102/C-104), 241-AZ-102 concentrated to 5 M Na (AZ-102C), 241-AZ-101 (AZ-101), and 241-AP-104 diluted to 5 M Na (AP-104). All ion exchange process steps were tested, including resin-bed preparation, loading, feed displacement, water rinse, elution, eluate rinse, and resin regeneration.

EXPERIMENTAL

All actual waste processing was conducted in a shielded facility using remote handling equipment because the Hanford tank waste samples were highly radioactive.

Resin Properties

The SL-644 resin is a proprietary, self-polymerizing, organic ion exchanger. Resin batch 010319SMC-IV-73 was received from the vendor and used within one month of its production, minimizing any impacts from possible degradation due to resin aging. This material exhibited a black-red appearance peppered with light-brown specs. The resin was dry-sieved, and 4.2 g of the 212- to 425-μm particle-size fraction was used in each (lead and lag) ion exchange column.

Feed Characterization

The AW-101 simulant was prepared as described by Golcar et al. (6). The AP-101 tank waste was diluted by a factor of 1.12 to nominally 5 M Na with deionized water (7). The AN-102 tank waste was mixed with leach and wash solutions from pretreating tank C-104 solids and evaporated to approximately 5 M Na (8). Radioactive Sr and the transuranium (TRU) components were removed with precipitation and a cross-flow filtration process before ion exchange processing (9). The AZ-102 tank waste was concentrated by evaporation to nominally 4.6 M Na (10). The AZ-101 tank waste was not pretreated. The AP-104 tank waste was diluted by a factor of 1.15 to nominally 4.9 M Na with 0.01 M NaOH. All feeds were filtered through a 0.45-μm pore-size nylon filter before testing to remove any entrained solids. Feeds were characterized before ion exchange processing, and selected characterization results are summarized in Table 1.

Column Testing

A schematic of the ion exchange column system is shown in Fig. 1. The system consisted of two small glass columns containing the ion exchange material, a small metering pump, three valves, a pressure gauge, and a pressure-relief valve. Valves 1, 2, and 3 were stainless-steel, three-way valves that could be turned to the flow position, sample position, or no-flow position. The columns were connected in series with the first column referred to as the lead column and the second column referred to as the lag column. The columns were 15-cm high with an inside diameter of 1.46 cm. The inlet sample lines extended through the port opening to the top of the column. The connecting tubing was 1/8-inch OD, 1/16-inch ID polyethylene. Valved quick-disconnects were installed in-line to allow for ease of column switching between the lead and lag positions. The total holdup volume of the Cs ion exchange system was the summed volume of all fluid-filled parts and was estimated to be 42 mL, which was denoted as one apparatus volume (AV).

Initial SL-644 resin-bed preparation was performed using a procedure similar to that recommended by Hassan (11). Before packing the resin beds, 4.2 g aliquots of the SL-644 resin were soaked in 40 mL of 1 M NaOH (~10:1 solution to resin-volume ratio) with light agitation for 2 h. The NaOH was decanted and the SL-644 slurried with about 40 mL of deionized (DI) water, then the resin was quantitatively transferred into the columns. The expanded Na-form resin bed volume (BV) was nominally 10 mL in both the lead and lag columns. All solutions were transferred down flow through the ion exchange column at 3 BV/hour except as indicated. The resin beds were conditioned in parallel with 13 BV 0.5 M HNO_3 at a flow rate of 1 BV/hour, followed by 3 AV DI water at 2 BV/hour, then 5 BV of 0.25 M NaOH at 2 BV/hour. A typical process cycle began with resin regeneration of 6 BV 0.25 M NaOH processed at 1 BV/hour. Tank waste (tank-waste simulant on the first cycle) was then processed. The tank waste was

Table 1. Feed characterization

Analyte	AW-101 Simulant	AP-101	AN-102/C-104	AZ-102C	AZ-101	AP-104
Density, g/mL	1.234	1.256	1.244	1.246	1.224	1.225
AlO_2^-, M[a]	4.84E − 1	2.59E − 1	3.04E − 1	3.44E − 2	2.09 E − 1	3.97E − 1
C, inorganic, M	1.15E − 1	4.46E − 1	6.86E − 1	1.25E + 0	8.2E − 1	3.5E − 1
C, organic, M	1.41E − 1	1.36E − 1	9.79E − 1	8.33E − 2	4.2E − 2	3.5E − 1
Cl, M	7.50E − 2	4.1E − 2	5.39E − 2	<3.9E − 3	2.03E − 3	1.51E − 1
CrO_4^{-2}, M[a]	Not added	2.92E − 3	2.08E − 3	2.90E − 2	1.21 E − 2	7.84E − 3
Cs (total), M	8.57E − 5	4.5E − 5	5.99E − 5	5.21E − 4	4.48E − 4	6.88E − 5
K, M	4.17E − 1	7.61E − 1	2.4E − 2	1.70E − 1	1.15E − 1	4.64E − 2
Na, M	5.15E + 0	4.97E + 0	4.8E + 0	4.61E + 0	4.85 E + 0	4.92E + 0
NO_2^-, M	8.33E − 1	7.1E − 1	9.23E − 1	1.69E + 0	1.54 E + 0	1.52E + 0
NO_3^-, M	1.73E + 0	1.68E + 0	1.66E + 0	6.08E − 1	9.92 E − 1	1.76E + 0
OH^-, M	1.9E + 0	1.94E + 0	2.0E − 1	1.11E + 0	6.8E − 1	1.16E + 0
PO_4^{-3}, M[a]	1.9E − 3	1.24E − 2	2.41E − 2	9.25E − 3	1.64 E − 2	4.39E − 2
SO_4^{-2}, M	<2.6E − 3	4.82E − 2	6.84E − 2	3.68E − 1	1.75E − 1	2.90E − 2
UO_2^{+2}, M[a]	Not added	1.7E − 4	1.15E − 4	6.37E − 5	9.33E − 5	4.07E − 5
^{137}Cs, μCi/mL	trace	1.26E + 2	1.61E + 2	2.00E + 3	1.64E + 3	1.68E + 2
$^{239+240}$Pu, μCi/mL	Not added	1.1E − 4	8.97E − 4	Not measured	1.81 E − 3	2.59E − 4
^{241}Am, μCi/mL	Not added	1.38E − 4	1.03E − 2	Not measured	1.05 E − 4	2.81E − 3

[a] Al, Cr, and P were determined by inductively coupled plasma-atomic emission spectrometry. U was measured by kinetic phosphorescence analysis. The ionic forms were assumed on the basis of waste chemistry.

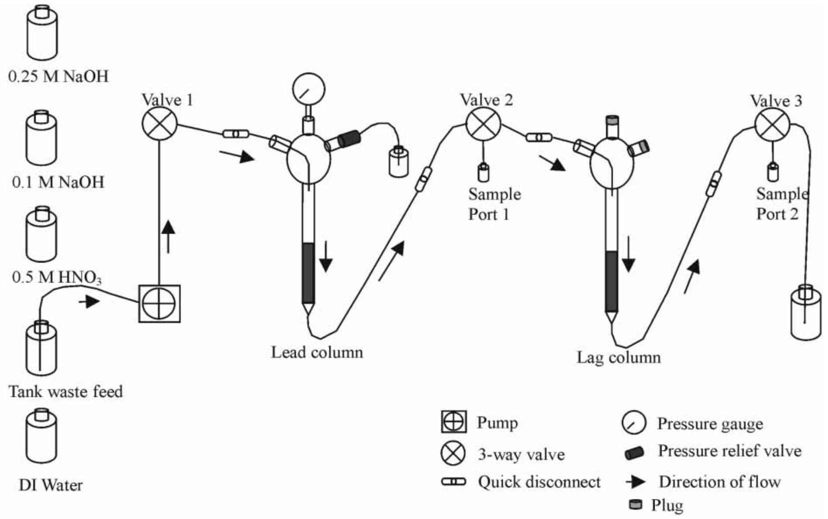


Figure 1. Cs ion exchange apparatus.

displaced with 3 AV of 0.1 M NaOH to prevent precipitation of aluminates and other hydroxides poorly soluble in low-hydroxide solutions. The 0.1 M NaOH was displaced with 2 AV of DI water. The lead-column section was then disconnected from the lag column and eluted with typically 15 BV 0.5 M HNO_3 at 1 BV/hour. The lead column section was then rinsed with 3 AV of DI water and regenerated with 2 AV of 0.25 M NaOH at 1 BV/hour. The lead column was rinsed with DI water for storage between tests. Before the next test cycle, the lead- and lag-column positions were switched; the system was rinsed with 1 AV of 0.25 M NaOH; and processing continued with the next tank waste. All processing was performed at ambient temperature, nominally 24–32°C.

All simulant and actual waste testing parameters are summarized in Table 2. Processing dates are given along with total load and eluate volumes and flow rates. The two columns were provided identifiers as Column 1 and Column 2. The column in the lead position for each test is identified. A total of eight complete process cycles (including the simulant cycle) were conducted on the system over 2 yrs (12–16). The lead and lag column positions were switched between each process cycle.

A few anomalies occurred during processing. Elution was paused for the weekend after processing 17 BV eluant (Cycle 3 AN-102/C-104 processing). A brief additional elution was conducted after Cycle 4 regeneration (AZ-102C processing). The column was then rinsed and regenerated again. Because of the time constraints, the second test elution for AP-104 (Cycle 8) was paused after processing 21 BV (after rinsing with water), then resumed 2 days later.

Table 2. Resin history summary

Tank waste	Cycle number	Process start date	Lead column number	Load volume, BV	Tank-waste flow rate, BV/h	Eluate volume, BV	Eluate flow rate, BV/h
AW-101 simulant	1	3/26/01	Column 1	143	2.6	12.5[a]	0.92
AP-101	2	4/23/01	Column 1	112	2.8	19.3	0.88
AN-102/C-104	3	6/25/01	Column 2	72	2.7	18.9[b]	0.95
AZ-102C	4	11/5/01	Column 1	105	1.4	14.8	0.74
Re-elute	–	–	Column 1	–	NA	6.5	2.8
AZ-101 (First Test)	5	12/3/01	Column 2	122	1.5	14.3	1.0
AZ-101 (Second Test)	6	1/28/02	Column 1	95.9	2.7	15.9	1.8
AP-104 (Short Test)	7	7/15/02	Column 2	17.4	2.5	28.4	1.7
AP-104 (Full Test)	8	7/17/02	Column 1	182	2.6/3.9[c]	29.8[d]	2.0

[a] Both the lead and lag column were eluted.

[b] Elution was paused for 2 days after processing 17 BVs.

[c] Flow rate increased after processing the first 17 BVs of feed.

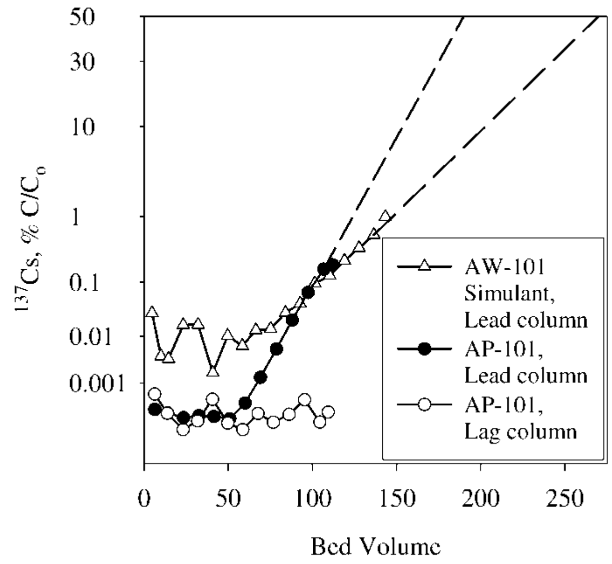
[d] Elution was paused for 2 days after processing 21 BVs.

Cesium-exchange behavior was monitored by measuring ^{137}Cs by gamma spectrometry. The ^{137}Cs was added to the AW-101 simulant as a tracer, ^{137}Cs was already present in the actual tank waste. Samples were taken from the lead column at Sample Port 1 and from the lag column at Sample Port 2 at nominal 10-BV loading increments. The samples were removed from the hot-cell containment facility for gamma counting.

RESULTS AND DISCUSSION

Cesium Loading

The simulant and actual waste Cs-load profiles are shown in Figs. 2–7. The Cs breakthrough is plotted on a linear-probability graph, where ^{137}Cs concentration (C) is normalized to the feed concentration (C_o). A probability scale is the inverse of the Gaussian cumulative distribution function (characteristic of ideal ion exchange theory) such that a graph of the sigmoidally

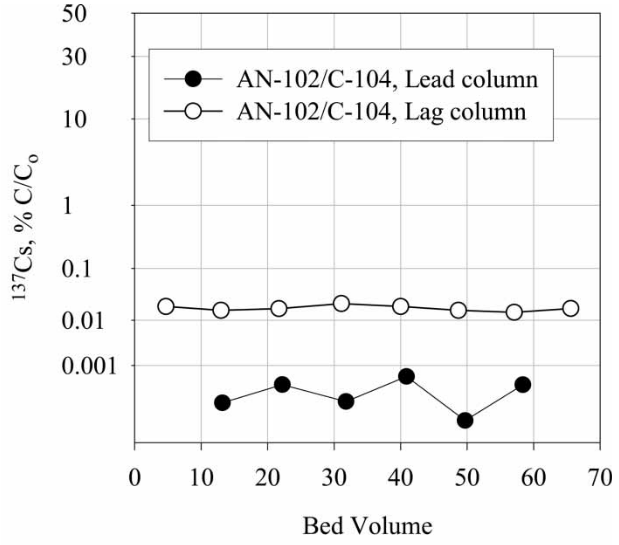


Flow rate = 2.7 BV/hour

AW-101 simulant total Cs C_o = 8.6E µ5 M, ^{137}Cs C_o = trace levels

AP-101 waste total Cs C_o = 4.5E µ5 M, ^{137}Cs C_o = 126 µCi/mL

Figure 2. AW-101 simulant and AP-101 waste cesium-load profiles.



Flow rate = 2.7 BV/h

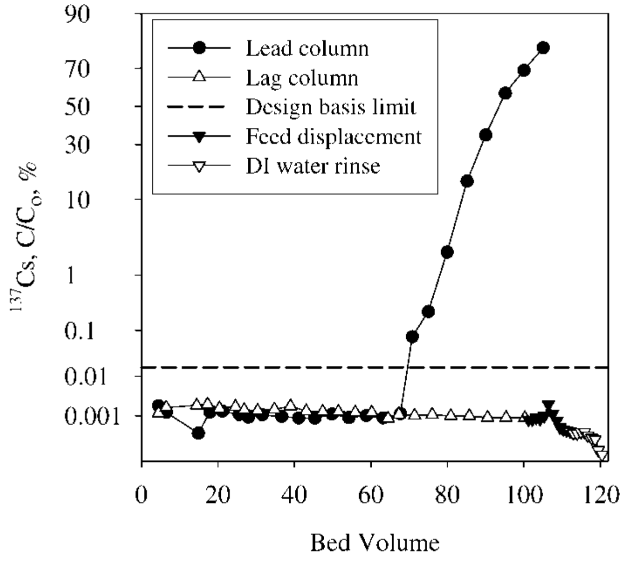
Total Cs C_o = 3.3E µ5 M

^{137}Cs C_o = 161 µCi/mL

Figure 3. AN-102/C-104 waste cesium-load profile.

shaped Gaussian cumulative distribution function appears as a straight line (17). The probability scale has a couple of advantages, including making low C/C_o data easily readable such that the initial load performance is discernable, and extrapolation to 50% breakthrough can be easily estimated in the sigmoidal region. Bed volumes are a function of the resin BV in the expanded Na form, nominally 10 mL. In all cases, a limited volume of waste feed was available for the ion exchange processing. In some cases the available waste volumes were insufficient to reach the breakthrough target of 50% C/C_o.

Only the lead-column load profile is shown (Fig. 2) for the AW-101 simulant; the lag-column sample results were at or below the detection limit (1.4E-2% C/C_o). The AW-101 simulant load profile resulted in ideal loading behavior. The effluent AW-101 simulant C/C_o did not increase until 80 BV had been processed. After this point, the Cs breakthrough increased sigmoidally (linear plot, breakthrough appears linear on the probability plot). After processing 140 BV, only 1% breakthrough on the lead column was observed. The 50% breakthrough was extrapolated to be



Flow rate = 1.4 BV/hour

Total Cs C_o = 5.21E µ4 M

^{137}Cs C_o = 2.00E + 3 µCi/mL

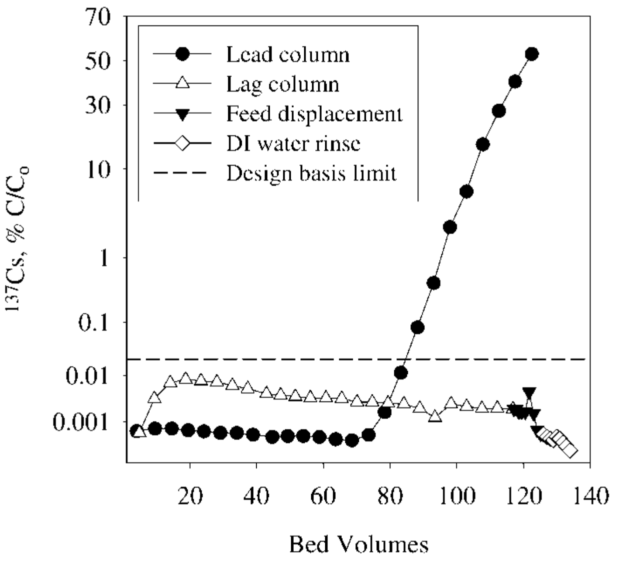
Figure 4. AZ-102C waste cesium-load profile.

270 BV; however, extrapolating from 1% breakthrough to 50% breakthrough introduces significant uncertainty.

Nearly 70 BV of AP-101 were processed before breakthrough on the lead column was observed. The extrapolated 50% breakthrough to 190 BV is shown; again, the large extrapolation from 0.2% breakthrough is subject to considerable uncertainty. Only a small, constant ^{137}Cs concentration broke through the lag column, nominally 2E-4% C/C_o.

Both the AW-101 and the AP-101 tank wastes are considered potentially problematic for Cs-ion exchange processing. Both have relatively large K concentrations; and K, as well as Na, act as competing ions with Cs for the resin-exchange sites. The effective Cs exchange onto the resin from these matrices shows that the high K concentrations were tolerated well.

The AN-102/C-104 (Fig. 3) load volume of 67 BV was insufficient to manifest a breakthrough profile. The lag-column samples resulted in higher ^{137}Cs concentration than those taken from the lead column. The lag column for this test apparently contained residual Cs, incompletely eluted, from the previous test with AP-101. This phenomenon is an important consideration



Flow rate = 1.5 BV/hour

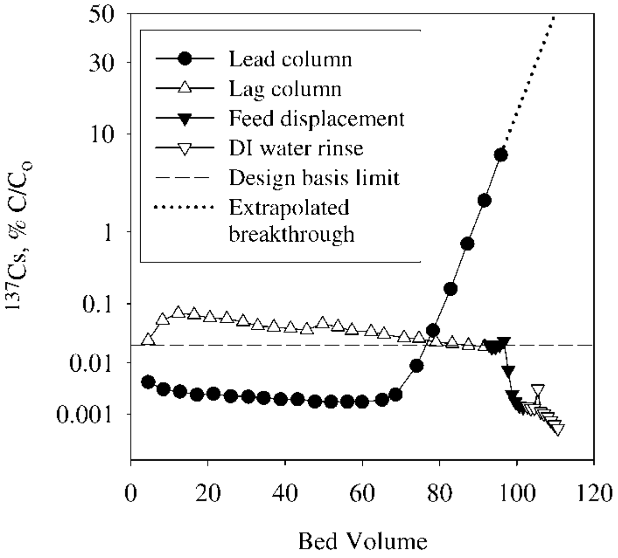
Total Cs C_o = 4.48E µ4 M

^{137}Cs C_o = 1.64E + 3 µCi/mL

Figure 5. AZ-101 (first test) waste test cesium-load profile.

for plant-scale operations as Cs bleed-off from column switching is shown to contribute to ^{137}Cs loading in the product waste.

The total Cs and ^{137}Cs concentrations in the AZ tank wastes are approximately ten times that of the other tank wastes. Therefore, Cs-decontamination requirements (~6000) are significantly greater for the AZ tank wastes than required for the other tank wastes (~1000). Figures 4 through 6 show the load profiles obtained for these tank wastes in the processing order, along with the product Cs-decontamination requirement. The AZ-102C process effluent met the Cs-removal requirement by a factor of 10 on both the lead and lag columns (Fig. 4). The subsequent cycle with AZ-101 demonstrated a significant Cs-bleed effect from the lag column where the lag-column effluent Cs concentration was up to a factor of 10 higher than that of the lead column effluent (Fig. 5). The same effect was again demonstrated with the second process cycle of AZ-101 (Fig. 6). In this case, however, the product effluent did not meet the minimum Cs-decontamination requirement.



Flow rate = 2.7 BV/hour

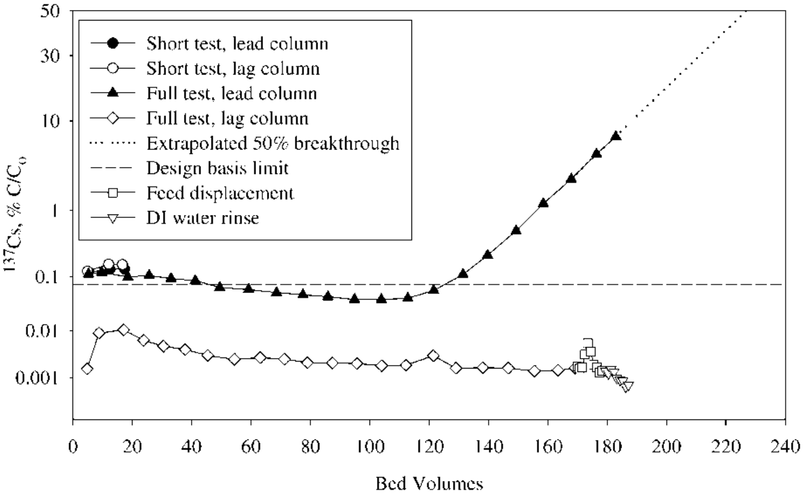
Total Cs C_o = 4.48E µ4 M

^{137}Cs C_o = 1.64E + 3 µCi/mL

Figure 6. AZ-101 (second test) waste test cesium-load profile.

The lead-column load behaviors for the three AZ tank-waste tests resulted in ideal load behavior. The lead-column effluent ^{137}Cs concentrations were constant until nominally 68 BV (AZ-102C), and 72 BV, and 76 BV (AZ-101 first and second tests, respectively) were processed. The breakthrough profiles were then linear on the probability scale with 50% breakthrough interpolated at 93 BV for AZ-102C and 110 BV and 122 BV (extrapolated) for the two AZ-101 tests. The differences between the AZ-101 load profiles were not considered to be significant and were within experimental uncertainties rather than driven by the difference in flow rates (1.5 BV/hour vs. 2.7 BV/hour).

The problem of Cs bleed into the effluent was anticipated for the process cycle conducted with AP-104 (a lower Cs-concentration tank waste). The Cs bleed into the product effluent was demonstrated by processing 17 BV of AP-104 at the nominal feed flow rate of 2.5 BV/hour (Fig. 7). The cycle was stopped and the lead column was eluted with twice the nominal elution volume (28 BV) at 1.7 BV/hour, nearly twice the nominal flow rate. After switching the more extensively eluted column in the lag position, a new



Flow rate = 2.6 BV/hour for first 17 BVs, then 3.9 BV/hour

Total Cs C_o = 6.88E µ5 M

^{137}Cs C_o = 1.68E + 2 µCi/mL

Figure 7. AP-104 waste cesium-load profiles, short test and full test.

(full) process cycle was initiated. The column placed in the lead position continued to demonstrate the Cs-bleed effect through the first 100 BV of processing. The effluent from the lag column (that had been extensively eluted) met the minimum Cs-decontamination requirement by 1.5 orders of magnitude.

The AP-104 test demonstrated ideal load behavior. Onset of Cs breakthrough was evident at 120 BV. The Cs breakthrough continued in a linear profile (probability scale) to a total of 7.6% breakthrough. The 50% breakthrough was extrapolated to be 227 BV.

To summarize, the SL-644 resin provided adequate Cs removal from the waste matrix to meet follow-on ^{137}Cs waste loading in the glass form for the tests conducted on AW-101 simulant, AP-101, AN-102/C-104, AZ-102C the first AZ-101 cycle and the last AP-104 cycle. Decontamination factors (DFs) on the order of 1E+3 to 1E+4 are required for the effluent product (18). Overall DFs obtained for the waste volumes processed are shown in Table 3. The experimentally obtained DFs were larger than the target DFs, except for the second AZ-101 process cycle and the first AP-104 process cycle. These two process cycles exemplify the impact residual Cs on the lag-column resin bed has on the product effluent and the importance of

Table 3. Processing results

Feed identification	Cycle	DF obtained	DF required[a]	Met acceptance criterion?
AW-101 simulant	1	6.6E + 4	1.6E + 3	Yes
AP-101	2	1.7E + 6	1.0E + 3	Yes
AN-102/C-104	3	1.1E + 4	9.2E + 3	Yes
AZ-102C	4	1.1E + 5	6.9E + 3	Yes
AZ-101 (First Test)	5	2.5E + 4	4.8E + 3	Yes
AZ-101 (Second test)	6	2.3E + 3	4.8E + 3	No[b]
AP-104 (Short Test)	7	7.0E + 2	1.4E + 3	No[b]
AP-104 (Full Test)	8	3.1E + 4	1.4E + 3	Yes

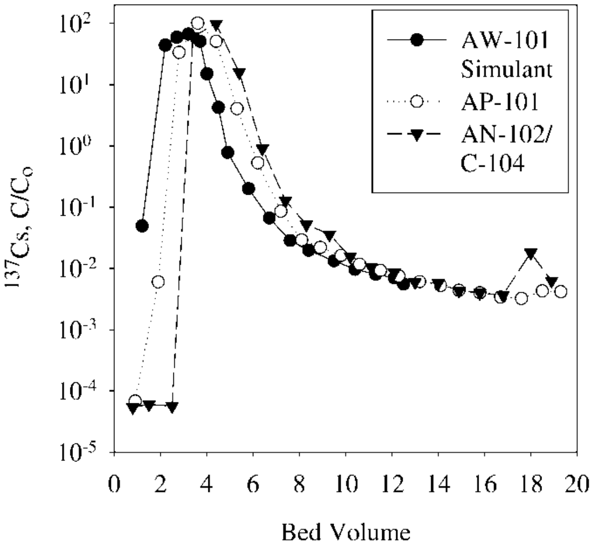
[a] Design-basis DF required to meet the ^{137}Cs waste loading limit in the final glass product.

[b] The experimentally obtained composite effluent product DF did not meet the required DF.

complete elution of the lead column at the end of the process cycle. The complete elution may be enhanced by longer elution volumes and the cycling process from the H-form to the Na-form and back to the H-form as was conducted after the AZ-102C elution.

Cesium Elution

The Cs-elution results are plotted on semilogarithmic graphs in Figs. 8 and 9. The applied elution profile name is associated with the particular waste load test that preceded the given elution. Thus, the "AP-101" elution represents the lead-column elution following the AP-101 actual tank waste loading. Elution profiles were generally consistent between the wastes tested. The Cs was primarily eluted in the 2- to 6-BV fractions. The maximum C/C_o was generally reached in 3–4 BV. Cs elution was completed to 1% C/C_o with 11 BV of eluate despite the variation in Cs mass loading. Virtually 100% of the Cs was accounted for in the composite eluates. Initial tests showed continuing the elution beyond 1% C/C_o resulted in a slow Cs bleed-off; even after processing 20 BV of eluate, C/C_o of 0.1% Cs was not reached (Fig. 8). The subsequent tests with the AZ tank wastes and AP-104 reached 0.1% C/C_o. These results indicate Cs may more effectively elute from the resin with repeated cycling. The elution profiles in Fig. 9 demonstrate the effect flow rate has on Cs elution. The lower the flow rate, the more effectively Cs is removed from the resin and the less pronounced is the associated Cs tailing.



Flow rate = 1 BV/hour

AW-101 simulant C_0 total Cs = 8.6E µ5 M, ^{137}Cs = trace levels

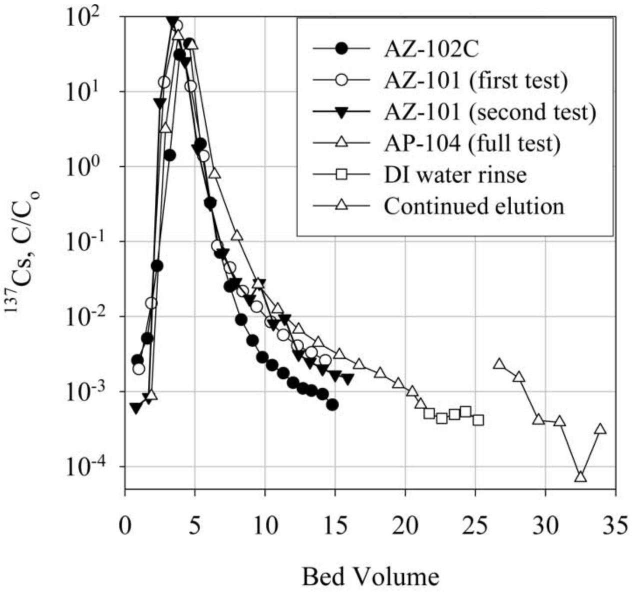
AP-101 C_0 total Cs = 4.5E µ5 M, ^{137}Cs = 126 µCi/mL

AN-102/C-104 C_0 total Cs = 3.3E µ5 M, ^{137}Cs = 161 µCi/mL

Figure 8. Cesium elution profiles.

The AN-102/C-104 elution showed a raised C/C$_0$ value at 18 BV (Fig. 8). At this point, the resin bed was allowed to stand for 13 h (overnight) in 0.5 M HNO_3. A similar phenomenon is shown in Fig. 9 with the AP-104 elution at 26 BV. After setting for a weekend in water (still slightly acidic), Cs concentration in the eluate increased slightly. During the stop-flow conditions, additional Cs exchanged out of the SL-644 indicating elution is particle-diffusion limited.

Minimal contamination of the eluate with other cations was observed with the notable exception of U. Over 85% of the feed U was found in the AP-101 eluate; the remaining U fraction was found with the AN-102/C-104 eluate. This indicated 85% of the U loaded on the lead column and the remaining 15% loaded on the lag column during AP-101 processing. The AZ-102C eluate recovered 34% of the feed U. The AZ-101 eluates recovered 106% and 100% of the feed U for the first and second tests, respectively. The AP-104 eluate recovered 72% of the feed U.



Flow rate = 0.74 BV/h AZ-102C, 1.0 BV/h AZ-101, 2.0 BV/h AP-104

AZ-102C C_o total Cs = 5.21E μ4 M, ^{137}Cs = 2.00E+3 μCi/mL

AZ-101 C_o total Cs = 4.48E μ4 M, ^{137}Cs = 1.64E+3 μCi/mL

AP-104 C_o total Cs = 6.88E μ5 M, ^{137}Cs = 1.68E+2 μCi/mL

Figure 9. Cesium elution profiles.

Despite the high Cs recoveries in the eluates (averaging 100% ± 3% 1-σ), a small amount (less than the uncertainty of the measurement) of residual Cs remained on the eluted column. Switching the lead and lag columns placed the eluted column with residual Cs in the lag position. The effect of this is apparent in Figs. 3, 5, 6, and 7, where the lag column results in a higher C/C_o relative to the lead column. The bleed effect after elution of the first AZ-101 waste processing (elution profile shown in Fig. 9) led to the failure to meet product decontamination requirements for the second process cycle of AZ-101 waste effluent (Fig. 6); the bleed effect after elution of the second AZ-101 waste processing similarly led to failure of the first process cycle with AP-104 waste effluent (Fig. 7) to meet the product decontamination requirements. This phenomenon might limit the DFs that can actually be achieved in plant operation with repeated resin cycling. To mitigate this risk, care will be needed to adequately elute Cs from the Cs-loaded column to minimize consequential carryover of Cs in subsequent ion exchange cycles. The contamination from ^{137}Cs bleed-off may be reduced by using larger elution volumes and/or judicious waste-processing sequences, such that lower ^{137}Cs-concentrated waste processing does not follow higher ^{137}Cs-concentrated waste processing.

CONCLUSION

Sequential ion exchange processing using SL-644 was shown to be an effective method for Cs removal from Hanford tank waste simulant AW-101 and actual tank wastes AP-101, AN-102/C-104, AZ-102C, AZ-101, and AP-104. All small-scale test-processing parameters mimicked those anticipated for use in plant-scale operations, thus helping to validate the efficacy of this pretreatment method for Cs removal. The eluted Cs fraction was contained in a small-volume, simple, 0.5 M HNO_3 matrix for disposition as high-level waste. Except for two cases, the Cs-decontaminated waste product met the ^{137}Cs waste-loading criteria for the final vitrified waste. More rigorous elution conditions were shown to be effective at minimizing Cs carryover.

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18. The conversion requires the following assumptions: AP-101DF and AW-101 simulant will contain 14 wt% Na_2O and AN-102/C-104 will contain 10 wt% Na_2O, all Na comes from the glass tank waste, the glass density is 2.66 g/mL, a maximum of 0.3Ci/m^{3137}Cs is in the final waste form, and the waste Na concentration is shown in Table 1.