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REMOVAL OF ^{137}Cs

FROM ALKALINE CONDENSATE WASTES

November 1968

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REMOVAL OF ^{137}Cs FROM ALKALINE CONDENSATE WASTES

By

B. W. Mercer, L. L. Ames, R. G. Parkhurst

Water and Waste Management Section
Water and Land Resources Department

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TABLE OF CONTENTS

LIST OF FIGURES	iv
INTRODUCTION.	1
SUMMARY AND CONCLUSIONS	2
ORIGIN AND COMPOSITION OF THE CONDENSATES	3
METHODS OF INVESTIGATION.	4
Loading Experiments	4
Elution Experiments	5
RESULTS AND DISCUSSION	9
Cesium Loading Studies	9
ITS Condensate.	9
SX Condensate	13
242-T Condensate	13
Elution Experiments	16
Regeneration of 1 in. diam AW 500 Column	28
REFERENCES	33
DISTRIBUTION.	35

LIST OF FIGURES

1. 1 in. diam Column Flow Diagram	6
2. Effect of Flow Rate on Cesium Breakthrough	11
3. Effect of Temperature on Cesium Breakthrough at High Flow Rate	12
4. Computed ^{137}Cs Breakthrough Curves	14
5. ^{137}Cs Removal from SX Condensate	15
6. Column Pressure Differential and ^{137}Cs Breakthrough for 242-T Condensate	17
7. Elution Curve for Column 1	18
8. Elution Curve for Column 2	19
9. Elution Curve for Column 3	20
10. Elution Curve for Column 4	21
11. Elution Curve for Column 5	22
12. Elution Curve for Column 6	23
13. Elution Curve for Column 7	24
14. Elution Curve for Column 8	25
15. Cesium Breakthrough After Elution with NaNO_3	30
16. Cesium Breakthrough with a Fresh Column of AW 500	31
17. Fraction of ^{137}Cs Eluted as a Function of Volume of 7M NaNO_3	32

REMOVAL OF ^{137}Cs FROM ALKALINE CONDENSATE WASTES

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INTRODUCTION

The evaporation of alkaline wastes with the first In-Tank-Solidification (ITS) unit⁽¹⁾ began in 1965 in the 200 East Area of the Hanford complex. This operation was part of the Waste Management Program⁽²⁾ initiated by the Chemical Processing Department* to render these wastes less mobile and to release needed tank storage space. Since discharge of radioactivity to the environs via the ITS condensate was to be minimized, studies were undertaken to evaluate treatment of the ITS condensate prior to disposal. These studies were later extended to include other alkaline condensate wastes.

More than 90% of the total radioactivity in the supernatant solutions of aged alkaline wastes consists of ^{137}Cs . The bulk of the remaining long-lived isotopes such as ^{90}Sr is contained in the sludge on the bottoms of the storage tanks. Consequently, evaporation of the supernatant solution produces an intermediate level condensate in which the most significant radionuclide is ^{137}Cs . The volatilization of ruthenium is generally not a problem in the evaporation of alkaline wastes. However, tritium is volatilized along with the water.

Studies on the decontamination of low and intermediate level wastes have proceeded for a number of years at Pacific Northwest Laboratory under the sponsorship of the AEC Division of Reactor Development. The application of cesium-selective zeolites to the removal of trace amounts of cesium from

* Hanford Atomic Products Operation, General Electric Company

radioactive wastes has been studied extensively in this program.^(3,4) In the case of Cs⁺, the ion exchange performance of a zeolite column can be predicted with reasonable accuracy. However, the process performance of a zeolite column in removing trace cesium from an actual condensate waste may not be predictable due to the presence of varying amounts of suspended solids and/or organics in the waste. Reported herein are results of laboratory studies on the removal of trace quantities of ¹³⁷Cs from ITS condensate, SX condensate, 242-T evaporator condensate with AW 500, and results of studies on the regeneration of AW 500 with NaNO₃ solutions.

SUMMARY AND CONCLUSIONS

Cesium-137 is effectively removed from ITS, SX, and 242-T condensates by ion exchange on AW 500 columns. The AW 500 columns were capable of processing 5000 or more column-volumes to breakthrough of the ¹³⁷Cs. Suspended matter in the ITS and 242-T condensate required filtration of these wastes to allow efficient utilization of the AW 500 ion exchange capacity. Filtration with 5μ Cuno filters reduced the turbidity sufficiently to prevent rapid plugging of the columns.

A 7M NaNO₃ solution was effective for regenerating the AW 500 columns. Regeneration was accomplished in 10 to 20 column-volumes at 65 to 70 °C. Regression equations are given for computing the percent ¹³⁷Cs eluted as a function of NaNO₃ concentration, temperature, and flow rate within the ranges studied. Temperature and NaNO₃ concentration were found to be the most important parameters with respect to elution efficiency.

Although ¹³⁷Cs may be reduced to drinking water limits (1/10 MPC_w 168 hr) it does not appear likely that all of the radionuclides in ITS condensate can be economically reduced to this level. While the other fission products such as ¹⁰⁶Ru can be removed with strong base and strong acid ion exchange resins,

no practical method exists for removing the tritium. A DF of about 10 is required to meet the drinking water limit in ITS condensate for both ^{106}Ru and ^3H .

ORIGIN AND COMPOSITION OF THE CONDENSATES

The ITS condensate is produced by the evaporation of supernatant waste from nonboiling high level waste storage tanks in the 200 East Area. Evaporation is accomplished in the first ITS unit by contacting the alkaline waste in an underground storage tank with electrically heated air. Moisture laden air emanating from the storage tank is passed through a wire mesh scrubber-humidifier, a Brink Mist Eliminator, a condenser, a teflon mesh de-entrainer, and a filter before being exhausted to the atmosphere. The concentrations of significant radionuclides and other constituents found in the ITS condensate used in these studies are given in Table I, along with those of the other condensates. The ITS samples were taken prior to installation of the scrubber-humidifier and Brink Mist Eliminator. All of the radionuclides (except ^3H), suspended solids, and Na^+ appear in the ITS condensate as a result of the waste droplets entrained in the vapor. Ammonia and tritiated water are volatilized from the heated waste. Spectrochemical analysis of the suspended solids reveals that aluminum is the major metallic constituent of the solids. Entrainment of aluminate ion and subsequent precipitation of alumina in the condensate is believed to be the major source of the suspended matter.

TABLE I. Constituents of Condensate Wastes

Condensate Waste	pH	Suspended Solids, mg/l	Ammonia, mg/l	Sodium, mg/l	^{137}Cs , $\mu\text{Ci/ml}$	^{90}Sr , $\mu\text{Ci/ml}$	$^{144}\text{CePr}$, $\mu\text{Ci/ml}$	^{106}Ru , $\mu\text{Ci/ml}$	^3H , $\mu\text{Ci/ml}$
ITS	7-10	5-50	10-117	12-45	$2.2-8.6 \times 10^{-3}$	$2-3 \times 10^{-6}$	--	$2-7 \times 10^{-4}$	$2-4 \times 10^{-2}$
SX	7	<1	1-3	1-2	$1-3 \times 10^{-3}$	$2-5 \times 10^{-4}$	$1-3 \times 10^{-2}$	$1-3 \times 10^{-2}$	--
242-T	9	--	158	0.1	$1-5 \times 10^{-4}$	--	--	--	--

SX condensate is a low volume stream produced by self-boiling Redox alkaline waste in the SX tank farm. Vapor from the boiling tanks is routed through the 106 SX tank (10^6 gal capacity) where entrained droplets of waste settle out prior to condensation. Although no undissolved matter was detected, the concentration of ^{90}Sr , ^{144}Ce , and ^{106}Ru relative to that of ^{137}Cs was higher than expected, based on Purex tank farm condensate.^(3,4)

242-T evaporator condensate is produced by the evaporation of supernatant waste from nonboiling, high-level waste storage tanks in 200 West Area. The supernatant wastes are continuously fed to, and discharged from, a pot evaporator with vertical tube bundles. De-entrainment is provided by a cyclone separator and a wire mesh de-entrainer.

METHODS OF INVESTIGATION

LOADING EXPERIMENTS

AW 500, the zeolite used in this study, is a synthetic chabazite manufactured by the Linde Company of Tonawanda, New York. The AW 500 was placed in water several days prior to use in columns to allow the escape of air from the pores of the zeolite.

Several types of filter media were used to remove suspended matter. Data on these filter materials are given in Table II.

Figure 1 is a diagram of the ion exchange column and associated equipment. The influent pump is a variable stroke piston type manufactured by Lapp Pump Company. A 1 in. diam glass column 30 in. high was employed. Influent was passed through a coiled line immersed in a constant temperature water bath. Water from this bath was also circulated through a plastic jacket around the column.

TABLE II. *Filter Material Data*

<u>Filter</u>	<u>Type</u>	<u>Vendor</u>
Cellofloc PB-33	Cellulose wood pulp derivative	Puget Sound Pulp and Timber Co., Bellingham, Wash.
Carbon	Activated cocoanut charcoal, 6 x 14 mesh	Fisher Scientific Co., Fair Lawn, N. J.
Diatomite-4200	Processed diatomaceous earth	Dicalite Dept., Great Lakes Carbon Corporation, Los Angeles, Calif.
Cuno	Cylindrical cellulose, pore size 5 μ 10 x 2-3/4 in. cartridge	American Machine and Foundry, Meriden, Conn.
Millipore	0.45 μ cellulose plastic porous membrane, 47 mm diam with an effective pore size of 0.45 μ	Millipore Filter Corp., Bedford Mass.

Temperature measurements were taken from a thermocouple situated in a well 3 in. below the surface of the zeolite.

Suspended solids were determined by filtering 1 liter samples of the condensate through 0.45 μ Millipore filters. The filters were weighed before filtration, air-dried overnight after filtration and reweighed. The difference in weight was taken as the total solids content in grams per liter.

ELUTION EXPERIMENTS

Eight columns of 20 x 50 mesh AW 500, 1 cm diam by 14 cm high, were used in the factorial design elution study. The 11 ml column-volume of AW 500 weighed 8 g. Each column was loaded with 12.5 liters of filtered ITS condensate waste (0.2M NaNO_3 added). The NaNO_3 was added at a flow rate of 20 column-volumes/hr to facilitate the attainment of ^{137}Cs breakthrough. An average of 19% of the original cesium activity

FIGURE 1. 1-in. Diam Column Flow Diagram

was found in the column effluent samples taken at 12.5 liters of ITS condensate throughput. The amount of cesium radioactivity on the AW 500 column was computed from a breakthrough curve obtained during column loading.

The eight loaded AW 500 columns were then eluted under the experimental conditions shown in the statistical design (Table III). Independent variables of the two-level factorial design were flow rate, NaNO_3 concentration, and temperature. The two levels used were 5 and 10 column-volumes/hr for the flow rate, 3.5 and 7.0M for the NaNO_3 concentration, and 23 and 65 °C for the temperature. A constant temperature bath was used for the 65 °C elutions. Twenty effluent samples of 1 column-volume (11 ml) were collected for each elution. All samples were counted as ^{137}Cs on a 400-channel analyzer so that cesium counts could be corrected for the presence of ^{106}Ru - ^{106}Rh .

An unsuccessful attempt was made to load several columns with filtered ITS condensate without the added NaNO_3 . Approximately 50 liters of the condensate would be required to load each column to 1% cesium breakthrough. Before the columns were loaded to the 1% breakthrough, bacterial or algal growth on the column resulted in an increasing pressure differential across the column. Even could the column be further loaded, the radioactive cesium to be eluted would be distributed in a very narrow band at the top of the column at 1% cesium breakthrough. An elution of this band in a direction opposite to loading would require very little movement down the column.

TABLE III. Two-Level Factorial Design for Elution Experiments

	<u>3.5M NaNO_3</u>		<u>7.0M NaNO_3</u>	
	<u>23 °C</u>	<u>65 °C</u>	<u>23 °C</u>	<u>65 °C</u>
10 Column-Volumes/hr	2	4	6	8
5 Column-Volumes/hr	1	3	5	7

Note: Numbers identify treatment combinations, and each represents a column

Conversely, elution in the loading direction would require a long movement distance. However, by adding 0.2M NaNO_3 to the ITS condensate waste influent the ^{137}Cs was spread over the entire column length. Resulting elution data should be analogous to the results obtainable with an AW 500 column fully loaded with ITS condensate only. Furthermore, with much less volume of throughput required for loading, the bacterial or algal growth problem would be eliminated.

After completing the design shown in Table III, the same point on an elution curve was chosen as the dependent variable and the fraction of cesium activity eluted from the column at 15 column-volumes of throughput. The eight-treatment combinations were then subjected to a Yates analysis,⁽⁵⁾ and the significant effect totals determined with a t-test at the 1% significance level. Still further use of the effect totals may be gained through an equation describing the response of the dependent variable, or the fraction of cesium activity eluted from the column = $b_0 + b_1x_1 + b_2x_2 + b_3x_3$. The regression coefficients are b_0 through b_3 , while x_1 through x_3 are flow rate, temperature and NaNO_3 concentration, respectively. The regression coefficients may be obtained directly from the effect totals by dividing in this case, the grand and main effect totals by eight. If agreement between experimental and predicted dependent variable values is satisfactory, other dependent variable values within the range of the independent variables can be successfully predicted.

Most of the ITS condensate waste for the column experiments was obtained in an 1800 gal tank trailer. SX condensate was provided in polyethylene carboys on a daily basis during the course of the column run with this waste.

RESULTS AND DISCUSSION

CESIUM LOADING STUDIES

ITS Condensate

The first sample of ITS condensate obtained for experimentation contained only 7×10^{-6} $\mu\text{Ci/ml}$ of ^{137}Cs and no suspended solids. Additional ^{137}Cs was added to facilitate determination of the cesium decontamination across the AW 500 column. The condensate was pumped through a 6 cm^3 column of 20 x 60 mesh AW 500 at 47 column-volumes/hr to a total of 17,500 column-volumes. No cesium breakthrough was detected throughout the run. A cesium decontamination factor greater than 1000 was observed.

The high quality of the first ITS condensate sample was the result of vapor filtration in the ITS unit prior to condensation. However, filtration of the vapor was subsequently eliminated due to rapid plugging of the filters. Elimination of vapor filtration resulted in suspended matter in the ITS condensate which plugged the AW 500 columns prior to full utilization of the ion exchange capacity. The 20 x 50 mesh AW 500 became plugged after 200 to 500 column-volumes of condensate had been processed. The use of a larger grain size, 14 x 30 mesh, offered no solution to the problem. Table I shows the amount of suspended solids in various samples taken in 1966.

Suspended solids in the ITS condensate caused some agglomeration of the zeolite particles. Infrared spectrochemical analysis of a sample of the condensate taken from the laboratory tank trailer showed 0.8 mg/liter TBP and 1.6 mg/liter of unidentified organics (straight chain hydrocarbon plus some alkyl aldehyde or carboxylic acid).

Laboratory results indicate no radiation problem in filtration created by the presence of a small fraction of the ^{137}Cs in the suspended solids.

Various methods of filtration were studied in the laboratory. Filtration on beds of granular activated carbon and Cellofloc did not remove sufficient solids for optimum operation of the ion exchange column. A 0.24 in. precoat of diatomaceous earth on a 6 in. diam filter bed produced a very clear filtrate but the precoat plugged rapidly. Addition of diatomaceous earth to the feed did not significantly prolong the life of the filter bed, which was about 12 hr.

A 5 μ Cuno filter installed ahead of the ion exchange column proved to be the most effective filter studied. Over 5000 liters were pumped through the first filter cartridge with a pressure increase of only 1.4 lb across the filter. The filtrate from the Cuno filter is slightly turbid. However, cesium breakthrough from the AW 500 column usually occurred before the column plugged.

The effects of temperature and flow rate on cesium breakthrough with the 1-in. diam AW 500 columns are illustrated in Figures 2 and 3. A cesium DF of 325 ($C/Co = 3.02 \times 10^{-3}$) was required to reduce the ^{137}Cs concentration to $1/10 \text{ MPC}_w$ (168 hr). The required DF was attained through 4600 column-volumes at a flow rate of 12 column-volumes/hr. The breakthrough curves in Figure 3 indicate that an increase in temperature from 25 to 38 °C will increase the ^{137}Cs DF across the AW 500 column at high flow rates.

Cesium breakthrough curves computed by the method of Gluekauf for the flow rates of 12, 30, and 41 column-volumes/hr at 25 °C are shown in Figure 4. The 50% breakthrough point (column K_d) was computed from equilibrium data assuming 42% ionization of the dissolved ammonia at pH 9.4. The curves show

FIGURE 2. Effect of the Flow Rate on Cesium Breakthrough

FIGURE 3. Effect of Temperature on Cesium Breakthrough at High Flow Rate

^{137}Cs breakthrough above $1/10$ MPCw ($C/\text{Co} = 3.02 \times 10^{-3}$) at 5450, 5100, and 4600 column-volumes at 12, 30, and 41 column-volumes/hr, respectively. Deviation of experimental breakthrough from computed breakthrough is believed due to non-ideal conditions such as suspended matter in the feed, and channeling in the AW 500 column.

SX Condensate

A column experiment was performed to evaluate the use of AW 500 for decontaminating SX condensate. Daily samples of SX condensate were taken in 26-liter polyethylene carboys to supply feed for the 1 in. diam AW 500 column. No filtration of the condensate was necessary prior to the ion exchange treatment. The ^{137}Cs removal as shown in Figure 5 was not as high as that attained in the ITS runs. In addition, the presence of significant concentrations of other radionuclides (see Table I) makes necessary such further treatment as (1) anion exchange for ruthenium removal, and (2) acidification and strong acid cation exchange for ^{90}Sr and ^{144}Ce removal. Essentially, no cerium or ruthenium was removed from the SX condensate with AW 500. Strontium removal was not determined. However, based on previous studies with Purex tank farm condensate, strontium removal under a neutral or alkaline condition would not be adequate to attain discharge limits.

242-T Condensate

A small column (5g) of 20 x 50 mesh AW 500 was used to determine the ^{137}Cs capacity with 242-T evaporator condensate. Due to the presence of undissolved solids in the 1800 gal batch of condensate obtained for the laboratory study, filtration of condensate was necessary. The amount of these solids in the 1800 gal batch was not determined, since the contents of the tank trailer could not be adequately stirred.

FIGURE 4. Computed ^{137}Cs Breakthrough Curves

FIGURE 5. ^{137}Cs Removal from SX Condensate

A portion of the undissolved solids in the 242-T condensate would settle, whereas those of the ITS condensate remained suspended. A previous sample of 242-T contained no detectable suspended solids.

Cesium breakthrough was not attained after 18,000 column-volumes through the 5 g column of 20 x 50 mesh AW 500. Cesium DF's of 50 or more were obtained at flow rates up to 900 column-volumes/hr at 25 °C. The condensate was filtered through 0.45 μ filters.

Results of experiments with the 1 in. diam column of 20 x 50 mesh AW 500 and a 5 μ Cuno pre-filter are shown in Figure 6. The experiment was terminated after 5540 column-volumes because of the high pressure differential across the AW 500 column. Increased removal of ^{137}Cs near the end of the run, coinciding with an increase in pressure differential across the bed, indicated that some of the ^{137}Cs might have been in the suspended matter which is more effectively removed as the bed plugs.

Initial plans called for discarding the AW 500 when its exchange capacity was exhausted. This practice is currently followed at Savannah River where the spent AW 500 is dumped into a waste storage tank. However, a cost evaluation showed that, by regenerating the AW 500 with a reasonable volume of regenerant such as NaNO_3 , a savings in material could be effected. A factorial design experiment was conducted to evaluate the flow rate, temperature, and NaNO_3 concentration parameters.

ELUTION EXPERIMENTS

Elution curves for the eight treatment combinations of Table III are given in Figures 7 through 14. Respective treatment combinations are identified. It is possible to ascertain by visual inspection alone that flow rate is not a statistically significant variable over the range used here. Comparison of combinations one and two, or of three and four show little difference in their elution rates. It is easily observed, on the other hand, that the

FIGURE 6. Column Pressure Differential and ^{137}Cs Breakthrough for 242-T Condensate

FIGURE 7. Elution Curve for Column 1

FIGURE 8. Elution Curve for Column 2

FIGURE 9. Elution Curve for Column 3

FIGURE 10. Elution Curve for Column 4

FIGURE 11. Elution Curve for Column 5

FIGURE 12. Elution Curve for Column 6

FIGURE 13. Elution Curve for Column 7

FIGURE 14. Elution Curve for Column 8

elution rates for combinations one and three, or two and four differ considerably. It also should be noted that all of the columns initially contained more than a column-volume of ITS condensate influent loading solution at the beginning of the elution experiment (zero column-volumes of eluting solution throughput). Hence, the eluted fraction of cesium is very low on all the elution curves until this waste volume passes through the column. The eluting salt solution first emerges from the column at between 1 and 2 column-volumes. Dispersion caused some mixing of waste and eluting salt solution within the column. Therefore, it was difficult to pinpoint where, in the exact volume of throughput, the collection of ITS waste left off and eluting salt solution began.

To rigorously show that flow rate was not a significant variable in the design, the fraction of original cesium activity eluted from the column at 15 column-volumes was chosen as the dependent variable. These data were then arranged and treated statistically to give the results shown in Table IV. Flow rate, although not statistically significant, could most certainly become so by substantially extending the range.

TABLE IV. Statistical Results for Fraction of Cesium Eluted at 15 Column-Volumes of Throughput

<u>Eluting Solution</u>	<u>Fraction Eluted</u>	<u>Effect Totals</u>	<u>Identification</u>
1	0.29	5.02	Grand Total
2	0.29	0.06	A (Flow Rate)
3	0.64	1.28*	B (Temperature)
4	0.66	0.00	AB
5	0.63	1.26*	C (NaNO ₃ Concentration)
6	0.66	0.02	AC
7	0.92	-0.16	BC
8	0.93	-0.04	ABC

Note: $\sigma^2 = 0.00086$, $\sigma = \pm 0.0293$, σ effect totals = $(\sqrt{8})(\pm 0.0293) = \pm 0.0826$, and t at 1% level and four degrees of freedom = 4.604. An effect total is significant if greater than $(\pm 0.0826)(4.604) = \pm 0.380$. Eluting solution numbers correspond to those in Table III. The two and three-factor interactions were used in the estimation of error. An asterisk indicates an effect total significant at the 1% t-test level.

We may also utilize the effect and grand totals given in Table I to determine the coefficients in a regression equation of the type fraction eluted = $b_0 + b_1(A) + b_2(B) + b_3(C)$, where $b_0 = 5.02/8 = 0.628$, $b_1 = 0.06/8 = 0.008$, $b_2 = 1.28/8 = 1.60$, and $b_3 = 1.26/8 = 0.158$. The coefficient b_1 may be ignored if desired, since it has not been shown to be statistically significant. A, B, and C are flow rate, temperature, and NaNO_3 concentration, respectively, and must be coded for the equation to be of any utility. This is easily done by setting the maximum value of each independent variable range equal to plus one and the minimum values equal to minus one. Hence, they become

$$A = (\text{flow rate} - 7.5)/2.5,$$

$$B = (\text{temperature} - 44)/21 \text{ and}$$

$$C = (\text{NaNO}_3 \text{ concentration} - 5.25)/1.75.$$

It should be kept in mind that the dimensions of A are column-volumes/hr, of B are degrees centigrade, and of C are moles.

Computed values of fraction eluted, using the above regression equation and coefficients, are shown in Table V.

TABLE V. *Actual and Computed Fractions
Eluted for the Figure 1 Design*

<u>Treatment Combinations</u>	<u>Experimental</u>	<u>Computed</u>
Grand Total	0.29	0.31
A (flow rate)	0.29	0.32
B (temperature)	0.64	0.62
AB	0.66	0.64
C (NaNO_3 concentration)	0.63	0.62
AC	0.66	0.63
BC	0.92	0.94
ABC	0.93	0.95

The agreement between experimental and computed fractions eluted is satisfactory, and the equation may therefore be used to extrapolate fractions eluted values over the range of independent variables used in the design. Thus with the conditions 5.0M NaNO_3 , 55 °C, and 5 column-volumes/hr given

the equation becomes fraction eluted = $0.628 + 0.008(-1) + 0.160(0.524) + 0.158(-0.143) = 0.681$. If the NaNO_3 concentration is increased to 6.0M and the temperature to 60°C with the same flow rate, fraction eluted = $0.628 + 0.008(-1) + 0.160(0.762) + 0.158(0.429) = 0.810$.

Inherent in the above regression method of fraction eluted prediction is the assumption that the response of independent variables between range extremes is linear. The assumption, while probably not strictly valid, is a reasonable first assumption over the relatively restricted ranges involved in the present design.

Statistical treatment of fraction eluted values at 10 column-volumes of throughput gave very similar results. However, the results of statistically treating such values at 2 or 3 column-volumes of throughput would seriously lack precision due to choice of values still influenced by initial dispersion across the ITS condensate loading solution- NaNO_3 eluting solution interface. Fraction eluted values at column-volumes of six or greater are suggested for statistical study.

REGENERATION OF 1 in. diam AW 500 COLUMN

Three loading and elution cycles were completed with a 1 in. diam AW 500 column with ITS condensate and 7M NaNO_3 eluant. No data were obtained for the first elution cycle because of difficulties encountered in pumping the eluant through the column. The column had plugged during the first loading cycle and much of the AW 500 was agglomerated. All but one of the lumps of agglomerated AW 500 were broken up during the first elution. The effect of the remaining lump which settled to the bottom (effluent end) of the column is illustrated in Figure 15, curve 2. Due to lack of adequate contact of the eluant with the AW 500 particles in the lump, elution of these particles was incomplete. Since the lump

was located at the effluent end of the column, the remaining ^{137}Cs was slowly removed by the condensate feed of the next loading cycle.

The ^{137}Cs breakthrough (Figure 15, curve 3) following the second elution compares favorably with that of a fresh column of AW 500 (Figure 16). However, the ^{137}Cs removal shown by Figure 15, curve 3, is not sufficient to attain $1/10 \text{ MPC}_w$ due to the high ^{137}Cs concentration in the feed. To attain this level of ^{137}Cs removal, a reduction in the flow rate and/or an increase in loading temperature is indicated.

The percent ^{137}Cs eluted as a function of volume of 7M NaNO_3 eluant is shown for the second and third elution cycles in Figure 17. The elution rates are greater than those shown in Figure 14 largely because of a higher elution temperature and less penetration of the ^{137}Cs down the bed during the loading cycle. The loading cycles of both curves 2 and 3, Figure 15 were terminated because of bed plugging rather than breakthrough. The column of AW 500 in Figure 13 was loaded in depth to accurately assess the effects of the various parameters studied.

FIGURE 15. Cesium Breakthrough After
Elution with NaNO_3

FIGURE 16. Cesium Breakthrough with Fresh Column of AW 500

FIGURE 17. Fraction of ^{137}Cs Eluted as Function of 7M NaNO_3 Volume

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3 Battelle Memorial Institute