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RESORCINOL-FORMALDEHYDE ADSORPTION OF CESIUM ( $\text{Cs}^+$ ) FROM  
HANFORD WASTE SOLUTIONS—PART I: BATCH EQUILIBRIUM STUDY

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## ABSTRACT

Batch equilibrium measurements were conducted at  $25 \pm 2$  °C with a granular Resorcinol-Formaldehyde (RF) resin to determine the distribution coefficients ( $K_d$ s) for cesium. In the tests, Hanford Site actual waste sample containing radioactive cesium ( $^{137}\text{Cs}$ ) and a pretreated waste sample that was spiked with non-radioactive  $^{133}\text{Cs}$  were used. Initial concentrations of non-radioactive cesium in the waste sample were varied to generate an equilibrium isotherm for cesium. The majority of the tests were conducted at  $25 \pm 2$  °C using a liquid to solid phase ratio of  $\sim 100$  mL/g and a contact time of 72 hours. Two additional tests were conducted using a liquid to solid phase ratio of 10 and a contact time of 120 hours.

The measured distribution coefficient ( $K_d$ ) for radioactive cesium ( $^{137}\text{Cs}$ ) was 948 mL/g; the  $K_d$  for non-radioactive cesium ( $^{133}\text{Cs}$ ) was 1039 mL/g. The  $K_d$  for non-radioactive cesium decreased from 1039 to 691 mL/g as the initial cesium concentration increased from  $\sim 8$  to 64  $\mu\text{g/mL}$ . Very little change of the  $K_d$  was observed at initial cesium concentrations above 64  $\mu\text{g/mL}$ . The maximum sorption capacity for cesium on granular RF resin was 1.17 mmole/g dry resin. This value was calculated from the fit of the equilibrium isotherm data to the Dubinin-Radushkevich equation. Previously, a total capacity of 2.84 mmole/g was calculated by Bibler and Wallace for air-dried RF resin.

## INTRODUCTION

The U. S. Department of Energy (DOE) is building a nuclear waste treatment facility at the Hanford Site, in Richland, Washington, where millions of gallons of high-level and low-level radioactive waste are currently stored in underground storage tanks. The Hanford Site has 177 underground tanks that store 204 million liters (54 million gallons) of high-level and low-level radioactive waste. Large portions of the waste exist as liquid solution (supernatant) that contain the following radionuclides:  $^{137}\text{Cs}$ ,  $^{99}\text{Tc}$ ,  $^{90}\text{Sr}$ , and transuranic actinides. The major contaminants in the supernatant prior to pretreatment include  $^{137}\text{Cs}$  ( $t_{1/2} = 30$  y),  $^{99}\text{Tc}$  ( $t_{1/2} = 2.13 \times 10^5$  y), and  $^{90}\text{Sr}$  ( $t_{1/2} = 28.6$  y). The radioactivity in the Hanford Site waste supernatant is primarily from the fission products  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ . These radionuclides are produced by the fission of uranium or plutonium in relatively high yield and they pose a serious radiation hazard to health and environment.

Removal of  $^{137}\text{Cs}$  from the bulk waste is required to produce a low-activity waste (LAW) that can be vitrified into LAW glass. The design of the facility provides for total cesium removal via ion exchange, recovery of separated Cs concentration into a relatively small volume, and incorporation in high-level waste sludge. This sludge is vitrified into HLW glass logs suitable for permanent disposal in a federal repository. Cesium ( $^{137}\text{Cs}$ ) removal from nuclear waste solutions using inorganic ion exchange materials has been widely investigated [1-8]. The ion exchange materials examined include potassium and cobalt hexacyanoferrates, ammonium molybdophosphate incorporated in a polyacrylonitrile support (AMP-PAN), and crystalline silicotitanate

(CST). Prout and co-workers showed that potassium hexacyanoferrates ( $K_2CoFe(CN)_6$ ) was highly selective for cesium, but the ion exchange material was not stable in very high alkaline waste solutions [1]. The AMP PAN material exhibited good performance in acidic waste solution and the elution of cesium from the resin with 8 M nitric acid was effective [2, 3]. Studies on crystalline silicotitanate (CST) resin indicated that the material exhibits strong retention for cesium in both acidic and alkaline solutions [4-8]; but it is chemically unstable in the alkaline waste and it cannot be regenerated.

Organic ion exchange resins, such as the resorcinol-formaldehyde (RF), Duolite<sup>®</sup> CS-100, Diphonix-CS<sup>™</sup>, and SuperLig<sup>®</sup> 644, have been used for cesium removal from Hanford Site nuclear waste solutions. The RF resin was developed by Bibler and Wallace [9] and it was tested for uptake of cesium in alkaline radioactive waste at Hanford and the Savannah River Site [10-12]. The performance of the RF resin was highly variable because the resin was subject to oxidation during storage and pretreatment. Other investigators used Resorcinol-Formaldehyde resins for cesium removal from nuclear waste solutions [13, 14]. Studies to remove cesium from waste supernatants with commercially available Duolite<sup>®</sup> CS-100 carboxylic acid were reported [15, 16]. Duolite<sup>®</sup> CS-100, a polymer of phenol-carboxylic, is similar to the RF resin but the resin was less selective for cesium over sodium, and multiple loading and elution cycles were required to obtain the desired performance. Chiarizia and Co-workers developed Diphonix-CS<sup>™</sup> resin with phenol groups attached to the polymeric matrix to bind cesium [17-19]. The resin can be used to simultaneously adsorb actinides, cesium, and strontium from high level waste solutions. Although the resin has not yet been tested with actual

waste it has performed well with Hanford Site simulated waste solution. Extensive ion exchange testing was recently performed at the Hanford and Savannah River sites using small-scale columns with resin to remove cesium from actual waste samples retrieved from various Hanford Site waste tanks [20-23]. SuperLig<sup>®</sup> 644 resin, a crown ether ligand attached to an organic substrate, exhibited excellent loading and elution performance with all Hanford Site waste categories. However, pilot-scale tests revealed high pressure drops across the resin bed columns during transition from regeneration to loading and elution. Therefore, due to concerns of poor hydraulic performance and inability to maintain a homogeneously packed resin bed for efficient removal of cesium, an alternate ion exchanger, Resorcinol-Formaldehyde (RF) resin is under consideration to be used in place of SuperLig<sup>®</sup> 644. The RF resin was chosen because it has high loading capacity per unit volume of resin (as demonstrated by extensive historical testing) and it is compatible with the Hanford Waste Treatment Plant process flow sheet and will require minimal design changes. In addition, The RF resin is commercially available in granular and, if desired, in spherical form to avoid hydraulic problems.

## EXPERIMENTAL

### Ion Exchange Material

The resorcinol-formaldehyde (RF) resin was obtained as granular product from Boulder Scientific Co. (Boulder, Colorado). The resin was prepared by caustic condensation polymerization of resorcinol and formaldehyde. It is highly selective for cesium, which primarily exists as dissociated ion in highly alkaline waste solutions present in Hanford Site waste tanks. The ion exchange mechanism for resorcinol

formaldehyde involves a reversible equilibrium exchange of cesium with sodium, the dominant bound species on the resin. The major competitors against cesium for adsorption on RF active sites are potassium and hydrogen ions. High selectivity for cesium over the competitor ion is required for the overall effectiveness of the resorcinol formaldehyde resin for cesium removal from different Hanford Site waste types. Since both potassium and sodium are present in Hanford tank wastes at concentrations that are orders of magnitude larger than the cesium ion concentration. The equations representing the exchange of sodium with cesium and potassium are as follows:



Where  $\overline{\text{R-Na}^+}$  with the over bar represents the resin matrix in the sodium form. The RF resin is eluted with dilute nitric acid (0.5 M  $\text{HNO}_3$ ), which promotes the protonation of the resin to release cesium into the aqueous solution, leaving behind the resin in the hydrogen form.

The RF resin sample used in this work was prepared by combining a 6-L production batch (BCS-187-1-0002) with a 600-g production batch (BCS-187-4-0001). The combined resin was split several times using an open-pan riffle sampler (Model H-3980, Humboldt Manufacturing, Co., Norridge, IL) to produce representative sub-samples. Two 1-liter sub-samples were transferred into air-tight polyethylene bottles and

the headspace above the resin was purged with nitrogen. The resin was stored dry in the potassium-form. The resin was converted to the sodium-form immediately before being used in the batch contact measurements.

### Hanford Site Waste Solutions

In the tests, Hanford Site actual waste sample containing radioactive cesium  $^{137}\text{Cs}$  and a pretreated waste sample that was spiked with non-radioactive cesium  $^{133}\text{Cs}$  were used. The waste samples were retrieved from Hanford Site Tank 241-AW-101. The as-received samples were homogenized, and then diluted with deionized water to provide approximately 5 M  $\text{Na}^+$  concentration in the waste sample. After dilution, the bulk solution was sampled and analyzed. The bulk solution was then filtered through a 0.1-micron sintered metal Mott filter to remove entrained solids. A total of 15 L of the AW-101 filtrate at 5 M  $\text{Na}^+$  was treated in a multiple ion exchange column tests with SuperLig<sup>®</sup> 644 resin [24]. A total of two liters of the pretreated waste sample was later spiked with non-radioactive cesium ( $^{133}\text{Cs}$ ) and used for cesium removal with the RF resin. The compositions of treated and actual waste solution used are shown in Table 1.

### Procedure

Five batch contact tests were conducted with the Resorcinol-Formaldehyde (RF) resin using Hanford Site waste tank samples. The tests were conducted by adding 0.5-g portions of damp RF resin in the Na-form to 50-mL portions of waste sample from Hanford Site tank 241-AW-101. The resin with solution was placed in 125-mL polyethylene bottles equipped with Teflon<sup>®</sup>-lined screw caps and shaken with a Maxi-



Mix III orbital shaker (Type 65800, Barnstead/Thermolyne, Dubuque, Iowa) at 550 to 580 rpm. Additional tests were conducted with 10-mL portions of the waste samples with 1.0 g of dry Na-form resin. A Mettler-Toledo (Columbus, Ohio) analytical balance (model AG285) with an accuracy of  $\pm 0.001$  g was used to weigh the samples.

The bottles were equilibrated for predetermined times at a temperature of  $25 \pm 2$  °C. All batch contact tests were conducted in a shielded hot cell. After equilibration, the solutions were separated from the resin by vacuum filtration. Nalgene (Rochester, New York) 0.45- $\mu$ m nylon filters connected to a vacuum and trap assembly were used for the filtration. Aliquots (1-3 mL) of the filtrate were placed in glass vials with Teflon<sup>®</sup>-lined screw caps for analyses. The amount of cesium adsorbed was determined from the initial and final concentrations of cesium in solution. Control waste solutions were prepared in the same manner as the batch contact test solution, as previously described. Control solutions contained no resin and were utilized to determine the initial concentration of the desired constituent in the waste solutions. The volume of control solutions was reduced to 10 mL because of the limited waste availability.

To generate an equilibrium isotherm for cesium, the solutions used in the first three batch contact tests contained varying amounts of non-radioactive <sup>133</sup>Cs in the form of cesium nitrate as shown in Table 3 and 4. All batch contact measurements were conducted in duplicate, except the control samples for test #4, #5, and #6 were single measurements. The initial concentration of the last two sets (i.e. #5 and #6) was that of <sup>137</sup>Cs in actual waste from Tank 241-AW-101.

A cesium mass balance was conducted for batch contact tests #2 and #6 in Table 3 and 4. Those two tests were performed using a liquid to solid phase ratio of 10 mL/g and a longer contact time of 120 hours. After equilibration, the resin was separated from the solution using a 0.45-micron Nalgene filter unit. The filtrates from the test and control solutions were analyzed for cesium to determine the residual cesium on the resin. To directly measure the cesium on the spent resin, additional steps were carried out to permit removal of the resin from a shielded hot cell. The following steps were performed to essentially reduce the dose of  $^{137}\text{Cs}$  on the resin.

1. Using a new filtrate reservoir, the spent resin was washed with 20 milliliters of 0.1 M NaOH. The 0.1 M NaOH solution was collected in the reservoir.
2. After attaching a new filtrate reservoir to the filter top, the spent resin was rinsed with 20 milliliters of DI water. The rinse solution (DI water) was collected separately from the 0.1 M NaOH solution.
3. The spent resin was then transferred into a 50-mL polyethylene bottle containing 20 milliliters of 0.5 M  $\text{HNO}_3$  and the bottle was shaken on a Maxi-Mix III Shaker for 24 hours at a speed of 550-580 rpm.
4. After 24 hours, the solution (0.5 M  $\text{HNO}_3$ ) was separated from the resin using vacuum filtration; the filtrate was collected separately from the 0.1 M NaOH and deionized water using a new filtrate reservoir.

The Nalgene filter units had a 0.45  $\mu\text{m}$  nylon filter. Vacuum filtration was continued following all the preceding steps until the solution dripping had ceased. The filtrate solutions and spent resin from steps 1-4 were analyzed to determine the concentration of cesium.

## RESULTS AND DISCUSSION

The batch distribution coefficients ( $K_d$ s) represent the ratio of the cesium adsorbed on the resin to the cesium left in solution at equilibrium. They are determined from the following equation:

$$K_d = \left[ \left( \frac{C_o}{C_e} \right) - 1 \right] \left[ \frac{V}{m * F} \right]$$

where  $C_o$  is initial concentration of cesium in the waste sample,  $C_e$  is equilibrium concentration,  $V$  is the volume of solution in contact with resin,  $m$  is the mass of the sodium-form, air dried resin, and  $F$  is a factor that corrects for the dry mass of the resin in contact with solution. The  $K_d$  is useful to determine the adsorption capacity of the resin at equilibrium.

Tables 2 and 3 show the results for the batch contact measurements for cesium adsorption on the Resorcinol-Formaldehyde (RF) resin. In addition to the  $K_d$  values, these tables list the contact time, equilibrium loading, and percent relative standard deviation between duplicate measurements. The  $K_d$  value for the non-radioactive cesium ( $^{133}\text{Cs}$ ) at initial concentration of  $\sim 8 \mu\text{g/mL}$  was 1,039 mL/g dry resin at the following experimental conditions: liquid to solid phase ratio of 100 mL/g, contact time of 72 hrs, temperature of  $25 \pm 2 \text{ }^\circ\text{C}$ . At a liquid to solid phase ratio of 10 mL/g and at a contact time (120 hours), the  $K_d$  for the non-radioactive cesium was 1,743 mL/g dry resin. A  $K_d$  value of 948 mL/g dry resin was obtained for radioactive cesium ( $^{137}\text{Cs}$ ) from actual AW-101

waste with initial  $^{137}\text{Cs}$  concentration of 173  $\mu\text{Ci/mL}$ ) and at a phase ratio of 95 mL/g and a contact time of 72 hours. This  $K_d$  is 31% less than that previously observed for SuperLig<sup>®</sup> 644 (1,368 mL/g dry resin) with actual AW-101 waste sample (initial  $^{137}\text{Cs}$  concentration equal to 175  $\mu\text{Ci/mL}$ ) at the same experimental conditions ; the  $K_d$  value for the RF resin with non-radioactive cesium ( $^{133}\text{Cs}$ ) was 33% lower than that observed for SuperLig<sup>®</sup> 644 with AW-101 simulant [24].

Figure 1 shows a log-log plot of cesium  $K_d$  versus final or equilibrium concentration, in solution,  $[\text{Cs}^+]_f$ . The dependence of  $K_d$  on  $[\text{Cs}^+]_f$  was exhibited using a simple linear regression with two parameters. The curve fit (dashed line) agrees with experimental data. The equation for the curve fit can be written as

$$K_d = 10^3 \times (C_e)^{-0.18}$$

Figure 2 shows a log-log plot of the amount of cesium loaded ( $\mu\text{moles/g}$ ) on the RF resin as a function of equilibrium cesium concentration in the AW-101 waste sample spiked with varying amounts of non-radioactive cesium; the graph also contains the data for radioactive cesium ( $^{137}\text{Cs}$ ) from AW-101 actual waste samples. The cesium loading on the RF resin exhibited a linear correlation as a function of the equilibrium concentration. In other words, the total amount of cesium that can be loaded on the RF resin will decrease as the equilibrium concentration of cesium in solution decreases. The equilibrium capacity for cesium on the RF resin was calculated from Dubinin-Radushkevich (D-R) equation as follows [25].

$$\ln(q) = \ln(q_m) - \beta \varepsilon^2$$

where  $q_m$  is the maximum loading capacity (mole/g dry resin in Na-form),  $\beta$  is a constant related to sorption energy ( $\text{mol}^2 \times \text{kJ}^{-2}$ ), and  $\varepsilon$  is the Polanyi potential [26]

$$\varepsilon = RT \times \ln\left(1 + \frac{1}{C_e}\right)$$

where R is a gas constant (kJ/mole), T is the temperature in Kelvin (K),  $[Cs]_e$  is the final, or equilibrium concentration of cesium in solution (mole/L). The cesium loading data from the batch contact measurements using actual and treated AW-101 waste were plotted as  $\ln(q)$  against  $\varepsilon^2$  in Figure 4. The parameters in the D-R equation,  $q_m = 1.17$  mmole/g of air dried resin and  $\beta = -0.0058$ , were calculated from the intercept and the slope of the plot, respectively. Thus, the  $q_m$  value for  $Cs^+$  on the RF resin using our experimental conditions is less than half of the 2.84 mmole/g of air-dried resin total capacity, which was previously reported for RF resin [9]. The mean free energy of sorption (E) for cesium on RF resin was calculated from  $\beta$  value using the following equation [27]

$$E = (-2\beta)^{-1/2}$$

The mean free energy for cesium sorption on the RF resin was 9.3 kJ/mole, which is within the energy range of 8-16 kJ/mole for ion-exchange reactions [28].

The cesium mass balance for tests # 2 and #6 is shown in Tables 4 and 5, respectively. In the procedure section, the steps taken to prepare the resin for analysis after the equilibration period are described. These steps include separation of the resin

from solution by filtration, sodium hydroxide wash of the resin, DI water rinse of the resin, elution of the resin with 0.5 M nitric acid solution, and dissolution of the resin by microwave digestion. To close the mass balance, the amount of cesium on the resin was first calculated by concentration difference of the test solutions before and after contact with the resin (see upper portion of Tables 4 and 5). This was compared to total the amount of cesium found in the 0.1 M NaOH, DI water, 0.5 M HNO<sub>3</sub>, and resin dissolution solutions (see lower portion of Tables 4 and 5). The results in Table 4 for non-radioactive cesium (test #2) exhibit a 97% recovery of cesium from the resin.

The results for radioactive <sup>137</sup>Cs mass balance in the batch contact test # 6 are shown in Table 5. The high dose of the <sup>137</sup>Cs loaded on the resin prevented direct gamma analysis to measure the amount of cesium on the resin. To dilute the test solution, the resin was contacted with 20 mL of 0.1 M sodium hydroxide, followed by 20 mL of deionized water, then eluted using 20 mL of 0.5 M HNO<sub>3</sub>. The data presented in the bottom of Table 5 show the amount of <sup>137</sup>Cs stripped from the resin into each contact solution. The sum of <sup>137</sup>Cs found in the resin dissolution sample and in the aqueous solutions (0.1 M NaOH, DI water, and 0.5 M HNO<sub>3</sub>) was compared with the results in the upper portion of Table 5 (i.e., the amount of <sup>137</sup>Cs adsorbed on the resin that was determined by concentration difference of <sup>137</sup>Cs in test solutions before and after contact with the resin). As expected, the majority of the <sup>137</sup>Cs (74%) was found in the 0.5 M HNO<sub>3</sub> solution. In addition, a good agreement was found between the measured amount of <sup>137</sup>Cs on the resin (1,814 μCi) and the amount determined from concentration difference (1,750 μCi); the difference of < 4% suggests the integrity of the experiment

was fairly good. It should be noted that the amount of  $^{137}\text{Cs}$  found in the 0.1 M NaOH caustic solution and in DI water solutions was very small compared to that in the 0.5 M  $\text{HNO}_3$  and spent resin.

## CONCLUSION

This experimental study evaluated resorcinol-formaldehyde (RF) resin for removal of cesium from high potassium waste from tank 241-AW-101, at the Hanford site. The experiments consisted of equilibrium batch contact test. The following conclusions were drawn from this study: The batch distribution coefficients ( $K_d$ s) for cesium  $^{137}\text{Cs}$  (radioactive) and  $^{133}\text{Cs}$  (non-radioactive) were 948 and 1,039 mL/g dry resin, respectively. The  $K_d$  decreased with increasing initial cesium concentration, as expected. Using the isotherm data, the maximum sorption capacity of cesium was calculated from the Dubinin-Radushkevich (D-R) equation and a value of 1.17 mmole/g dry resin was found.

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FIGURES

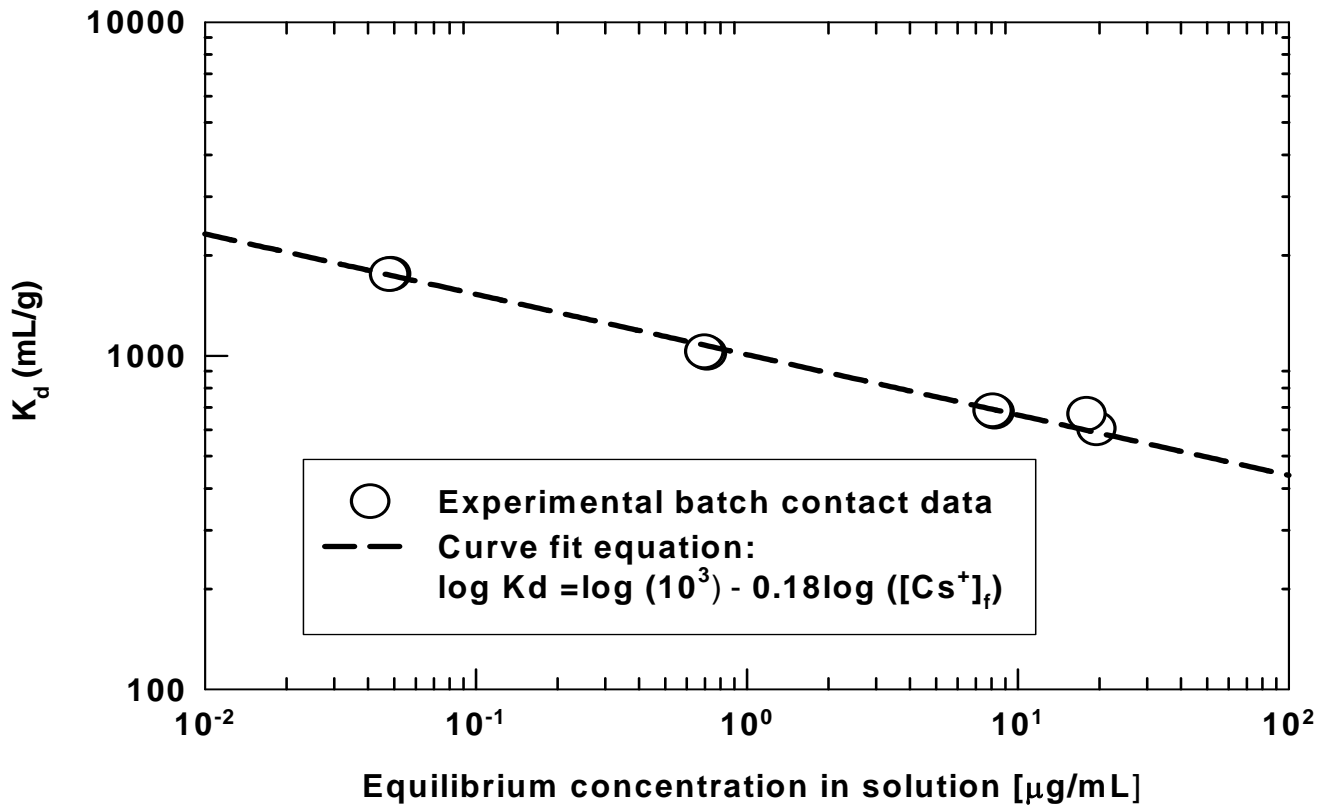


Figure 1.  $Cs^+$  Batch Distribution Coefficients ( $K_{ds}$ ) Using RF Resin

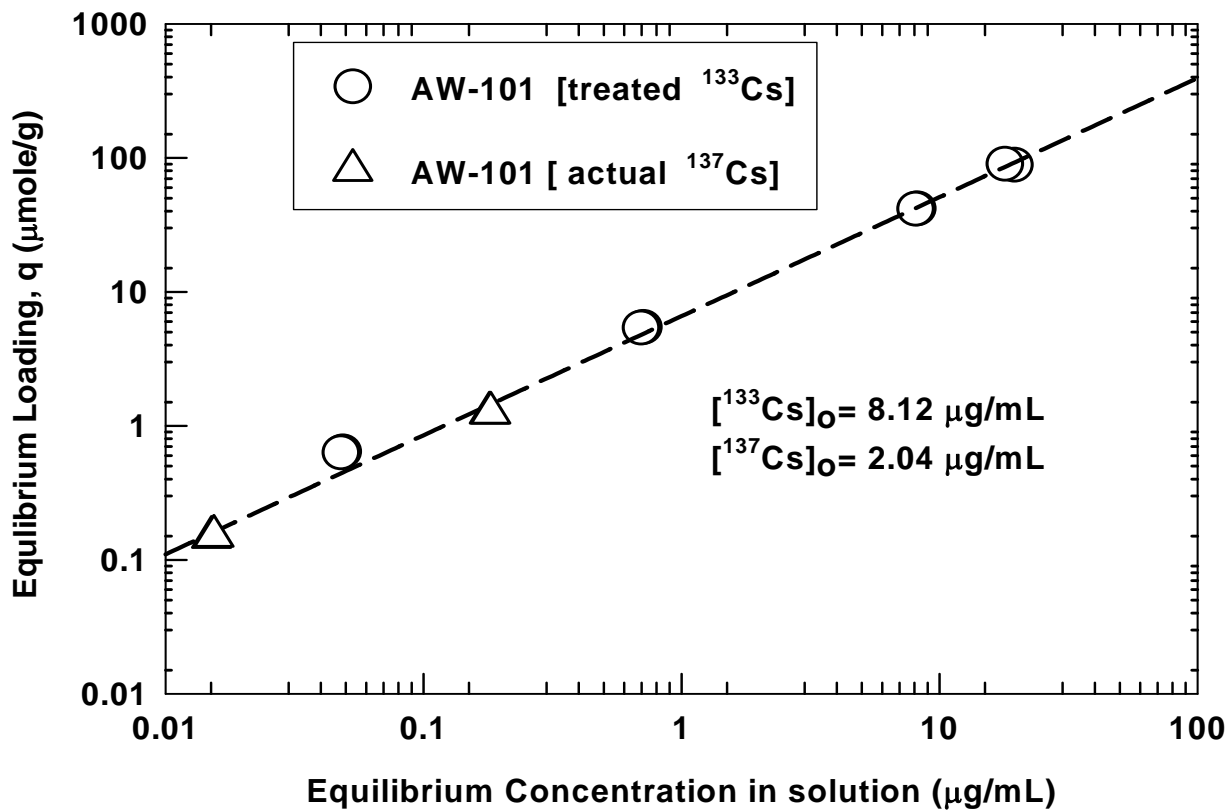


Figure 2. Equilibrium Isotherm for  $\text{Cs}^+$  on RF Resin

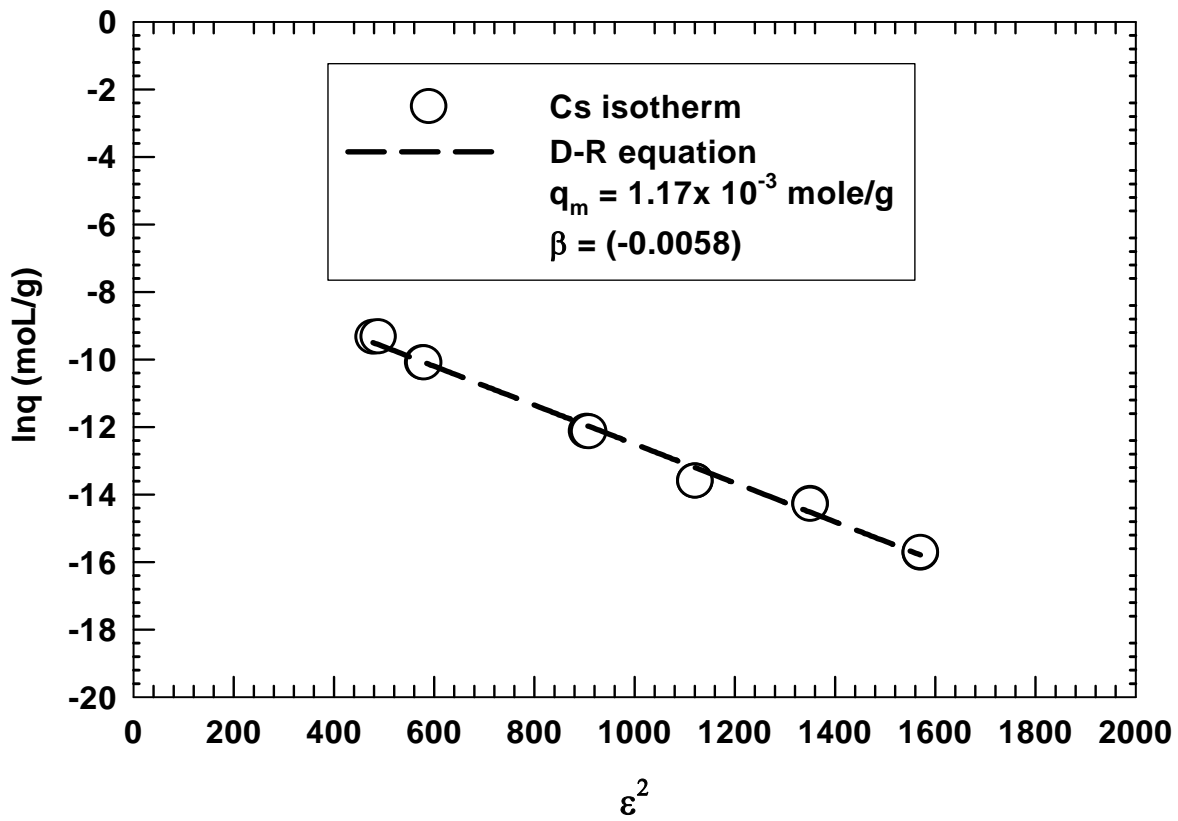


Figure 3. Dubinin-Radushkevich (D-R) Curve Fit of Cs<sup>+</sup> Equilibrium Data





# TABLES

TABLE 1. COMPOSITION OF HANFORD SAMPLES (TANK 241-AW-101)

Analyte	Treated AW-101 µg/mL	Actual AW-101, µg/mL	Analyte	Treated AW-101, µg/mL	Actual AW- 101, (µg/mL)
Ag	0.245	<0.150	F <sup>-</sup>	93.1	131
Al	12000	12305	(HCOO) <sup>-</sup>	403	805
B	35.5	<16.2	Cl <sup>-</sup>	2290	2623
Ba	0.323	<0.150	NO <sub>2</sub> <sup>-</sup>	42550	33718
Ca	7.32	<4.53	NO <sub>3</sub> <sup>-</sup>	79680	89600
Cd	1.46	<0.200	PO <sub>4</sub> <sup>-</sup>	257	380
Ce	2.87	<2.48	SO <sub>4</sub> <sup>-</sup>	134	163
Cr	34.0	45.1	(C <sub>2</sub> O <sub>4</sub> ) <sup>2-</sup>	185	229
Cu	1.22	<0.310	Total Carbon (mg/L)		
Fe	1.78	0.820	TIC	14,115	nm
Gd	< 0.284	<0.270	TOC	1,050	nm
K	26,600 (0.68 M)	20,068 (0.52 M)	Total Base, M	2.83	nm
La	0.418	<0.200	Free OH <sup>-</sup> , M	2.09	nm
Li	1.00	<0.850	Density, g/mL	1.23	1.24
Mg	< 0.62	<0.620	Radionuclides	µg/mL (µCi/mL)	µg/mL (µCi/mL)
Mn	< 0.22	<0.220	<sup>137</sup> Cs	0.073 (0.847)	2.04 (173)
Mo	32.2	33.3	<sup>133</sup> Cs	8.12	5.43
Na	112,000 (4.87 M)	113,563 (4.93 M)	<sup>135</sup> Cs	0.08	1.51
Ni	4.33	<0.750	Total Cs	8.27	9.03
-P	143	144	<sup>137</sup> Cs /Total Cs	0.009	0.226
Pb	20.6	28.3	<sup>60</sup> Co	nm	(2.11 x 10 <sup>-4</sup> )
S	191	194	<sup>154</sup> Eu	nm	< (9.92 x 10 <sup>-5</sup> )
Sb	32.9	33.6	<sup>155</sup> Eu	nm	< (3.41 x 10 <sup>-4</sup> )
Si	205	157	<sup>235</sup> U	nm	< 0.00015
Sn	60.2	730	<sup>238</sup> U	nm	1.24
Sr	2.27	<1.00	<sup>238</sup> Pu	nm	5.04 x 10 <sup>-4</sup>
Ti	< 0.06	<0.060	<sup>239</sup> Pu/ <sup>240</sup> Pu	nm	2.28 x 10 <sup>-4</sup>
U	< 7.55	<7.55	<sup>241</sup> Am	nm	< 1.00 x 10 <sup>-4</sup>
V	3.40	3.54	Gross Alpha	nm	< 1.08 x 10 <sup>-2</sup>
Zn	4.96	<0.55			
Zr	5.45	2.97			

Nm = not measured

TABLE 2. BATCH CONTACT DATA FOR NON-RADIOACTIVE Cs<sup>+</sup> ON RF RESIN (25 ± 2 °C)

TREATED AW-101 WASTE SAMPLE SPIKED WITH NON-RADIOACTIVE CESIUM								
Test #	[ <sup>133</sup> Cs] <sub>o</sub> , (μg/mL)	[ <sup>133</sup> Cs] <sub>f</sub> , (μg/mL)	Phase Ratio (mL/g)	Time, (hrs)	<sup>133</sup> Cs on resin (μg/g)	K <sub>d</sub> (mL/g)	Avg. K <sub>d</sub> (mL/g)	% RSD**
1	8.042	0.712	100	72	735	1,035	1,039	0.7
	7.914	0.696	101	72	726	1,043		
2	8.567	0.0486	10	120	85	1,745	1,743	0.2
	8.398	0.0478	10	120	83	1,742		
3	64.32	8.198	100	72	5,633	687	6,91	0.7
	63.76	8.062	100	72	5,595	664		
4	138.3	19.49	100	72	11,934	612	6,45	7.1
	138.3	17.91	101	72	12,128	677		

\*\* Relative Standard Deviation

TABLE 3. BATCH CONTACT DATA FOR RADIOACTIVE Cs<sup>+</sup> ON RF RESIN (25 ± 2 °C)

ACTUAL AW-101 WASTE SOLUTION WITH RADIOACTIVE CESIUM								
Test #	[ <sup>137</sup> Cs] <sub>o</sub> , μg/mL (μCi/mL)	[ <sup>137</sup> Cs] <sub>f</sub> , μg/mL (μCi/mL)	Phase ratio (mL/g)	Time (hrs)	<sup>137</sup> Cs resin (μCi/g)	K <sub>d</sub> (mL/g)	Avg. K <sub>d</sub> (mL/g)	% RSD*
5	1.98	0.180 (15.70)	95	72	172 (14,930)	954	948	0.7
	(172.27)	0.182 (15.83)	95	72	171 (14,915)	942		
6	2.00	0.0151 (1.314)	10	120	20.3 (1,766)	1,343	1,344	0.02
	(173.81)	0.0154 (1.337)	10	120	20.7 (1,797)	1,344		

\* Relative Standard Deviation

TABLE 4. MASS BALANCE FOR NON-RADIOACTIVE Cs<sup>+</sup>

Sample ID	[ <sup>133</sup> Cs] <sub>o</sub> (μg/mL)	[ <sup>133</sup> Cs] <sub>f</sub> (μg/mL)	Solution volume (mL)	<sup>133</sup> Cs on resin (μg)
RF-Kd-120-N	8.567	0.0486	9.977	85
RF-Kd-120-ND	8.398	0.0478	9.985	83.4
			Average	84.2
			% RSD	1.35
Cs <sup>+</sup> recovered in different solutions	[ <sup>133</sup> Cs] <sub>sol</sub> (μg/mL)	Solution volume (mL)	mass of resin (g)	<sup>133</sup> Cs stripped from resin (μg)
<b>0.1 M NaOH</b>				
Kd-120-N	0.00585	20	na	0.117
Kd-120-ND	0.00425	20	na	0.085
<b>De-ionized Water</b>				
Kd-120-N	0.00084	20	na	0.0168
Kd-120-ND	0.00072	20	na	0.0144
<b>0.5 M HNO<sub>3</sub></b>				
Kd-120-N	2.884	20	na	57.68
Kd-120-ND	2.828	20	na	56.56
<b>Resin Dissolution</b>	[ <sup>133</sup> Cs] <sub>sol</sub> (μg/mL)	Resin dissolution volume (mL)	Resin dissolution ratio	<sup>133</sup> Cs remained on resin (μg)
Kd-120-N	0.153	10	15.3	23.4
Kd-120-ND	0.166	10	15.3	25.3
<b>Cs<sup>+</sup> Recovered</b>				Total (μg)
RF-Kd-120-N	na	na	na	81.2
RF-Kd-120-ND	na	na	na	82.0
				Average
				% RSD
				81.6
				0.70

TABLE 5. ACTIVITY BALANCE FOR RADIOACTIVE CESIUM

Sample ID	$[^{137}\text{Cs}]_o$ ( $\mu\text{Ci/mL}$ )	$[^{137}\text{Cs}]_f$ ( $\mu\text{Ci/mL}$ )	Solution volume (mL)	$^{137}\text{Cs}$ on resin ( $\mu\text{Ci}$ )
RF-Kd-120-act-N	174	1.3142	10.05	1735
RF-Kd-120-act-ND	174	1.3373	10.23	1766
			Average	1751
			% RSD	1.2
$\text{Cs}^+$ recovered in different solutions	$[^{137}\text{Cs}]_{\text{sol}}$ ( $\mu\text{Ci/mL}$ )	Solution volume (mL)	mass of resin (g)	$^{137}\text{Cs}$ stripped from resin ( $\mu\text{Ci}$ )
<b>0.1 M NaOH</b>				
Kd-120-act-N	0.0635	20	na	1.27
Kd-120-act-ND	0.0657	20	na	1.31
<b>De-ionized Water</b>				
Kd-120-act-N	0.0256	20	na	0.51
Kd-120-act-ND	0.0223	20	na	0.45
<b>0.5 M HNO<sub>3</sub></b>				
Kd-120-act-N	59.5	20	na	1,190
Kd-120-act-ND	74.6	20	na	1,492
<b>Resin Dissolution</b>				
	$[^{133}\text{Cs}]_{\text{sol}}$ ( $\mu\text{Ci/mL}$ )	Resin dissolution volume (mL)	Dry mass of Resin	$^{133}\text{Cs}$ remained on resin ( $\mu\text{Ci}$ )
Kd-120-act-N	424	na	0.9879	419
Kd-120-act-ND	532	na	0.9875	525
<b><math>\text{Cs}^+</math> Recovered</b>				Total ( $\mu\text{Ci}$ )
RF-Kd-120-act-N	na	na	na	1,611
RF-Kd-120-act-ND	na	na	na	2,018
			Average	1,815
			% RSD	15.9