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Axial Dispersion during Hanford Saltcake Washing

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Abstract: This paper describes laboratory-scale testing conducted to evaluate Selective Dissolution of cesium from non-radioactive Hanford tank 241-S-112 salt cake simulant containing the primary chemicals found in the actual tank. A modified axial dispersion model with increasing axial dispersion was developed to predict cesium removal. The model recognizes that water dissolves the salt cake during washing, which causes an increase in the axial dispersion during the wash. This model was subsequently compared with on-line cesium measurements from the retrieval of tank 241-S-112. The model had remarkably good agreement with both the lab-scale and full-scale data.

Keywords: Axial dispersion, Hanford, salt cake, mass transport, washing

INTRODUCTION

Water moving through porous salt cake in the Hanford waste tanks dissolves some of the solid salt cake and also displaces the soluble radionuclides (e.g. ^{137}Cs and $^{99}TcO_4^-$). The initial liquid leaving the waste is high in radioactivity due to the soluble radionuclides, and the remaining solids have lower radioactivity than the original waste. The separation that occurs from this displacement, known as "Selective Dissolution," may play an important role in Hanford clean up. ("Selective dissolution" is considered by some to be a

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misnomer because the Cs^+ does not crystallize and is not subsequently dissolved. Whether the term is precisely correct or not, it is widely used within the DOE complex.) Selective Dissolution is a potential pretreatment for low-curie salt to allow for subsequent waste immobilization via "Supplemental treatment."

"Supplemental treatment" is a general term for immobilization of the low activity waste (LAW) to supplement the Waste Treatment Plant (WTP) LAW vitrification plant. DOE is currently investigating two potential Supplemental treatment technologies - bulk vitrification, and steam reforming. The WTP is the cornerstone of the Hanford clean up strategy, separating tank waste in a pretreatment facility and then vitrifying the separated high-level waste (HLW) and low activity waste (LAW) fractions into durable waste forms. The WTP is expected to have sufficient capacity to pre-treat the waste and vitrify the HLW fraction; however, the capacity of the LAW vitrification facility currently being constructed is not adequate to complete all tank waste processing within the current schedule. Supplemental treatment or additional WTP LAW vitrification capacity will be needed to complete the Hanford clean up mission by 2028 (1). Most of the waste that would feed the Supplemental treatment would come from the WTP pretreatment facility. However, before the pretreatment facility comes on line, the Supplemental treatment could be fed with low-curie salt (2).

Low-curie salt is dissolved salt cake waste that has previously been treated to remove most of the Cs and Sr such that the residual Cs activity is <0.05 Ci/L. Waste with a cesium activity <0.05 Ci/L has been considered to be not economically feasible to justify cesium removal (3, 4).

Selective Dissolution may be an important component to prepare Low Curie salt waste for Supplemental treatment before the WTP pretreatment facility comes on line (5). Estimates of the low-curie salt to be immobilized range between 3,100 MT Na and 8,000 MT Na (1), or between 6% and 17% of the total Hanford waste. The amount of Low Curie waste that could be processed through Supplemental treatment depends in part upon the effectiveness of Selective Dissolution during retrieval.

This paper describes lab-scale testing to evaluate Selective Dissolution of Cs from Hanford tank 241-S-112 simulant. The data were fitted with a modified axial dispersion model. The model was subsequently compared with on-line cesium measurements during the retrieval of tank 241-S-112.

METHODS AND MATERIALS

Laboratory experiments were conducted to investigate cesium removal by single-stage washing using an S-112 simulant. Simulant preparation, apparatus, test conditions, and analyses are described below.

The composition of the S-112 simulant is provided in Table 1. Despite concern about cesium in the S-112 waste, it is not actually a significant

Table 1. S-112 simulant recipe

Chemical	% of salt by mass	Mass (g)
Sodium chloride (NaCl)	1.0	18.3
Sodium oxalate ($Na_2C_2O_4$)	2.0	36.8
Sodium fluoride (NaF)	0.1	1.5
Sodium aluminate ($NaAlO_2 \cdot 2H_2O$)	9.3	173.3
Sodium nitrate ($NaNO_3$)	49.3	917.8
Sodium nitrite ($NaNO_2$)	2.0	37.4
Sodium phosphate ($Na_3PO_4 \cdot 12H_2O \cdot 0.25NaOH$)	14.3	266.7
Sodium sulfate (Na_2SO_4)	5.2	97.2
Sodium carbonate (Na_2CO_3)	15.3	285.9
Sodium hydroxide (NaOH)	1.4	26.7
Cesium nitrate (CsNO3)	0.1	1.7
Total salt	100.0	1863.3
DI water		4069
Total mass (before evaporation)		5932
Total mass (after evaporation)		3351
Crystallization yield	36	

mass component (neither are any of the other radionuclides). To assure cesium concentrations high enough for accurate analyses, (non-radioactive) cesium nitrate was added to the other chemicals, resulting in a cesium nitrate mass fraction of about 0.1% of the total chemical mass. This level of cesium is many times greater than actual tank concentrations, but still low enough so that cesium should not precipitate into the salt cake.

The simulant was prepared by adding the mass of each salt listed in Table 1 to 4069 g of filtered deionized (DI) water. The simulant was heated on a hot plate in a fume hood under constant agitation from an impeller type mechanical stirrer. After all of the solid chemicals were dissolved the solution was evaporated at 95°C. The evaporation continued until 2580 g of water was removed. After evaporation the mixture was allowed to cool to room temperature and equilibrate with constant mixing.

The simulant was characterized prior to testing to determine the physical properties of the slurry and the filtered crystallized salt cake. Table 2 provides measured physical properties of the simulant. Physical property data were generally measured in triplicate. Data causing the standard deviation to be greater than 0.05 were considered to be outliers and were not included in the average.

Crystal washing was performed with laboratory scale glassware. A 40 mm diameter x 152 mm high glass filtration funnel with 1-micron filtration paper and a graduated cylinder (10 mL, 25 mL, or 100 mL depending on the volume of wash water) were used. Between the filtration funnel and the bottom

Table 2. Physical properties of S-112 simulant

Description	Units	Simulant batch
Bulk density	g/mL	1.45
Density of centrifuged solids	g/mL	1.49
Supernatant density	g/mL	1.44
Wt.% dissolved solids in supernatant	%	49.2
Wt.% total solids in filter cake	%	59.7
Wt.% crystallized solids in Slurry	%	16.5
Void fraction of filtered crystal cake		0.60+/−0.10
Supernatant viscosity	poise	0.118

graduated cylinder was another graduated cylinder with a Teflon valve. This setup allowed for the separation of the initial filtrate from the final filtrate in separate graduated cylinders.

Testing was conducted by adding a known mass and volume of salt slurry to the filter apparatus. Vacuum filtration started when the vacuum valve was opened, applying vacuum to the filter. Filtration continued until the filtrate slowed to approximately 1 drop every 5 seconds and the volume of permeate was measured. Vacuum was turned off and samples of the filtrate were taken.

After the initial filtration to remove the brine, a known amount of DI wash water was added to the filter cake. The wash water was distributed evenly over the salt cake with a spray bottle. Vacuum was immediately applied to pull the wash liquid through the porous salt cake. The filtrate was collected in two cuts in the two graduated cylinders. When approximately half of the filtrate was remaining, the valve on the middle graduated cylinder was closed to collect the second cut in the middle cylinder. Filtrate samples from both cylinders were taken. The density and total mass of filtrate collected was measured. In addition, all samples were measured for (non-radioactive) cesium by atomic emission on a Varian SpectrAA 800.

An underlying assumption for "Selective Dissolution" to provide a good separation of cesium during dissolution retrieval is that the cesium exists entirely, or nearly entirely, in the interstitial liquid within the salt cake. If the cesium were actually within the crystallized salt (either precipitated or as inclusions) "Selective Dissolution" could not remove that cesium until the salt dissolved.

To determine the amount of cesium that might be bound (or included) within the crystals and not washable, a second batch of slurry was prepared without any cesium. Brine from the non-cesium bearing slurry was used to wash filtered crystals from the cesium bearing slurry. For each wash the filter cake was re-suspended into the dilution wash and well mixed. The re-suspended slurry was then filtered. The filtrate volume was measured and the cesium concentration analyzed by atomic emission. The filter cake was dilution washed with fresh (non-cesium bearing) brine three times.

The efficiency of dilution washings is readily calculated based upon the Cs concentration and volume of interstitial liquid, and the volume of each wash. The cesium concentration is reduced (diluted) by the ratio of the held up interstitial liquid in the cake divided by the total liquid (wash brine plus interstitial hold up). After the crystals were washed three times they were dried, dissolved in acid, and analyzed for cesium.

RESULTS AND DISCUSSION

Table 3 shows the concentration of the cesium in the filtrate after each wash with brine and the cesium remaining in the cake after three washes. After three dilution washes approximately 0.28% (0.042 mg) of the initial Cs remained in the washed cake. Some of that cesium was deposited when the crystals were dried, as the liquid remaining from the third wash contained 0.017 mg cesium. The remaining 0.025 mg cesium, or 0.16%, must have been bound to the crystals and not washable. Expressed in the converse, >99.8% of the cesium was unbound to the salt cake and therefore separable by "Selective Dissolution," depending upon the contacting efficiency of the wash.

Table 4 contains the results from seven washing tests taking two cuts of filtrate from each test. The cesium concentrations in each of the inputs, outputs and the wash volumes for each of the cuts are shown. The volume of each wash was converted to a dimensionless wash ratio (*RW*), which is defined as the wash volume divided by the initial void volume of the cake. In Table 4 *RW* is based on the total wash volume, so for the second cut in each test the *RW* is the sum of the volumes of the first and second wash cuts.

Figure 1 is a plot of the fraction of cesium removed from the cake as a function of *RW*.

Table 3. Dilution washing with saturated brine

Stream	Wash vol. (mL)	Cesium (mg)
Separated (Cs bearing) brine	15	10.60
Wash 1	31	3.940
Wash 2	28	0.493
Wash 3	38	0.085
Crystal product	7.3 g	0.042
Cesium held in final interstitial water		0.017
Cesium "bound" in crystal product		0.025 (0.16% of initial Cs)

Table 4. Single-stage salt cake washes

	Input (unwashed filter cake)		Outputs							
			Filtrate					Washed Cake		
	Vol., mL	Total Cs, mg	Vol., mL	RW	Cs conc., mg/L	Cs, mg.	Fraction of Cs	wt., g.	Cs conc., mg/g	Cs, mg.
Test #1	32.7	10.8								
First cut			32.0	1.6	175	5.6	0.52	17.4	0.230	4.0
Second cut			14.4	2.4	84.7	1.2	0.11			
Test #2	32.7	12.4								
First cut			28.0	1.4	248	7.0	0.56	21.7	0.200	4.3
Second cut			11.0	2.0	99.0	1.1	0.09			
Test #3	32.7	11.6								
First cut			18.5	0.9	286	5.3	0.46	21.0	0.271	5.7
Second cut			9.8	1.5	64	0.6	0.05			
Test #4	32.7	11.7								
First cut			11.3	0.6	379	4.3	0.36	25.3	0.223	5.6
Second cut			12.6	1.2	146	1.8	0.16			
Test #5	32.7	12.1								
First cut			9.5	0.5	464	4.4	0.36	28.7	0.186	5.3
Second cut			10.0	1.0	238	2.4	0.20			
Test #6	32.7	9.6								
First cut			7.0	0.4	504	3.5	0.37	34.0	0.133	4.5
Second cut			4.8	0.6	324	1.5	0.16			
Test #7	32.7	10.2								
First cut			61.0	3.1	134	8.2	0.80	13.8	0.073	1.0
Second cut			12.8	3.8	81	1.0	0.10			

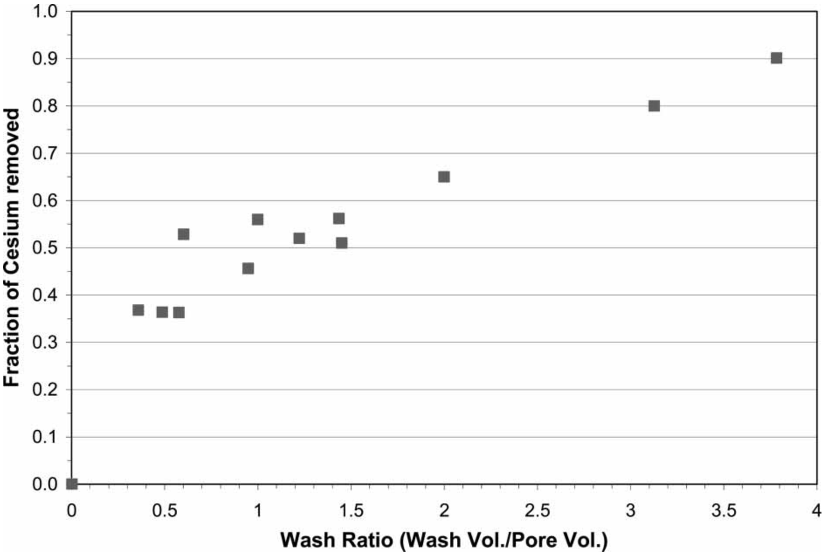

Figure 1. Laboratory single-stage salt cake washes.

Axial Dispersion Modeling of Single Stage Salt Cake Washes

To model the axial dispersion during washing we assumed the salt cake behaves as a porous medium. Flushing of solute-saturated liquid in a slab of porous medium by unsaturated liquid can be approximately described by (6)

$$\frac{\partial S}{\partial t}+\frac{\partial}{\partial x}\left(US-E_x\frac{\partial S}{\partial x}\right)=0 \tag{1}$$

where S is a species concentration in solution, U is liquid flow velocity, E_x is the axial dispersion coefficient, x is distance into the porous slab, and t is time. In Equation (1), the flux of the species in solution is the sum of an advective transport contribution and a dispersion term:

$$J_x = US - E_x\frac{\partial S}{\partial x} \tag{2}$$

The axial dispersion term (containing E_x) describes the spreading of concentration profiles in the flow direction due to non-uniformity of flow, originating from laminar flow in pores, from structure- and turbulence-induced eddying, and from molecular diffusion. If we take S as C_{Cs}, the concentration of cesium in interstitial liquid, and $C_{Cs,0}$ its value prior to the introduction of wash water, and take E_x as constant, a solution to Equation (1) is (3)

$$C_{Cs}(x, t) = C_{Cs,0}\frac{1}{2}\left[1 + erf\,\frac{x - Ut}{\sqrt{4E_x t}}\right] \tag{3}$$

Initial and boundary conditions satisfied by Eq. (3) are C_{Cs} $(x > 0, t \downarrow 0) = C_{Cs,0}$, and C_{Cs} $(x = 0, t > 0) = 0$. This describes the addition of wash water containing no Cs into the initial Cs-contaminated pore liquid.

Equation (3) can be re-expressed in terms of a dimensionless distance $z = x/L$ and a dimensionless time $\theta = t/t_{transit} = t/[L/U] = Ut/L$. Here $t_{transit} = L/U$ is a typical liquid transit time through the saltcake slab of thickness L. The dimensionless time θ has a useful alternate interpretation, which follows from an expression for the volumetric flow rate, Q, through the porous slab whose geometrical cross section is A and whose liquid-filled pore fraction is ϕ:

$$Q = A_{interstitial} \times U = A\phi U \tag{4}$$

$$\theta = \frac{U}{L}t = \frac{Q/(\phi A)}{L}t = \frac{V}{\phi AL} = \frac{\text{Volume flowed}}{\text{Interstitial liquid volume}} = RW \tag{5}$$

Equation (5) defines the dimensionless "wash ratio", RW, or the ratio of the transmitted volume to the liquid-filled pore volume.

Equation (3) can be expressed in a form useful for the analysis of data as

$$C_{Cs}(z, \theta) = C_{Cs.0}\frac{1}{2}\left[1 + erf\,\frac{z - \theta}{\sqrt{4\tilde{D}\theta}}\right] \tag{6}$$

where θ is now interpreted as the wash ratio RW, and $\tilde{D}$ is $E_x/(UL)$. Note, of course, that Equation (6) applies rigorously only if E_x, U, and L are constant. This is certainly not the case in the flushing of salt cake by liquid, in which the size and shape of pores is altered during the flushing. Nevertheless, Equation (6) is useful in the interpretation of data. The $E_x/(UL)$ parameter, the axial dispersion number, is useful in fitting experimental data over finite time periods by the idealized forms of Equations (3) or (6), for insights into the non-idealized processes (like channel formation or pore enlargement) which were shown to occur during these experiments.

Useful quantities predicted by Equations (3) or (6) are the instantaneous concentrations of the exiting fluid (at $z = 1$ and varying t or θ), and also

$$M_{Cs} = \int_0^t J_x A\phi\, dt \quad \text{Amount of Cs flushed (evaluated at } x = \text{L}, \text{ or } z = 1) \tag{7}$$

$$M_{Cs}/M_{Cs,0} = M_{Cs}/(C_{Cs,0}AL\varphi) \text{ Fraction of initial interstitial Cs flushed} \tag{8}$$

Combining Eqs. (2–8) we get an expression for the fraction of Cs flushed from the salt cake as a function of the wash ratio, θ.

$$\text{Fraction of initial } Cs = \int_0^{\theta} \left\{ \frac{1}{2}\left[1 + erf\,\frac{z-\theta}{\sqrt{4\tilde{D}\theta}}\right] - \tilde{D}\frac{1}{\sqrt{\pi}} \exp\left[-\left(\frac{z-\theta}{\sqrt{4\tilde{D}\theta}}\right)^2\right]\frac{1}{\sqrt{4\tilde{D}\theta}}\right\} d\theta \qquad (9)$$

Application of Axial Dispersion Model to Salt Cake Washing

Figure 2 shows the predicted cesium concentrations (as a fraction of the cesium concentration in the original interstitial liquid) as the salt cake is washed with increasing volumes of water, expressed as wash ratios, *RW*. All cases show that the initial liquid to leave the salt cake contains cesium at the concentration in the interstitial liquid. If the axial dispersion is very low the interstitial liquid continues at the original cesium concentration until about one void volume has been displaced and then the concentration quickly drops to near zero. If axial displacement is high the concentration drops right away after the washing begins, but does not drop as rapidly. The cesium concentration in the wash liquid only approaches zero at very high wash ratios.

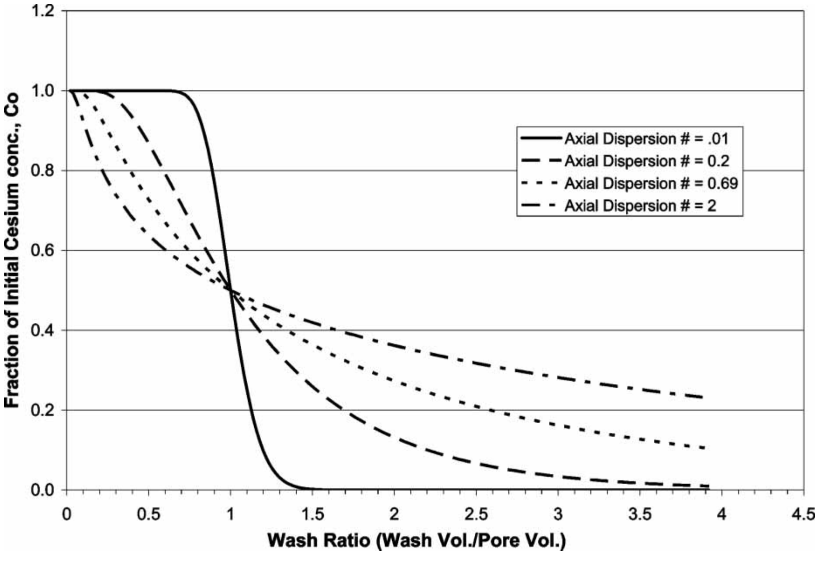

Figure 2. Cesium concentration in retrieved liquid.

Figure 3 shows the model predictions for cumulative Cs removal for four different axial dispersion numbers, $\check{D} = E_x/UL$, superimposed on the laboratory data from Fig. 1. A low axial dispersion number approaches plug flow where the wash water pushes the interstitial water in front of it with almost no mixing between the wash liquid and the original interstitial liquid. The liquid leaving the cake is completely interstitial liquid until one pore volume of liquid has been retrieved and then there is a sharp transition to added wash liquid and the cesium concentration drops to zero. As the axial dispersion number increases there is more mixing of the original brine and the washing liquid so that the amount of cesium recovered is reduced at any given wash ratio, *RW*. The curves begin to break off from the nearly plug flow curve at lower fractions of cesium removed. All the curves will eventually approach recovering all of the cesium, but the curves for high axial dispersion numbers do not approach full cesium recovery until high wash ratios. Washes with very low dispersion numbers show that nearly all of the cesium is recovered within approximately the first pore volume ($RW = 1$)—as would be expected for perfect plug flow. At higher wash ratios the slope of the curve is flat showing that no more cesium is recovered; it has all been displaced.

The laboratory data fit best with an intermediate axial dispersion number, 0.69, but the fit is less than satisfying. Early in the washing, for wash ratios up to about 0.5, the model under predicts the rate at which cesium is removed from the cake. At higher wash ratios the model over predicts the cesium that is removed. The curve of the model is leveling off, but the last four data points seem to be continuing up at a slope more like the slope of the

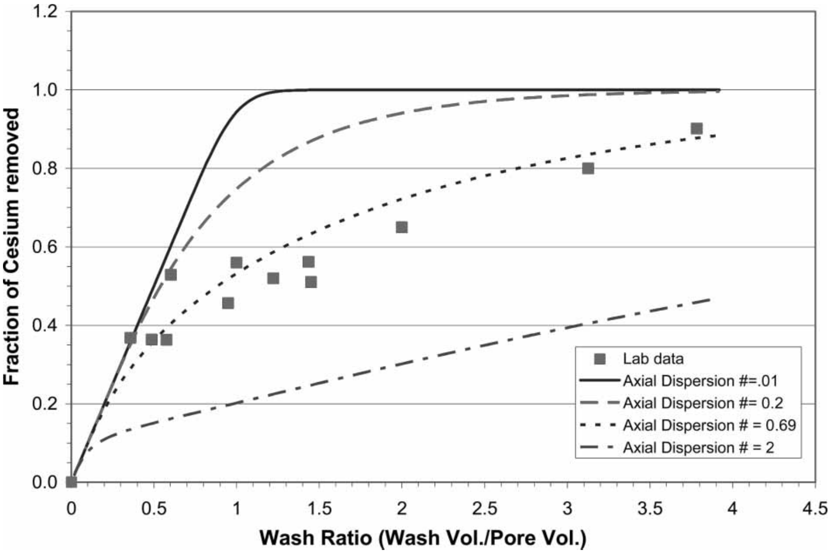

Figure 3. Fraction of cesium removed by washing.

model with an axial dispersion of 2. Early in the washing, the shape of the data is closer to the model with a low axial dispersion number; and later in the washing the data look more like the model with an axial dispersion number about an order of magnitude higher.

One would intuitively expect such behavior when the washing dissolves salt cake and changes the character of the porous media. As the salt dissolves, flow paths are enlarged, but not uniformly throughout the cake. Larger flow paths flow faster, causing U to increase locally and leading to fractions of the water moving faster, in effect increasing axial dispersion.

Figure 4 shows the axial dispersion model when the RW range has been divided into five sections each with a different axial dispersion number. The five sections of the model curve are based on *RW* ranges of $0 \rightarrow 0.25$, $0.25 \rightarrow 0.5$, $0.5 \rightarrow 1.0$, $1.0 \rightarrow 2.0$, and > 2.0. Initially, the axial dispersion number is low and was selected to be a good visual fit to the initial data points, starting at 0.25. Above a wash ratio of 2 the largest axial dispersion number was selected to be a good visual fit to the last three data points, 1.5.

For this simple analysis the axial dispersion number is increased proportionately between the selected initial and final axial dispersion numbers. At the transition points (e.g. 0.25, 0.5, 1.0, and 2.0) the solution for the higher axial dispersion segment is forced to have a value equal to the value of the end point for the previous segment. This is the simplest of splining techniques. Referring to Fig. 3, the model with an axial dispersion of 0.69 has a value of about 0.55 at an *RW* of 1.0. The model with an axial dispersion of

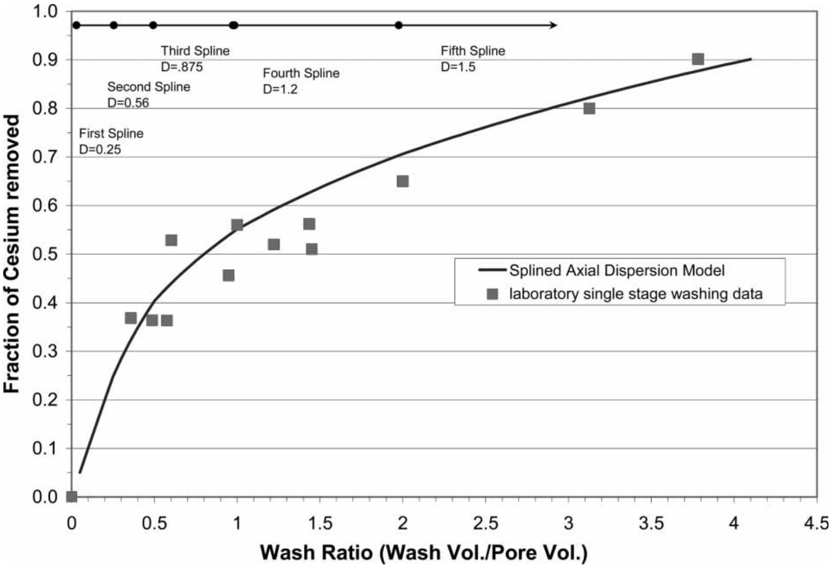

Figure 4. "Splined" axial dispersion model fit to lab data.

2.0 has a value of about 0.2 at the same *RW*. If we were to transition from the model segment for a 0.69 axial dispersion number to the model segment for a 2.0 axial dispersion at an RW of 1.0 we would add 0.35 to the model value calculated for the 2.0 axial dispersion number. The splined model would have the slope of the model with a 2.0 axial dispersion number, but with a higher cesium recovery attributed to the better washing and lower axial diffusion at lower wash ratios.

Mathematically, the solution to the axial diffusion differential equation is only correct for a constant axial dispersion number, $\tilde{D}$. This technique holds the axial dispersion number constant over a range, which is consistent, but artificially forces a fit of the cesium recovery at the transition points.

One must be careful applying this tool, because the splined Cs recovery fraction model is no longer constrained to be $<= 1.0$. If you add 0.35 to the final segment to match the transition point, the maximum recovered cesium will approach 1.35 as $RW \rightarrow \infty$. Obviously, one cannot recover more cesium than originally was in the cake.

The number of segments, selection of transition points, and how one adjusts the increase in axial dispersion number as washing progresses are all variables that one could select to get a good fit for almost any set of data. For these data, we selected simple transitions and the selections, other than the initial and ending dispersion numbers, were admittedly arbitrary. The key to whether this approach is a worthwhile tool is whether one can apply the same "splined" model fitted to one set of lab data and have it reasonably match another set of data. More importantly, can the "splined" model approximating laboratory data actually be used to match or predict selective dissolution of an actual tank retrieval?

Application of Axial Dispersion "Splined" Model to Hanford Retrieval of S-112

Tank S-112 is one of 149 single shell tanks (SSTs) on the Hanford site. The tank is 75 ft. in diameter and 30 ft. tall, with a total capacity of approximately 1 million gallons. Before retrieval the tank contained approximately 614,000 gallons of salt cake waste. The salt cake surface had a mildly inverted cone shape being 170 in. deep at the center of the tank and 235 in. deep near the outer edge. The bottom 100 in. of salt cake were hydraulically saturated with brine.

The primary water distribution system included three remote water distribution nozzles installed around the tank periphery about 30 ft. from the center and 120° apart. (A second distribution system employing an automatic commercial tank cleaning system was also installed. Nearly all of the S-112 dissolution was accomplished using the primary system, so the secondary system has been ignored.) Each of the remotely controlled nozzles had the capability to direct a relatively forceful, solid stream of water at 50 gpm over a range of at least 30 feet. The direction of the stream could be rotated 90 degrees in elevation (straight down to horizontal) and 360 degrees in azimuth by an operator in the control trailer. The operator could view the waste retrieval via two in-tank video cameras installed 9 ft. north and 6 ft. south of tank center.

Figure 5 shows the location of the spray nozzles in the tank (identified by riser number) and a simple elevation of the tank showing the profile of the original waste (8).

Brine containing the dissolved salt cake was pumped through a progressive cavity pump located about 6 ft. from the center of the tank. The inlet of the pump was approximately 2 in. off the tank bottom and the bottom was slightly

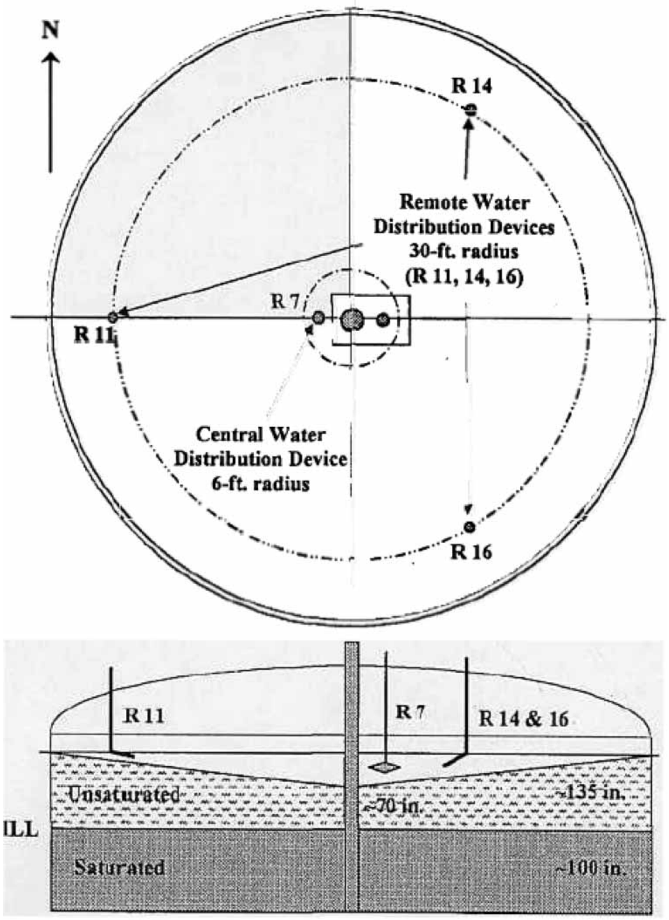

Figure 5. S-112 tank equipment configuration.

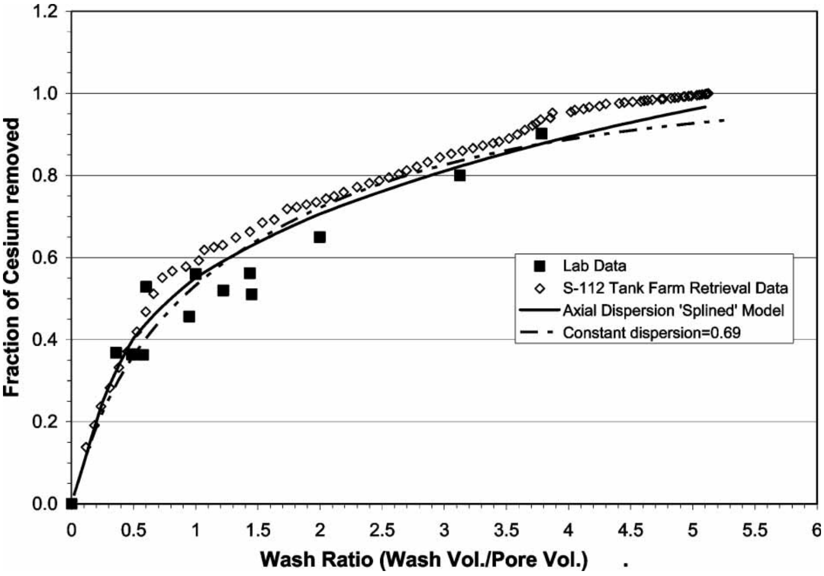

Figure 6. S-112 Selective dissolution data with "splined" axial dispersion model.

conical so essentially all of the liquid draining from the salt cake could be pumped.

Brine was pumped through a Coriolis flow meter that monitored discharge volume and specific gravity (Sp. Gr.). The specific gravity was controlled to 1.35 or less to prevent any potential for crystallization and plugging of the lines if flow of the solution had to be stopped. The cesium content of the discharge brine was calculated from an in-line gamma detector, using a NaI scintillation counter.

Retrieval of S-112 began on Sept. 28, 2003 and data were collected over a period of 16 mos. until about 95% of the original waste was retrieved. Figure 6 shows the concentration of cesium in the retrieved brine (corrected to a constant 1.35 Sp.Gr.) and the "splined" axial dispersion model predictions based upon the lab scale washing.

The similarity of the laboratory data based upon small scale samples (<100 mL) is quite surprising when compared to full-scale retrieval of a Hanford tank containing over 2,000,000 L of salt cake waste.

CONCLUSION

Selective dissolution during retrieval of Hanford salt cake tanks may be an important pretreatment for preparation of Low Curie waste to be immobilized by Supplemental treatments. How effective Selective Dissolution will be for removing cesium to meet the definitions of Low Curie waste has been only speculated and no viable tool has been developed to predict even gross approximations of the Selective Dissolution as it will occur during retrieval. This technique, nicknamed "splined" axial dispersion modeling, could be a valuable tool for predicting Selective dissolution.

It is somewhat surprising, and perhaps only coincidental, that the "splined" axial dispersion model fitted to lab scale data could fit full-scale tank data so closely. It will take some additional testing and comparisons to verify whether the good agreement found here is rooted in fundamentals that span over 6 decades of scale or is a single happenstance.

NOMENCLATURE

A	flow area, (m^2)
C_{Cs}	concentration of cesium in liquid, (Ci/L)
$\check{\mathrm{D}}$	axial dispersion number, $=E_x/UL$
E_x	axial dispersion coefficient, (m^2/sec)
erf	error function
J_x	flux of species, [species quantity(Ci)/(area*sec)]
L	total length of porous media, (m)
M_{cs}	total quantity of cesium, (Ci)
MT	metric tons mass
Q	volumetric flow rate, (m^3/sec)
RW	dimensionless wash ratio, defined in equation (5).
S	concentration of solute in liquid, Ci/L or mg/L
S_0	fractional concentration of solute in liquid at time = 0
t	time, (s)
U	liquid velocity, (m/s)
V	volume, (m^3)
x	distance into porous media, (m)
z	dimensionless length, $= x/L$
ϕ	void fraction of porous media, dimensionless
θ	dimensionless time, $= U/L \times t$

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