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R. J. Serne
V. L. LeGore

January 1996

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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Executive Summary

Characterization data obtained on 12 new boreholes at the 100-N Area of the Hanford Site have improved our understanding of the distribution of Strontium-90 (^{90}Sr) within the aquifer and the overlying vadose zone sediments. The bulk of the ^{90}Sr that in sediments not directly underlying the Liquid Waste Disposal Facilities (LWDF) is found bound to sediments in a relatively thin layer at depths that correspond to the top of the elevated water table formed during the period of active disposal from 1963 to 1991 and the current water table. The narrow layer is as thin as 5 to 10 feet near the Columbia River, and as thick as 40 feet near to the LWDF. Considerable amounts of ^{90}Sr reside above the current water table.

Adsorption-desorption tendencies and key geochemical issues for ^{90}Sr interactions with Hanford sediment and groundwater were evaluated using several laboratory test methodologies. The data clearly show that ^{90}Sr adsorption-desorption is reversible, that the Kd construct is applicable to describing the adsorption-desorption, and that time has not made the ^{90}Sr more recalcitrant to leaching off the sediments compared to strontium nuclides recently adsorbed to Hanford sediments in laboratory studies. The strontium reactions between the Hanford sediment and groundwater appear to be controlled by simple ion exchange.This process is readily characterized and modeled by well known mathematical constructs. This knowledge and improved understanding of the existing hydrogeology and ^{90}Sr distribution in the 100-N Area subsurface will allow accurate predictions of the fate of ^{90}Sr to be performed using available models/computer codes. The kinetics of the adsorption-desorption reaction for ^{90}Sr with Hanford sediment and groundwater from 100-N Area is quite rapid with equilibrium occurring somewhere between 2 hours and 2 days. Thus, the assumption of local equilibrium used in all simple modeling exercises is reasonable for the ^{90}Sr issue at the 100-N Area.

Unfortunately from the standpoint of using leaching or pump-and-treat, the ^{90}Sr is selectively bound to the Hanford 100-N Area sediment with a Kd value of at least 15 ml/g for the bulk coarse-grained sediment. A Kd as high as 15 ml/g will make it difficult, time-consuming, and expensive to cleanse the aquifer sediments using pump-and-treat with natural groundwater as the leaching fluid. The value of the Kd found in over 80 separate tests ranged from a value of ~15 to a value of 40, depending on the particle size distribution and location of the coarse-grained sediment from the Hanford and Upper Ringold E Unit formations. The finer grained the sediment the higher the Kd value. Actual flow-through leach tests of bulk coarse grained sediment from the most contaminated borehole yielded Kd values of 15 ml/g and should simulate most closely a pump-and-treat process.

Using a simple algorithm for reversible ion-exchange and a constant Kd value of 15 ml/g, we performed calculations to estimate how long it would take to remove various percentages of the ^{90}Sr estimated to be present currently in the aquifer. Using the estimated size of the existing plume and two pump rates (50 gpm, the current field demonstration value, and 180 gpm, the maximum design value) it would take about 90 and 75 years (these calculations include natural radioactive decay), respectively, to remove 90% of the ^{90}Sr. Ninety percent removal is the Tri-Party target goal. It would take about 27 and 23 years, respectively, at these pump rates to remove 50% of the ^{90}Sr currently in the aquifer. Natural radioactive decay will "remove" 90% of the ^{90}Sr in 95 years and 50% of the ^{90}Sr in 29 years, which

suggests that groundwater extraction at the stated pump rates will not substantially improve the removal of ^{90}Sr at 100-N Area.

This report includes a discussion of why the efficiency of field-scale pump-and-treat is likely to be much less effective than the laboratory column results. Thus, the estimates of time needed to remove ^{90}Sr (presented above) are optimistic minimum values. The Kd for ^{90}Sr binding to the Hanford sediments could be reduced such that removal would be easier by injecting solutions with higher concentrations of competing cations such as Ca and Mg, or less effectively, Na and K. Unfortunately, use of the competing ions would also challenge the ability of the ex situ water treatment using clinoptilolite or other exchange media to remove the leached ^{90}Sr from the fluid withdrawn from the aquifer. Another water treatment process such as chemical precipitation would be a logical choice for water treatment.

Acknowledgments

The authors wish to acknowledge the support of Bechtel Hanford Inc.'s 100-N Remedial Actions Project Manager Merl J. Lauterbach for the funding to perform this work and Jane V. Borghese for preparing the Statement of Work and facilitating the contract. We also wish to thank Ron Jackson, Ed Shorey, Bruce Ford, Tony Knepp, and Mike Connelly for many useful discussions and critiques on the proposed laboratory tests. We are especially grateful to Randy Havenor and Les Walker for coordinating the sample collection and transfer to Pacific Northwest National Laboratory and their help in identifying the location of the historic high water table and the existing water table, and field radionuclide monitoring results. All of this helped us decide quickly which subsamples warranted more characterization. Steve J. Trent, L. C. (Craig) Swanson, James M. Faurote, and Kirk J. Cantrell provided detailed technical review on the report.

The authors also wish to acknowledge the help of S.V. Mattigod of Pacific Northwest National Laboratory, who generated several of the figures used in Sections 4.0 and 5.0 of this report.

The authors acknowledge editorial review by Rosalind Schrempf, and final word processing by Jean Cheyney of Pacific Northwest National Laboratory.

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1.0 Introduction

Strontium-90 (^{90}Sr) has been seeping into the Columbia River since the early 1980s (BHI 1995). The likely source is subsurface migration of ^{90}Sr from once-through cooling water from the Hanford N Reactor disposed into the two disposal crib/trench facilities, 1301-N and 1325-N. Knepp et al. (1995), DOE/RL(1995), and Alexander and Johnson (1993) provide background information on the operational history of the two liquid waste disposal facilities and some of the regulatory drivers that have lead to the various characterization activities and remediation demonstrations being performed to help choose future full-scale remediation alternatives. The work presented in this topical report had two main objectives.

First, we obtained numerous borehole samples from newly installed wells/borings and performed physical and chemical characterization that included particle size analysis, moisture content, and Strontium-90 (^{90}Sr), Tritium (^{3}H), and gamma activity analyses to help improve the conceptual model of where the contaminants currently reside in the sediments. The second objective was to perform laboratory adsorption-desorption tests using both batch and flow- through column techniques to gather data for use in contaminant transport conceptual models and to aid in specific pump-and-treat calculations needed to interpret a field demonstration (BHI 1995 provides details on the pump-and-treat demonstration.)

Some of the data have been reported previously (Knepp et al. 1995, Johnson et al. 1995, and Miller et al. 1995); however, in this report we have combined all the data and provide comment in regard to the two main objectives stated above.

Throughout the report depths for the sediment samples obtained from the boreholes are referred to in the English units of feet below ground surface (ft. bgs) instead of metric units as preferred in scientific publications. These were the designations provided from the field geologists and we did not choose to perform conversions.

Throughout this document wherever precision ranges (± values) are given, the values refer to one standard deviation about the arithmetic mean values.

2.0 Sediment and Groundwater Characterization

2.1 Description of Borehole Samples

Sediment samples from the eight boreholes placed along the Columbia River near N Springs and three boreholes placed nearer to the liquid waste disposal facilities (LWDF) were collected by the Environmental Restoration Company (ERC) employees and transported to Pacific Northwest National Laboratory (Northwest National Laboratory). Figure 2.1 shows the location of the new wells/boreholes in relation to older wells and facilities. For the eight boreholes along the Columbia River, ERC field geologists placed the drive barrel cuttings samples in either 1-L or 2-L wide-mouthed, high-density polyethylene jars with screw-top lids. For three boreholes nearer the disposal facilities, the split-spoon samples were shipped directly to Northwest National Laboratory inside the steel liners in which they were collected. Upon receipt, the samples were inventoried (Table 2.1) and decisions were made about which samples would be used for radionuclide analyses and ^{90}Sr adsorption-desorption testing. Samples were selected based on the available drilling logs, field radioactivity readings, and visual inspection of particle size. It became clear early that for the eight boreholes along the Columbia River, boreholes N-94A and N-95A contained the highest radioactivity. For the three boreholes near the disposal cribs, hand-held radiation detection instruments showed that boreholes N-103A and especially N-105A contained relatively high amounts of radioactivity. Therefore, more characterization and testing were performed on samples from these four boreholes and less work was performed on samples from the other boreholes.

Table 2.1 lists all the samples received and identifies those samples that were sieved (after air-drying) to obtain the <2 mm-sized material traditionally used to perform analyses and sorption tests. After sieving, the <2-mm-sized material was oven-dried at 105° C to constant weight. Oven-dried samples were subjected to gamma energy analyses, ^{90}Sr analysis, adsorption testing, and desorption testing. The numbers in each box of Table 2.1 refer to the number of analyses performed. That is, duplicates, or in some cases up to 6 aliquots, were used from the original sample to obtain data. The replication allows some measure of precision or reproducibility to aid in evaluating the data.

Just before this report was finalized, data from four samples were made available for borehole N-106A, which has been found to be the best well for extracting ^{90}Sr-laden groundwater out of the contamination plume. Strontium-90 and gamma energy analyses for four depth intervals were performed by Quanterra Environmental Services, Richland, Washington for Bechtel Hanford, Inc. (BHI). These data have been included here.

2.2 Dry Sieving

Samples in the column labeled "sieved" in Table 2.1 were removed from the wide- mouth jars (boreholes 94A-97A) or from the split tube samples (boreholes 103A-105A) and air- dried to constant weight using the standard method of Gardner (1986). The dried material was then sieved through two screens,

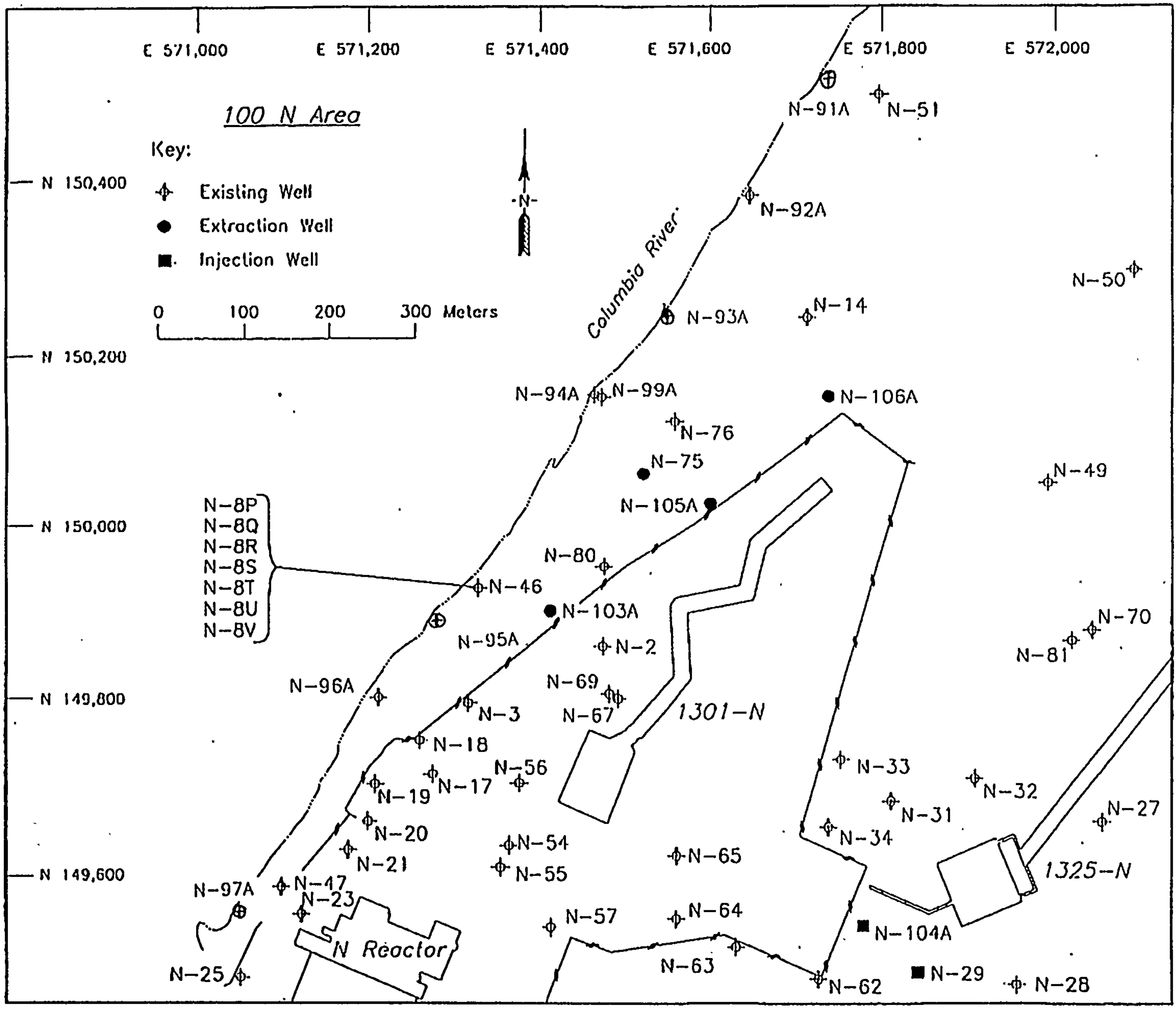

Figure 2.1. Location of New Boreholes, Existing Boreholes, and Facilities at the 100-N Area

Table 2.1. Sample/Analyses Inventory

Borehole Samples and Analyses Performed							
Borehole	Depth(ft) below ground surface	Sieved	Gamma Energy Analysis	^{3}H	^{90}Sr	K_d Adsorption	K_d Desorption
N-91A	5						
	10-11.5	1	1		2		
	15	1	1		1		
	20	1	1		1		
	25						
	30						
	35						
	40						
	45	1	1		1		
	50						
	55						
	60						
N-92A	5						
	10						
	15	1	1		1	1	
	20	1	1		1		
	30						
	35						
	40						
	45	1	1		1	1	
	50						
N-93A	5	1	1	1	1		
	10	1	1	2	1	1	3
	15	1	1	2	2	1	3
	20						
	25						
	30						
	35	1	1	1	1	1	
	40						
N-94A	5	1	1	1	2		
	10-11.5	1	1	1	3	3	6
	15-17	1	1	1	2	3	6

Table 2.1. (contd)

Borehole Samples and Analyses Performed							
Borehole	Depth(ft) below ground surface	Sieved	Gamma Energy Analysis	^{3}H	^{90}Sr	K_d Adsorption	K_d Desorption
N-94A	25-27	1	1	1	2		
	32	1	1	1	1		
	37						
	40						
	45	1	1	1	1	3	
	51.5						
	52.5						
	61.5						
N-95A	5	1	1	1	2		
	10-11.0	1	1	1	2	3	6
	15.5	1	1	1	3		3
	20	1	1	1	2	3	6
	25-26.5	1	1	1	2		
	30						
	35-39	1	1	1	2	3	
	40						
	43						
N-96A	5						
	10-11.5	1	1	1	1	3	
	15-17	1	1	2	1		
	20.5-22	1	1	2	1	3	
	25-26.5	1	1	1			
	30-32						
	35						
	40						
	45-46	1	1	1	1	3	
	55						
	60						
N-97A	0						
	5						
	9.5-11	1	1			1	
	14-16	1	1		1	1	

Table 2.1. (contd)

Borehole Samples and Analyses Performed							
Borehole	Depth(ft) below ground surface	Sieved	Gamma Energy Analysis	^{3}H	^{90}Sr	K_d Adsorption	K_d Desorption
	20-21.5	1	1		1		
N-97A	25						
	30						
	35-36.5	1	1		1	1	
N-103A	55-56.5	1			1		
	60.5-61.5	1			1		
	65-65.5	1			5		2
	66	1			1		1
	70-71.5	1			1		
	71.5-72	1			1		
	75-76.5	1			1		
	76.5-77	1			1		
	81-81.5	1			1		
	81.5-82	1			1		
	86-86.5	1			1		
	86.5-87	1			1		
	91-91.5	1			1		
	91.5-92	1			1		
	95.5-96	1			1		
	96.5-97	1			1		
N-104A	58.5-59.5	1			1		
	64-65	1			1		
	69-70	1			1		
	74-75	1			1		
	79.5-80.5	1			2		
	84-84.5	1			1		
	89.5-90.5	1			1		
N-105A	40	1			1		
	45	1			1		
	51-52	1			5		10
	54.5-55.5	1			1		2
	59.5-61.5	1			1		2

Table 2.1. (contd)

Borehole Samples and Analyses Performed							
Borehole	**Depth(ft) below ground surface**	**Sieved**	**Gamma Energy Analysis**	**^{3}H**	**^{90}Sr**	**K$_d$ Adsorption**	**K$_d$ Desorption**
	66-67	1			1		
	71-72	1			2		
N-105A	74-75	1			1		
	80-81	1			1		
	85.5-86.5	1			1		
	90.5-91.5	1			1		
	96-97	1			1		
N-106A	73-75		1		1		
	83-85		1		1		
	96-98		1		1		
	105-108		1		1		

one 13.2 mm and one 2 mm, yielding the three fractions shown in Table 2.2. In most instances, the <2 mm-sized material was used in the analyses and sorption testing, except for the tritium analyses and some of the desorption testing on samples fromboreholes 103A-105A.

Data in Table 2.2 show that the sediments from the shallow depths in all the boreholes adjacent to the Columbia River (N-91A to N-97A) are rather coarse, with 25 to 60% of the weight greater than 13.2 mm (pebbles, cobbles and boulders), and only 18 to 50% of the weight less than 2 mm (sand, silt, and clay). At depths of 25 to 45 feet in all boreholes, except N-96A, there is a distinct change in particle size to material that is essentially all less than 2 mm. These data confirm field logs that suggest these depths are the contact with the Ringold Upper Mud Unit. In borehole N-96A, 19 ft of berm/backfill was placed over the drill site before drilling. Thus, drilling did not go deep enough into the natural strata to find contact with the Ringold upper mud unit, which is actually found deeper than the borehole N-96A samples that were sieved.

For the three boreholes farther inland and closer to the LWDF, the contact between the surficial Hanford formation sediments and the Ringold Unit E appears to occur between the 55- and 60-ft. samples in borehole N-103A and between the 45- and 52-ft. samples in borehole N-105A, based on a discontinuity in greater than 13.2-mm-sized material. The Hanford formation contains less of the larger pebbles, cobbles, and boulders and more or about the same percentage of sand, silt, and clay as the Ringold Unit E contains. The contact between the Ringold Unit E and the Ringold Upper Mud units appears to occur at about the 85-ft. depth in borehole N-103A and at about 95 ft. in borehole N-105A, based on a significant drop in very coarse material and a significant increase in sand, silt, and clay-sized material. Borehole

Table 2.2. Particle Size Distribution and Moisture Content

Borehole ID	Sample Depth (ft) bgs	Air-Dried Fractions Fraction Size (mm)	Fraction wt (grams)	Fraction %	Moisture Content % (wt)
N-91A	10-11.5	> 13.2	982.34	42.07%	
		2 - 13.2	605.49	25.93%	
		< 2	708.22	32.00%	
	15	> 13.2	1650.25	56.16%	
		2 - 13.2	464.08	15.79%	
		< 2	767.81	28.04%	
	20	> 13.2	1424.46	60.75%	
		2 - 13.2	485.6	20.71%	
		< 2	365.02	18.54%	
	45	> 13.2	0	0.00%	
		2 - 13.2	168.89	12.82%	
		< 2	1107.81	87.18%	
N-92A	15	> 13.2	485.94	28.04%	
		2 - 13.2	334.58	19.31%	
		< 2	860.73	52.65%	
	20	> 13.2	54.27	3.56%	
		2 - 13.2	19.77	1.30%	
		<2	1390.9	95.14%	
	45	> 13.2	0	0.00%	
		2 - 13.2	0	0.00%	
		< 2	775.7	100.00%	
N-93A	5	> 13.2	478.45	25.39%	
		2 - 13.2	594.58	31.56%	
		< 2	738.58	43.05%	
	10	> 13.2	665.82	38.37%	
		2 - 13.2	437.05	25.18%	
		< 2	572.45	36.45%	
	15	> 13.2	501.75	33.27%	
		2 - 13.2	119.09	7.90%	
		< 2	827.64	58.83%	

Table 2.2. (contd)

Borehole ID	Sample Depth (ft) bgs	Air-Dried Fractions Fraction Size (mm)	Fraction wt (grams)	Fraction %	Moisture Content % (wt)
N-93A	35	> 13.2	0	0.00%	
		2 - 13.2	44.09	4.67%	
		< 2	832.38	95.33%	
N-94A	5	> 13.2	1198.25	46.82%	
		2 - 13.2	596.34	23.30%	
		< 2	674.55	29.87%	
	10-11.5	> 13.2	869.92	31.49%	
		2 - 13.2	969.33	35.09%	
		< 2	837.81	33.42%	
	15-17	> 13.2	1220.62	40.19%	
		2 - 13.2	766.08	25.22%	
		< 2	941.56	34.59%	
	25-27	> 13.2	1068.88	37.33%	
		2 - 13.2	559.33	19.53%	
		< 2	1121.35	43.14%	
	32	> 13.2	0	0.00%	
		2 - 13.2	158.1	5.76%	
		< 2	2493.17	94.24%	
	45	> 13.2	0	0.00%	
		2 - 13.2	186	11.31%	
		< 2	1397.38	88.69%	
N-95A	5	> 13.2	1252.46	37.04%	
		2 - 13.2	753.66	22.29%	
		< 2	1320.41	40.67%	
	10-11	> 13.2	1892.4	55.30%	
		2 - 13.2	740.4	21.64%	
		< 2	734.69	23.07%	
	15	> 13.2	1495.11	51.81%	
		2 - 13.2	569.82	19.74%	
		< 2	749.23	28.45%	

Table 2.2. (contd)

Borehole ID	Sample Depth (ft) bgs	Air-Dried Fractions			Moisture Content % (wt)
		Fraction Size (mm)	Fraction wt (grams)	Fraction %	
N-95A	20	>13.2	991.28	40.59%	
		2 - 13.2	619.82	25.38%	
		< 2	733.96	34.03%	
	25-26.5	>13.2	1534.08	55.95%	
		2 - 13.2	458.25	16.71%	
		< 2	643.66	27.33%	
	39	>13.2	215.85	11.07%	
		2 - 13.2	147.5	7.57%	
		< 2	1533.89	81.36%	
N-96A	10-11.5	>13.2	988.98	34.82%	
		2 - 13.2	378.24	13.32%	
		< 2	1410.66	51.87%	
	15-17	>13.2	1073.31	37.43%	
		2 - 13.2	858.4	29.94%	
		< 2	864.04	32.63%	
	20.5-22	>13.2	1907.35	78.38%	
		2 - 13.2	218.59	8.98%	
		< 2	228.35	12.63%	
	25-26.5	>13.2	970.9	35.40%	
		2 - 13.2	867.98	31.65%	
		< 2	849.3	32.95%	
	45-46	>13.2	1335.34	53.44%	
		2 - 13.2	622.82	24.92%	
		< 2	491.6	21.64%	
N-97A	9.5-11	>13.2	767.74	39.13%	
		2 - 13.2	689.99	35.17%	
		< 2	438.82	25.70%	
	14-16	>13.2	1513.77	50.92%	
		2 - 13.2	782.51	26.32%	
		< 2	612	22.75%	
	20-21.5	>13.2	1055.09	49.77%	
		2 - 13.2	452.71	21.35%	
		< 2	531.83	28.88%	

Table 2.2. (contd)

Borehole ID	Sample Depth (ft) bgs	Air-Dried Fractions Fraction Size (mm)	 Fraction wt (grams)	 Fraction %	Moisture Content % (wt)
N-97A	35-36.5	>13.2	0	0.00%	
		2 - 13.2	0	0.00%	
		< 2	1756.02	100.00%	
N-103A	55-56.5	>13.2	838.78	13.86%	4.67%
		2 - 13.2	2015.78	33.30%	
		< 2	3198.56	52.84%	
	60.5-61.5	>13.2	2364.78	40.49%	1.49%
		2 - 13.2	1296.78	22.20%	
		< 2	2179.56	37.31%	
	65-65.5	>13.2	1851.78	44.94%	1.97%
		2 - 13.2	947.78	23.00%	
		< 2	1320.78	32.06%	
	70-71.5	>13.2	2289.78	46.71%	2.72%
		2 - 13.2	1490.78	30.41%	
		< 2	1121.78	22.88%	
	75-76.5	>13.2	2457.78	40.85%	6.82%
		2 - 13.2	1756.78	29.20%	
		< 2	1802.56	29.96%	
	81-82	>13.2	1404.78	30.09%	5.79%
		2 - 13.2	1636.78	35.06%	
		< 2	1626.78	34.85%	
	85-87	>13.2	293.21	7.84%	14.37%
		2 - 13.2	800.80	21.42%	
		< 2	2645.22	70.74%	
	95.5-97	>13.2	2232.78	47.69%	6.18%
		2 - 13.2	1228.78	26.24%	
		< 2	1220.56	26.07%	
N104-A	58.5-59.5	>13.2	1880.78	40.86%	4.82%
		2 - 13.2	626.78	13.62%	
		< 2	2095.56	45.52%	
	64.0-65.0	>13.2	1208.78	31.06%	5.22%
		2 - 13.2	958.78	24.63%	
		< 2	1724.56	44.31%	

Table 2.2. (contd)

Borehole ID	Sample Depth (ft) bgs	Air-Dried Fractions			Moisture Content % (wt)
		Fraction Size (mm)	Fraction wt (grams)	Fraction %	
N-104A	69.0-70.0	>13.2	1779.78	45.66%	1.62%
		2 - 13.2	576.78	14.80%	
		< 2	1541.56	39.55%	
	74.0-75.0	>13.2	0.00	0.00%	17.12%
		2 - 13.2	9.07	0.25%	
		< 2	3664.56	99.75%	
	79.5-80.5	> 13.2	220.78	4.55%	
		2 - 13.2	2189.78	45.09%	
		< 2	2445.56	50.36%	
	84.0-84.5	>13.2	913.78	49.88%	6.81%
		2 - 13.2	335.65	18.32%	
		< 2	582.56	31.80%	
	89.5-90.5	>13.2	180.78	4.29%	12.34%
		2 - 13.2	835.78	19.82%	
		< 2	3200.56	75.89%	
N-105A	40	>13.2	63	4.88%	6.47%
		2 - 13.2	746.98	57.82%	
		< 2	481.98	37.31%	
	45	>13.2	16	1.38%	5.96%
		2 - 13.2	589.98	50.82%	
		< 2	554.96	47.80%	
	51.0-52.0	>13.2	832.98	28.97%	5.08%
		2 - 13.2	983.98	34.23%	
		< 2	1057.96	36.80%	
	54.5-55.5	>13.2	1160.98	31.31%	19.22%
		2 - 13.2	975.98	26.32%	
		< 2	1570.96	42.37%	
	59.5-61.5	>13.2	1108.98	31.35%	2.54%
		2 - 13.2	714.98	20.21%	
		< 2	1712.96	48.43%	
	66.0-67.0	>13.2	896.98	23.47%	2.89%
		2 - 13.2	936.98	24.52%	
		< 2	1987.96	52.01%	

Borehole ID	Sample Depth (ft) bgs	Air-Dried Fractions			Moisture Content % (wt)
		Fraction Size (mm)	Fraction wt (grams)	Fraction %	
N-105A	71.0-72.0	>13.2	1816.98	42.89%	6.49%
		2 - 13.2	1357.98	32.06%	
		< 2	1060.96	25.05%	
	74.0-75.0	>13.2	281.98	5.90%	6.72%
		2 - 13.2	2998.96	62.73%	
		< 2	1499.96	31.37%	
	80.0-81.0	>13.2	1169.98	27.52%	6.89%
		2 - 13.2	1267.98	29.82%	
		< 2	1813.96	42.66%	
	85.5-86.5	>13.2	1125.98	34.13%	17.87%
		2 - 13.2	771.98	23.40%	
		< 2	1400.96	42.47%	
	90.5-91.5	>13.2	1540.98	33.71%	8.50%
		2 - 13.2	1092.98	23.91%	
		< 2	1937.96	42.39%	
	96.0-97.0	>13.2	0	0.00%	21.94%
		2 - 13.2	55	30.91%	
		< 2	122.96	69.09%	

N-104A seems to show the contact between the Ringold Unit E and the Ringold Upper Mud unit at about 90 ft., but a break between the Hanford formation and the Ringold Unit E is not apparent in the samples that were sieved.

The moisture content data were at first thought to be useful in corroborating the current position of the water table. However, field geologists indicated that at the direction of the field radiation monitor, often the drive barrel was allowed to drain or the split spoon liners themselves were allowed to drain overnight before being sealed for shipment in hopes of removing mobile (water borne) radioactivity before shipment. Therefore, the moisture content data are now considered not useful.

2.3 Gamma Energy Analysis

Oven-dried <2-mm-sized material from boreholes N-91A through N-97A was packed in standard 250-g counting tins and counted for 8 to 16 hours on a high-efficiency intrinsic Germanium detector. The detector is routinely calibrated over the energy range of interest (60-2000 kev) using a National Institute of Standards and Technology (NIST) traceable mixed gamma standard in a similar geometry (details can be found in PNL-ALO-464, *Procedure for Gamma Counting and Data Reduction in the Low-Level Counting Room,* listed at the end of the Reference Section and available from Northwest National Laboratory's

Analytical Chemistry Lab).

The results of the gamma energy scan are shown in Table 2.3. The four gamma energy analyses performed for borehole N-106A by Quanterra Environmental Services do not specify what size fraction material was measured, so these data may not be exactly comparable to the other data in Table 2.3. Recall that the data are for <2-mm fraction and not the whole sample. The sediment samples contain natural gamma emitting isotopes such as K-40, Ra-226, Th-232, and U-235 at very low activities (less than or equal to a few pCi/g). These levels likely represent natural background. There appears to be some anthropogenic radioactivity bound in the sediments. The cobalt-60 and antimony-125 values suggest that trace amounts of these radionuclides have reached the river because of the proximity of these sediment samples to the Columbia River. This statement is in agreement with the findings of Fruchter et al. (1985a,b) and Robertson et al. (1983) based on their direct measurement of seepage from 100-N Area springs. Blank data entries in Table 2.3 can be interpreted as below an unspecified (but very low) detection limit. Specific detection limits were not calculated by the computer software used to quantify the raw counting data because of an oversight. No replicate analyses were performed because all the measured values of anthropogenic radionuclides were very low compared to ^{90}Sr.

2.4 Tritium in Sediments Analysis

Tritium was distilled out of selected aliquots of the wet sediment from boreholes N-91A through N-97-A. The tritium aliquots were quickly taken out of the collection containers upon receipt. An attempt was made to select <2 mm-size material but of greater concern was to obtain the sample before water evaporated, which would let tritium escape from the sample. Tritium was distilled out of the wet aliquot along with some carrier distilled water used to submerge the sample in the closed circuit distillation apparatus. Specific details on the procedure are found in PNL-ALO-418. The tritium results are shown in Table 2.4. Five replicate samples were run and are identified with "-2" in the Sample ID column. Four spike recovery samples were also run where additional tritium was added to sample aliquots. The spike recovery results were 95.2, 72.1, 94.5 and 94.9 % for spike samples 93A-10, 93A-15, 96A-15 and 96A-20.5, respectively. The tritium results for the borehole sediment are tabulated two ways. The second column in Table 2.4 is marked pCi/g of as received soil. This relates the measured tritium to the total weight of moist soil used. The third column relates the measured tritium to the amount of moisture actually present in the sediment as received. The units of the latter column are pCi/l. This latter tabulation can be compared to the measured tritium concentrations in groundwater in nearby monitoring wells. When this is done one finds that the values reported in Table 2.4 are very similar to the groundwater monitoring data; i.e., tritium likely is not adsorbed onto the sediment and is present only in the pore water within sediment. That is, the tritium Kd is effectively equal to zero in the Hanford sediment. High tritium concentrations are found associated with the pore water in sediments that came from boreholes N-93A, N-94A, and N-95A, the same wells that show the elevated ^{90}Sr values described below.

2.5 Strontium-90 in Sediment Analyses

Oven-dried <2 mm aliquots of selected sediments from the boreholes were used to determine the ^{90}Sr content. The procedure used relies on a strong-acid leach to dissolve ^{90}Sr out of the sediment followed by

Table 2.3. Gamma Activity in Sediments (pCi/g)

Borehole	Sample Depth	K-40	Co-60	Ru-106	Sb-125	Cs-137	Ra-226	Th-232	U-235
91A	10 ft	23.84	0.120	-	-	-	0.744	0.837	-
	15 ft	22.85	0.262	1.813	-	-	0.733	0.767	-
	20 ft	21.45	0.146	-	-	-	0.931	1.018	-
	45 ft	28.79	-	-	-	-	1.504	2.022	2.840
92A	15 ft	32.82	0.366	-	0.766	0.087	1.063	1.343	2.627
	20 ft	28.63	0.133	-	-	-	0.625	0.740	-
	45 ft	12.17	-	4.045	-	-	0.661	1.710	-
93A	5 ft	23.24	0.394	-	0.357	-	0.826	0.921	-
	10 ft	22.11	1.198	-	1.537	-	1.564	2.061	2.901
	15 ft	26.37	0.431	-	0.478	-	0.842	1.021	-
	35 ft	32.10	-	-	1.139	-	1.631	2.515	5.759
94A	5 ft	20.36	0.996	-	0.308	-	0.758	0.809	-
	10-12 ft	25.34	0.497	-	0.195	-	0.856	1.069	-
	15 ft	23.03	0.303	-	0.537	-	0.857	0.998	-
	25 ft	24.57	0.378	-	-	-	1.022	1.139	-
	32 ft	23.23	0.211	-	-	-	0.894	1.058	-
	45 ft	28.22	-	-	1.035	-	1.644	2.291	0.275
95A	5 ft	21.76	0.206	-	-	-	0.673	0.760	-
	10 ft	22.57	1.290	-	-	-	0.647	0.734	-
	15.5 ft	19.69	0.386	-	0.402	-	0.789	1.233	-
	20 ft	18.45	0.223	-	0.392	-	0.632	0.724	-
	25 ft	19.49	0.193	-	-	-	0.617	0.746	-
	39 ft	19.01	-	-	0.617	-	0.778	1.163	-
96A	10 ft	22.65	-	-	-	-	0.706	0.702	-
	15.5 ft	19.47	-	-	0.190	-	0.901	0.836	2.218
	20.5 ft	26.83	0.054	-	-	-	0.998	1.033	-
	25 ft	21.19	0.430	-	-	-	0.843	1.046	3.690
	45 ft	23.14	0.158	-	-	-	0.972	1.334	-
97A	9.5 ft	19.01	0.098	-	-	-	0.623	0.650	-
	14 ft	22.31	-	1.723	0.459	-	0.811	1.080	-
	20 ft	24.07	0.076	-	0.639	-	0.935	1.253	1.902
	35 ft	38.27	0.089	-	-	0.046	1.820	2.515	5.545
106A	74 ft	14.5	0.64	NR	NR	<0.02	0.36	0.49	NR
	84 ft	15.6	0.30	NR	NR	<0.02	0.29	0.37	NR
	97 ft	15.4	0.45	NR	NR	<0.02	0.53	0.80	NR
	106.5 ft	18.4	0.27	NR	NR	<0.02	0.31	0.57	NR

NR = not reported

– = less than an unspecified detection limit

Table 2.4. Tritium Content in Sediment

Sample ID*	As-Received Soil pci/kg	Tritium Conc. per Liter of Soil Moisture pCi/L
93A-05	289	9700
93A-10	4770	48800
93A-10-2	4660	47600
93A-15	8560	48400
93A-15-2	8380	47400
93A-35	3860	18800
94A-05	324	19800
94A-10	1710	26300
94A-15	3600	35400
94A-25	7340	35700
94A-32	6580	39700
94A-45	446	2500
95A-05	196	6200
95A-10	52	600
95A-15.5	2880	23900
95A-15.5-2	3890	32400
95A-20	2300	18900
95A-25	952	6000
95A-39	11800	100000
96A-10	50	1700
96A-15	32	1100
96A-15-2	120	4300
96A-20.5	189	7300
96A-20.5-2	170	6600
96A-25	144	8400
96A-45	798	6600

* borehole and depth (bgs)

loading the acid extract onto special chelating resin columns that retain strontium and let other radionuclides leach away. The ^{90}Sr is then eluted from the column and dried onto planchets that are analyzed by gas proportional counting to detect the beta emission. Stable strontium is used to determine the yield (to determine the percentage of the ^{90}Sr that was successfully captured and subsequently eluted from the special chelating resin). In a few cases, coarse-size fractions (2 - 13.2 and > 13.2 mm) were analyzed for ^{90}Sr. For the boreholes along the Columbia River, 15 samples were run in duplicate, or in two cases triplicates, (N-94A-10 ft and N-95A -15 ft) to allow precision/reproducibility to be evaluated. The replicate samples are identified in Table 2.5 with the letter "B" for duplicates or "C" for the triplicates after the depth designation. Strontium-90 recoveries were calculated based on adding a small volume of stable strontium carrier to the acid extract just before it was added to the special chelating column. About 9.7 mg of stable strontium should then be eluted with the ^{90}Sr along with any small amount of natural strontium leached from the sediments themselves. Eluants that had no extra stable strontium added showed only a few tenths of a mg added weight, at most, to the planchet upon drying. For those samples that had the 9.7 mg of added stable strontium loaded onto the chelating column, the recovered weight on the planchet ranged from 91.1 to 134.1% recovery, with an average recovery of 106.7 ± 7.8%. This recovery was deemed acceptable. Similar replication and recovery determinations were performed on samples from the three upland boreholes (N-103A, N-104A, and N-105A). All the ^{90}Sr data presented in Table 2.5 have been corrected for procedure background in which the reagents used to leach the ^{90}Sr and the carrier stable strontium are treated as if they were a sample. Actual sediment background levels of ^{90}Sr from past atmospheric nuclear bomb testing has been measured around Hanford and found to be about ~10 pCi/kg (personal communication, K.A. Saldi, Northwest National Laboratory 1995).

Specific details on the ^{90}Sr procedure can be found in PNL-ALO-106 (REV 0) and PNL-ALO-476. The data for borehole N-106A were performed by Quanterra Environmental Services using their own protocols for blank correction.

2.6 Strontium-90 Content of Particle Sizes Other Than <2 mm

In a few instances dry sieved material other than the <2 mm material was analyzed for ^{90}Sr content. For borehole N-103A, depth 65-65.5 ft., the size fractions >13.2 mm and from 2 to 13.2 mm were washed in distilled water overnight to remove "fine dust" that was adhering to the sediment to give a more accurate analysis of the ^{90}Sr content of coarse particles. After this wash, the material was redried and ^{90}Sr content measured. The fines removed from the coarse sediment were found to be less than 0.075 mm (75 microns), and their ^{90}Sr content was also measured.

As will be described in Section 3.6, the ^{90}Sr content of the >13.2-mm and from 2 to 13.2- mm-size fractions of borehole N-105A, depth 51-52 ft., was also measured after a 10-day desorption in simulated groundwater. After adding the ^{90}Sr that desorbed, one can estimate the as-received ^{90}Sr content of the sediment's various particle sizes. Data for both boreholes are shown in Table 2.6. Not surprisingly, the ^{90}Sr content of the various sizes increases as the particle size decreases, which is a common trend for contaminants that adsorb onto the sediment surfaces.

2.7 Summary of Sediment Characterization Data

The ^{90}Sr concentrations in sediments along the Columbia River reach their highest values in boreholes N-94A and N-95A. In both boreholes, the maximum ^{90}Sr concentrations are found in the shallow depths (~10 ft) below the existing land surface. Borehole N-93A also contains elevated levels of ^{90}Sr at the 10-ft.

Table 2.5. Strontium-90 Content in 100-N Area Borehole Sediments (pCi/kg dry wet basis)

Sample ID	Total ^{90}Sr Beta Activity pCi/kg
91A-10A	750
91A-10B	8
91A-15	395
91A-20	199
91A-45	433
92A-15	208
92A-20	600
92A-45	399
93A-05	1760
93A-10	21,600
93A-15A	6500
93A-15B	4670
93A-35	500
94A-05A	35,790
94A-05B	42,090
94A-10A	50,590
94A-10B	49,600
94A-10C	45,600
94A-15A	15,290
94A-15B	13,200
94A-25A	9450
94A-25B	11,800
94A-32	4700
94A-45	1630
95A-05A	850
95A-05B	770
95A-10	37,400
95A-10B	37,000
95A-15A	2350
95A-15B	9400
95A-15C	10,300
95A-20A	13,600
95A-20B	12,500
95A-25A	10,100

Table 2.5. (contd)

Sample ID	Total ^{90}Sr Beta Activity pCi/kg
95A-25B	930
95A-39A	810
95A-39B	350
96A-10	147
96A-15	190
96A-20.5A	408
96A-20.5B	185
96A-25	730
96A-45	292
97A-14	433
97A-20	448
97A-35	610
103A-55 to 56.5	148
103A-60.5 to 61.5	2135
103A-65 to 65.5A	120,053
103A-65 to 65.5B	118,607
103A-70 to 71.5	79,924
103A-75 to 76.5	2796
103A-81 to 82	476
103A-85 to 87	207
103A-95.5 to 97	0
104A-58.5 to 59.5	74
104A-64 to 65	205
104A-69 to 70	913
104A-74 to 75	597
104A-79.5 to 80.5A	153
104A-79.5 to 80.5B	108
104A-84 to 84.5	17
104A-89.5 to 90.5	0
105A-40	17
105A-45	-13
105A-51 to 52A	431,034
105A-51 to 52B	503,304
105A-54.5 to 55.5	135,129

Table 2.5. (contd)

Sample ID	Total ^{90}Sr Beta Activity pCi/kg
105A-59.5 to 61.5	148,915
105A-66 to 67	90,379
105A-71 to 72A	100,885
105A-71 to 72B	111,700
105A-74 to 75	69,840
105A-80 to 81	11,100
105A-85.5 to 86.5	1228
105A-90.5 to 91.5	2486
105A-96 to 97	339
106A-73 to 75	210,000*
106A-83 to 85	78,800*
106A-96-98	118,000*
106A-105 to 108	52,200*
* Particle size not known.	

Table 2.6. Strontium-90 Content of Various Particle Sizes of 100-N Area Sediments

Borehole Depth (ft)	Particle Size (mm)	^{90}Sr Content (pCi/kg)
N-103A-65 to 65.5	> 13.2	16,100
	2 to 13.2	55,700
	< 2 mm	119,330±1,020
	<0.075	491,700
N-105A-51 to 52	> 13.2	94,350
	2 to 13.2	335,200
	< 2 mm	467,650

level. The highest levels of ^{90}Sr are found over the depth range, where the top of past and the present water tables are located. At all depths sampled, boreholes N-91A, N- 92A, N- 96A, and N-97A show very low or no ^{90}Sr activity above values for blank reagents in the procedure utilized.

For the four boreholes nearer to the currently inactive disposal facilities, borehole N-105A contains the highest activity of ^{90}Sr. There is significant ^{90}Sr activity in the sediments between the depths (from land surface) of 51 and 80 ft., with the highest values again in the shallower depths where the historical high water table resided during liquid disposal operations. The ^{90}Sr activity in the sediments at the level of the current water table (about 75 feet below the surface) are also quite high. For borehole N-103A, overall ^{90}Sr values are not quite as high as those in borehole N-105A. Again, the activity-versus-depth relationship follows the same trend observed in all the boreholes; (i.e. the highest ^{90}Sr values are found at shallow depths between the top of the historical high water table during operations and the current water table that represents the ambient Hanford aquifer conditions. At boreholes N-103A and N-105A, thehistorical high and present day water tables occur at about 55 ft. and 75 ft. bgs, respectively. The Quanterra-measured ^{90}Sr contents in borehole N-106A are not complete enough to delineate the thickness of the ^{90}Sr plume, but the shallowest depth sample (73-75 ft. below ground surface) shows the highest activity. Unlike the other wells, considerable ^{90}Sr is still present 35 ft. deeper (110 ft.bgs) in the borehole. Based on the four data available, well N-106A may contain a thicker zone (>35 ft.) of high contamination than the other wells. Further, much of the ^{90}Sr is present in the existing water table, which is 86 ft. bgs at present. Therefore, this well might be a good producer of contaminated groundwater for the pump-and-treat demonstration.

Borehole N-104A is located farthest from the River, (see Figure 2.1) about 80 m southwest of the 1325-N LWDF crib, where contaminated cooling water first enters the facility (Knepp et al. 1985). The 1325-N facility was used in later Hanford operations and received a smaller mass of contaminants than the older 1301-N facility. The ^{90}Sr content in <2-mm sediment in this borehole is relatively low, with the bulk of the ^{90}Sr concentrated between 65 and 75 ft. bgs. The historical high water table and the present water table are estimated to be at 56 and 71 ft.bgs, respectively.

The characterization data presented in Section 2.0 have been used to develop better conceptual models for determining the fate of the radionuclides disposed in the N Reactor cooling water and to help elucidate the geologic and hydrologic models for the 100-N Area. The data also help in interpreting the adsorption-desorption fate of ^{90}Sr, which is discussed in the next section.

2.8 Groundwater Analyses

Groundwater samples from monitoring wells 199-N-46 and N-75 were obtained by ERC staff in November 1994, in large high-density polyethylene carboys. The N-46 water was used in the ^{85}Sr adsorption and desorption testing described in Sections 3.1 and 3.2. An aliquot of the water (500 ml) was filtered (0.4 micron) and gamma counted. Results are shown in Table 2.7. The K-40, Ra-226, and Th-232 are naturally occurring isotopes. There is measurable cobalt-60 in this groundwater sample, also.

Filtered aliquots of the N-46 and N-75 water were used to measure soluble ^{90}Sr using the procedure mentioned in Section 2.5. The ^{90}Sr content of the N-46 groundwater in Nov. 1994 was 4,150 pCi/l, which is similar to the most recent values (CY 1992) present in the Hanford Environmental Information System (HEIS) data base. The average ^{90}Sr content of four aliquots of the N-75 groundwater was 1,180 ± 110 (one standard deviation) pCi/l, which is also similar to the most recent values in the HEIS data base. This groundwater was used in bench-scale tests to evaluate the efficacy of using clinoptilolite (a natural zeolite) to remove ^{90}Sr from groundwater in a companion study (Mattigod et al. 1995).

Table 2.7. Gamma Activity in Groundwater (pCi/l)

Groundwater	K-40	Co-60	Cs-137	Ra-226	Th-232	U-235
199-N-46	0.9	17.5	<1	60.4	19.0	<10

3.0 Strontium-90 Adsorption-Desorption Attributes

An understanding of the adsorption-desorption reaactions of ^{90}Sr present in the disposed cooling water within the Hanford formation and Ringold subsurface sediments is necessary to evaluate the past, current, and future migration of this contaminant toward the Columbia River. Further, knowledge of adsorption-desorption reactions of adsorbed ^{90}Sr with groundwater and/or any other solutions that might be used during a pump-and-treat remediation is necessary to design appropriate systems.

3.1 Adsorption Tests Using Strontium-85 Tracers

One suite of adsorption tests was performed using aliquots of the oven-dried <2 mm sediments from some of the boreholes along the Columbia River using small samples (~1 g) and groundwater (~ 30 ml) from well 199-N-46 that was spiked with 10 Ci/L ^{85}Sr gamma emitting tracer. The tracer was used because it allows adsorption testing to be performed quickly and avoids expensive analysis of ^{90}Sr. The assumption is that all strontium isotopes, both stable and radioactive, act identically and rapidly come to dynamic equilibrium. Specific details on the adsorption test methodology can be found in Relyea et al. (1980). Further, the batch adsorption procedure is very similar to ASTM D 4319-83 (ASTM 1990) .

At contact times of 3, 10, and 31 days a small aliquot of the groundwater was removed from the tube of sediment/water after centrifugation and filtration (0.4 micron). The aliquot was counted for the ^{85}Sr content and compared to a "blank" solution aliquot (one that contained only solution and no sediment) to calculate how much ^{85}Sr was removed from solution. It is assumed that missing ^{85}Sr reflects adsorption onto the soil. Because the blank tube would account for container wall adsorption, the ^{85}Sr can be nowhere else but adsorbed onto the soil in the tubes that contained soil. Counting the blank solution and soil contact solution at the designated times allows one to calculate the Kd for ^{85}Sr and by inference all strontium isotopes at the specified times. Several times were considered to assure that steady state (~equilibrium) had been reached. The units of Kd are ml/g to normalize for the amount of solution and sediment that were used in the test. The Kd can then be used to calculate the retardation factor for ^{90}Sr, which is needed to predict strontium migration to the Columbia River. At the end of the batch adsorption test (31 days in this case), the sediment loaded with ^{85}Sr was directly counted to double check the earlier Kd value. By counting the final solution and the sediment itself, one can directly calculate the Kd. This effort is a check on the Kd calculated using the common methodology, where only solutions are measured.

The results of the ^{85}Sr adsorption tests are shown in Table 3.1. The first three Kd columns (noting "solution") represent calculations in which only solutions were counted. The fourth column (noting "soil Kd") represents the direct measurement of both the soil and the solution. This value should agree with the 31-day solution Kd if the test is truly in equilibrium. The data show that the 31-day "soil Kd" values are slightly lower than the 31-day "solution Kd" values. The difference is probably caused by a slight negative bias in the counting performed on the soil, which relies on the standard geometry and calibration for a water sample of similar size. For practical purposes, the values of the Kd pairs, "solution Kd" and "soil Kd", should be considered the same.

Table 3.1. Strontium Adsorption Data, Kd (units ml/g)

Sample ID -^{85}Sr	Sample Depth (Feet bgs)	3 Day Kd Solution	10 Day Kd Solution	31 Day Kd Solution	Soil Kd
N-94A	10-12 ft-1	27	33	31	27
	10-12 ft-2	-	32	30	26
	10-12 ft-3	-	31	30	25
	15-17 ft-1	24	32	27	25
	15-17 ft-2	-	26	26	24
	15-17 ft-3	-	25	30	26
	45 ft-1	273	272	269	208
	45 ft-2	-	260	234	188
	45 ft-3	-	266	252	202
N-95A	10 ft-1	41	42	47	39
	10 ft-2	-	49	53	44
	10 ft-3	-	51	46	40
	20 ft-1	25	28	29	27
	20 ft-2	-	54	24	19
	20 ft-3	-	27	26	24
	39 ft-1	124	113	123	105
	39 ft-2	-	136	125	114
	39 ft-3	-	143	125	112
N-96A	10-11.5 ft-1	33	33	40	28
	10-11.5 ft-2	-	36	35	29
	10-11.5 ft-3	-	36	34	29
	20.5-22 ft-1	17	19	20	18
	20.5-22 ft-2	-	24	20	19
	20.5-22 ft-3	-	21	20	13
	45-46 ft-1	63	64	68	54
	45-46 ft-2	-	47	43	34
	45-46 ft-3	-	37	35	29

A second suite of batch adsorption tests was performed on other samples in which larger amounts (~16 g) of sediment were contacted with N-46 groundwater (~480 ml) that had been spiked with much less ^{85}Sr (~1 nCi/L) to investigate whether sample size and tracer concentration would change the calculated Kd value significantly. Both issues, sample size and linearity of adsorption as a function of the mass of contaminant present, have been shown in some situations to be important. For these larger tests, only one contact time was used (10 days). The Kd results based on counting only solution phases are shown in Table 3.2. The results in Table 3.2 are very similar to the results in Table 3.1, suggesting that strontium adsorption onto N Spring sediments follows simple reversible ion-exchange theory for trace contaminants,

Table 3.2. Strontium-85 Kd Values for Lower Spike Concentration

Sample ID	10 D Kd Solution ml/g
N-97A	
9.5-11 ft	22
14-16 ft	24
35-36.5 ft	274
N-93A	
10 ft	27
15 ft	24
35 ft	250
N-92A	
15 ft	39
45 ft	>250

which is required for the proper use of Kds in transport predictions. The Kd values for the deepest depths in each borehole,excepting N-96A are much larger than Sr-90 Kd values for the shallower depths. These differences are caused by the change in sediment lithologies from the coarser-grained Hanford formation and Upper Ringold Unit E in the shallower sediments to the finer-grained Ringold Upper Mud sediments at the deeper depths.

3.2 Desorption Tests Using Strontium-85

The suite of small sample adsorption tests that contained the higher loading of ^{85}Sr was used to perform desorption tests to evaluate directly the reversibility of strontium adsorption. There are no published standard procedures for performing desorption tests, but there are many leach test procedures in the literature. We elected to use an approach in which sediment loaded with ^{85}Sr is contacted sequentially with batches of uncontaminated groundwater for set periods of time. This methodology is endorsed by ASTM which has recently published a standard, D5284-92 Standard Method for Sequential Batch Leaching of Waste with Acidic Extraction Fluid (ASTM 1994). We substituted groundwater for the acid extraction fluid to simulate more closely the expected conditions in the Hanford subsurface. After each contact period, the water was removed and fresh water was added with continued contact. Unspiked groundwater from well N-46 was used with sequential replacement after 3 and 10 days of contact. The amount of ^{85}Sr that is brought back into solution upon contacting the clean water with the contaminated sediments is measured directly by gamma counting the extraction solutions. By subtracting the amount of Sr-85 found in the extraction fluids from the known amount of ^{85}Sr that was bound to the sediment at the end of the 31-day adsorption test period, one can calculate the desorption Kd. The desorption Kd is thus calculated from the estimate of ^{85}Sr remaining on the sediment at each contact time, divided by the measured ^{85}Sr in the water at each given contact time. Minor corrections are made for the fact that all the water cannot be removed between the end of the adsorption portion of the test and each desorption time period. Finally, after the 32-day desorption period, the residual sediment was recounted to measure directly the ^{85}Sr remaining on the sediment. This allowed us to calculate a 32-day desorption Kd value directly using the soil and last desorption solution data. In a fashion similar to the adsorption testing, this Kd value is called "soil desorption Kd" in comparison to "solution desorption Kd" values that rely on solution counting only. The desorption data are found in Table 3.3.

If the ^{85}Sr (and by inference ^{90}Sr) adsorption and desorption reactions are completely reversible, then the Kd values calculated in all the tests would be identical. That is, the Kd values in Tables 3.1 and 3.3 should be the same. In general, we believe the data support the concept that the ^{85}Sr adsorbed onto the sediment over a 31-day period is removed reversibly over a 10 to 32-day period. The 3-day period for desorption appears to yield slightly higher Kd values, suggesting that 3 days is not long enough to pull an equilibrium amount of ^{85}Sr off the soil but 10 days appears to be long enough. The desorption data for the second replicate for borehole N-95A, 20-ft. sample is likely an "outlier" because the values are consistently lower than any others. More discussion of strontium desorption, especially of the actual ^{90}Sr present in the 100-N Area sediment is given in the next four subsections.

3.3 Desorption Tests Using Strontium-90

One final suite of tests was performed to measure directly ^{90}Sr desorption from the N-Spring sediments. There is literature pertaining to other contaminants (especially organics) suggesting contaminants that have been present in the environment and adsorbed/bound to sediment for tens of years, or longer, may not release as easily as identical contaminants recently bound to the same sediment in laboratory

Table 3.3. Strontium-85 Desorption Data (Kd in ml/g)

Borehole	Sample Depth (feet)	3 Day Soln Desorption	10 Day Soln Desorption	32 Day Soln Desorption	32 Day Soil Desorption
N-94A	10-12 ft-1	48	37	24	32
	10-12 ft-2	41	34	21	32
	10-12 ft-3	37	26	8	33
	15-17 ft-1	40	34	27	27
	15-17 ft-2	42	51	37	27
	15-17 ft-3	39	32	25	28
N-95A	10 ft-1	47	39	22	39
	10 ft-2	53	43	27	44
	10 ft-3	51	44	25	44
	20 ft-1	41	30	21	30
	20 ft-2	23	9	-14	24
	20 ft-3	35	33	26	27

testing. To investigate whether such a phenomenon as this "aging" effect could be occurring for ^{90}Sr, the following test was performed.

Using the measured ^{90}Sr contents in the borehole sediments (see Section 2.5),eight of the most contaminated samples from N-93A, N-94A, N-95A, N-103A, and N-105A were selected. Aliquots of these oven-dried <2 mm fractions were contacted with a simulated water that was prepared with the same major cation content as was well water from well N-46. Calcium, sodium, magnesium and strontium salts were dissolved at appropriate concentrations in deionized water. The pH was adjusted to ~7.7. The chemical composition of well N-46 water is shown in Table 3.4.

Ten grams of contaminated sediment was then contacted with 300 ml of this simulated groundwater that contained no radioactivity for periods of either 3 or 10 days. Separate samples were used for each time period. That is, there is only one solution and soil contact period for any given sample and no multiple solution exchanges. At the stated time, the solution and soil are separated by centrifugation and filtration. The ^{90}Sr content in both the water and the sediment aliquot is measured using PNL-ALO-106(REV 0) and PNL-ALO-476. The desorption Kd is then calculated directly as the ^{90}Sr content in the soil (per g) divided by the ^{90}Sr content in the solution (per ml). Because the test requires use of all the samples (both solution and solid), and ^{90}Sr analysis is difficult (precision is no better than 20%), the calculated Kd values can be quite scattered. The results for the 3 and 10-day contact periods are shown in Table 3.5.

In a separate test, the larger particle sized material (from 2 to 13.2 mm and >13.2-mm splits) from borehole N-105A , depth 51-52 ft., was used in 10-day ^{90}Sr desorption testing. In these tests with coarser sized fractions, the solution-to-solid ratios were changed from 300 ml to 10 g as follows: for the 2 to 13-mm-sized sediment, the solution-to-solid ratio was 300 ml to 20 g, and for the >13.2-mm sediment it was 300 ml to 104 g. The simulated N-46 groundwater was used to desorb the ^{90}Sr. The results of these two tests were used to evaluate whether the desorption Kd is a function of the sediment particle size. The results are shown in Table 3.5.

Table 3.4. Chemical Composition of the Synthetic Groundwater (After Well 199-N46)

Ca	Mg	Na	K	Sr	Cl	NO_3	SO_4
------------ppm----------							
23	4	3.3	1.6	0.13	40.9[a]	20.5[a]	8.6
[a] The actual groundwater has bicarbonate as a major anion. We have substituted additional Cl and NO_3. True values for Cl is 1 ppm and NO_3 is 2.8 ppm.							

The desorption results for ^{90}Sr in general appear to be slightly larger and much more scattered than the results for the ^{85}Sr desorption for the data on the < 2-mm-size fraction but the arithimetic means of the ^{85}Sr and ^{90}Sr desorption Kds agree within the variance associated with each data set (data not shown, but available from the authors). That is, a student's T statistical test does not support the hypothesis that the means of the two data sets truly differ. We suggest that the data can be interpreted as showing rather good correlation between isotopes. This is equivalent to saying that ^{90}Sr exhibits classical reversible ion exchange and that equilibrium is reached in a relatively short time period of 10 days or less. It is thus appropriate to use the Kd concept to evaluate the fate of ^{90}Sr in the 100 N Area groundwater underlying the two LWDF facilities. Further, much of the experimentation to evaluate pump-and-treat processes can be performed using the surrogate tracer ^{85}Sr at great savings in time and cost. We also recommend that all bench-scale and pilot testing include some confirmatory testing using a reduced number of samples for ^{90}Sr itself.

The ^{90}Sr desorption data for the coarser grained material shown in Table 3.5 show a trend towards lower Kd values as the particle size increases. Perhaps this reflects that the ^{90}Sr bound to coarse-grained sediments is less strongly held to the particle surfaces and thus more readily removed from the coarse material. This would suggest that ^{90}Sr removal from the native bulk sediments may occur more easily than predictions based on the desorption Kd values generated on the < 2-mm fractions. On the other hand, the bulk of the ^{90}Sr is adsorbed on the finer grained sediment even though the overall particle size distribution for the native sediments is skewed towards larger particle sizes. More discussion on the particle size issue is presented later in this report.

Table 3.5. Strontium-90 Desorption Results on Contaminated Sediments From the 100-N Area

Borehole	Sample Depth (Feet)	Particle Size	3-Day Soil Desorption	10-Day Soil Desorption
N-93A	10-12	<2 mm	48	23
	15-17	<2 mm	32	54
N-94A	5	<2 mm	39	31
	10-12	<2 mm	49	35
	15-17	<2 mm	27	45
N-95A	10-12	<2 mm	53	39
	15-17	<2 mm	30	61
	20	<2 mm	29	30
N-103A	65-65.5	<2 mm	--	30
	duplicate		--	26
N-105A	51-52	<2 mm	--	57
	51-52	2-13.2 mm	--	39
	51-52	>13.2 mm	--	7
	duplicate		--	9

3.4 Kinetics of Strontium-90 Desorption

The data presented in Tables 3.3 and 3.5 suggest that desorption reactions may take more than 3 days to come to equilibrium. Further, the effectiveness of pump-and-treat operations are sensitive to kinetics if it takes many days for a batch of invading water to desorb ^{90}Sr from contaminated sediments. We thus elected to perform one suite of desorption tests as a function of contact time. Sediment from borehole N-105A at a depth of 51-52 ft. in the particle size range <2 mm was used. The solution-to-solid ratio was 300 ml of synthetic groundwater (see Table 3.4) to 10 g of material. Separate aliquots of the sediment were contacted with the synthetic groundwater for 8 hours, 24 hours, 2.5 days, 4 days, 10 days, and 24 days, at which time the solution and solid were separated, the solution was filtered, and the ^{90}Sr content of each phase was measured as described in Section 2.5. The ^{90}Sr desorption Kd was then calculated directly from the amount of ^{90}Sr on the residual sediment and "equilibrium" solution at each time. The results are shown in Table 3.6.

Within the precision of the Kd analyses of this small data set it is not possible to state with certainty that there is not any kinetic influence on the Kd for ^{90}Sr desorption. The slightly higher values observed for 8 and 24 hours might suggest that it takes longer than one day for the ^{90}Sr to release into solution; however, the data point at 24 days shows the highest Kd value of all so it is not possible to state with certainty that there is a kinetic impact. If there is some kinetic hindrance to desorption, it appears to become insignificant after 8 hours to 2.5 days, based on all the batch-type laboratory studies described in this report. Upon applying pump-and-treat remediation processes in the field, the requirement to allow from 8 hours to 2.5 days to reach equilibrium likely will not be a problem, and pumped water should have adequate time to interact with the contaminated sediment to desorb an "equilibrium" amount of ^{90}Sr. Unfortunately, the Kd value for desorption, which ranges from about 35 to 60 ml/g for the <2-mm fraction of the 100-N area

Table 3.6. Strontium-90 Desorption Kd as a Function of Contact Time
(Borehole N-105A, 51-52 ft; < 2 mm)

Contact Time (hours [h] or days [d])	Kd (ml/g)
8 h	65
24 h	66
2.5 d	47
4 d	48
10 d	52
24 d	74
	Ave. = 59 ± 11

sediments, is rather high. This suggests that the ^{90}Sr will not readily desorb from the sediments into the pumped groundwater. It would thus require a very long period of pumping and the withdrawal/collection of large amounts of water to cleanse the contaminated sediments underlying 100-N Area. More discussion is presented in Section 5.0.

3.5 In Situ Kd Determination

One final activity was performed to estimate ^{90}Sr adsorption-desorption reactions between Hanford sediments and natural waters. The 66-ft.bgs sample from borehole N-103A was removed from the steel liner, and two aliquots of the finer material (~2 mm and smaller) were packed into special centrifuge cells. About 140 g of the sediment was packed into each centrifuge cell. The cells were then spun in the centrifuge for about 16 hours at high rpm to extract any drainable liquid. The cells are designed so porewater can drain and collect in a cup at the bottom of the cell holder. A small amount of drainable pore water was obtained in each cell cup and combined. The amount collected was 4.17 g, and after drying the centrifuged sediment, the dry weight of the two aliquots was 287.23 g. We were thus able to extract some pore water out of Hanford sediment with a moisture content (weight basis) of only 1.5%. The extracted pore water and the dried sediments were analyzed for ^{90}Sr content as described in Section 2.5. The ratio of the amount of ^{90}Sr found in the sediment to the pore water is an estimate of the Kd of the system as it exists in the field. Based on the fact that we purposefully selected only fine-grained sediment to pack into the centrifuge cells, the calculated in situ Kd value may not reflect the true field Kd value. However, one can make a few further calculations by knowing the ^{90}Sr content of the larger grained sediment and assuming that the pore water drained out of the sediment is in equilibrium with the whole range of particle-sized sediment. More discussion is presented in the next subsection.

The in-situ Kd for the two centrifuged samples was calculated from the observed ^{90}Sr content of the residual sediment (136,300 and 113,200 pCi/kg) and the ^{90}Sr activity in the pore water (6,286 pCi/L). The values are 21.7 and 18.0 ml/g, respectively. These values are somewhat lower than values presented in Tables 3.3, 3.5, and 3.6, perhaps reflecting that we did not have only <2-mm material in the centrifuge cells or that the pore water was somehow slightly contaminated during the drilling process with water that had less ^{90}Sr activity (e.g. drilling fluid).

3.6 Particle Size Issue

Most all of the sediment characterization presented in Section 2.0 and the adsorption-desorption tests presented above were performed on the <2-mm fraction of the sediment. For the Ringold Unit E formation and the Hanford formation, the <2-mm fraction makes up about 30 to 35% of the samples received from the field. Actual field conditions likely also have boulders, which were not included in the jar and split-spoon samples that were dry sieved, such that the percentage of material <2- mm in field conditions is even smaller. To use the Kd values listed in Tables 3.3 through 3.6 in contaminant transport modeling exercises to approximate true field conditions, one would have to account for the larger material present that was discarded before the lab studies were performed. One simple correction technique would be to reduce the lab-derived Kd value by the fraction of the weight of <2-mm particles present in the field. This would effectively require that the Kd for all particles greater than 2 mm be zero. As shown in

Table 3.5, that is not the case, although it is true that the Kd for the larger sized material is lower than the value for the <2-mm material. In reality, the Kd is a function of surface area more so than weight of fines, but surface area data and the appropriate correlation are not available. Corrections using a weight fraction construct such as just mentioned (Kd = 0 for all material >2 mm) should lower the Kd more than it would be in the field.

Alternatively, one could multiply the Kd measured for the three particle sizes shown in Table 3.5 by the weight percent that each particle size represents and sum the products to calculate a size-normalized Kd. Upon doing such for borehole N-105A, 51-52 ft., one calculates a size-normalized Kd for ^{90}Sr as 37.6 ml/g versus 21.7 for the value when the <2- mm particle size materials Kd value is corrected for the weight percent of <2-mm material (the calculation where all larger material is assumed to have no sorption-desorption properties). More discussion on desorption Kds for the bulk sediment is found in the discussion of flow-through test material in Section 4.0.

4.0 Column Desorption Tests (Bench-Scale Pump Tests)

4.1 Purpose

Contaminated sediments from within the 100-N Area ^{90}Sr plume were used to determine ^{90}Sr desorption attributes under flow-through conditions. These data will be used to help predict the efficacy of groundwater extraction, water treatment in surface facilities and reinjecton of treated groundwater upgradient of the contaminated area. This, in effect, sets up a recirculation system where the groundwater percolates through the contaminated sediments, is collected through withdrawal wells, treated at the surface to remove ^{90}Sr, and reinjected to be drawn through the contaminated sediments again and again under hydrologic control by the pumping and reinjection.

Two pumping scenarios were simulated in laboratory bench-scale testing. The first scenario was a continual, constant flow rate condition in which uncontaminated simulated groundwater (a proxy for N-46 well water) was percolated through sediment from borehole N-105A at depths of 54.5-55.5 ft. and 59.5-61.5 ft. These sediments contain the second highest activities of ^{90}Sr found in the samples that were available (see Tables 2.5 and 2.6). This scenario represents continual constant flow rate operation or the injection-withdrawal pumping to maintain hydrologic control. .

The second bench-scale test was performed with periodic active flow followed by a period of no flow (static condition) to simulate a "pulsed pumping" scenario. For pulsed pumping, the pumping is active for a period of time and then the system is shut off to allow the groundwater more time to equilibrate with the contaminated sediments. The pumps are then restarted for a period of time to remove the water that has hopefully desorbed significant amounts of ^{90}Sr during the inactive period. This cyclical operation is another standard technique to improve pump and treat remediation in aquifers that have either heterogenous hydraulics (preferred channeling, a large fraction of dead-end porosity, etc.) that requires more time for diffusion to move contaminants into the active portion of the flow field, or aquifers with kinetically hindered desorption reactions. In the latter case, the time necessary for the desorption or dissolution of ^{90}Sr from the contaminated sediments into the groundwater may be longer than the residence time allowed by the flow field created by the active pumping. As a result a unit volume of water that is withdrawn does not have time to reach equilibrium (gain a "full load" of ^{90}Sr), and the overall efficiency is diminished.

At the beginning of this pulsed pump test, we elected to simulate active pumping for 3 days and then to allow the system to remain static for 11 days, followed by another 3 days of pumping etc. The flow rate used in this scenario was 4.67 times as fast as the continual flow scenario. This value is 14/3 the continual flow rate such that at the end of 14 days both tests have pumped exactly the same volume of solution, and thus every 14 days the two tests have both recorded identical volumes of pumped water. This allows for simple comparisons of leach curves as a function of time and volume pumped for the two scenarios. After three cycles, when the kinetic data (discussed in Section 3.4) became available, we changed the cycling parameters. We found that the desorption kinetics were quite fast such that the 3-day pumping and 11-day inactive period was effectively no different than the continual slow flow. The data to be presented for the first three cycles of the pulsed-pump test corroborated this finding. As a result we increased the active pumping rate by a factor of three and shortened the pump time from 3 days to 10 hours. For the inactive period, we changed to 158 hours (6 days and 14 hours) such that the complete cycle was 1 week. We ran the pulsed-pump test (column #2) through five of these modified cycles, after the three slower flow cycles.

4.2 Column Description and Initial Conditions

The two columns were Plexiglas tubes with a 8.73-cm inner diameter and 21-cm length. The column volume was 1,260 cm^3 for each, and the amount of sediment packed into the columns was 2,560.46 g and 2,611.38 g, respectively, for column #1 and column #2. The sediment used was a mixture of two split spoon samples from borehole N-105A. Unlike most of the other adsorption-desorption tests discussed in Section 3.0, here we used the entire particle size range. All the material from the steel liner was removed and air-dried. Next, the material was sieved through the 13.2 and 2-mm screens, and the weight fraction of each was recorded. We then reconstituted the material by mixing all fractions. We attempted to pack the columns using a standard technique used for other testing of Hanford sediment (<2-mm sizes). We generally get well-mixed and homogeneous packing with a bulk density of about 1.6 g/cm^3 using the packing methodology (Relyea 1981). For this more coarse 100-N Area sediment we obtained homogeneous columns at a dry bulk density of 2.03 and 2.07 g/cm^3, respectively, for columns #1 and #2. Assuming a particle density of 2.78 g/cm^3, which is the average value of many measurements performed on Hanford sediments (see Serne et al. 1993), the pore volumes of the two columns were calculated to be 319 and 300 ml, respectively. The specific flow rate used in column #1 was 4.43 ml/h. For the pulsed-pump test (column #2) two flow rates were used; 20.65 ml/h for the first three cycles followed by 60 ml/h for five additional cycles.

Details on the particle sizes and weight percentages of each size for the reconstituted sediment packed into the two columns are shown in Table 4.1. This information along with the ^{90}Sr content could be used to calculate the total amount of ^{90}Sr in the two columns before initiating the groundwater pumping. We did not have enough material left to measure directly the ^{90}Sr content of the three size fractions for the material placed in the columns. We did obtain measurements on the <2-mm material for the 54.5-55.5 and 59.5-61.5-ft. samples before combining. These results are found in Table 2.5. We also have analyses of the ^{90}Sr content of the 51-52 depth sample for all three size fractions as shown in Tables 2.5 and 2.6. The <2-mm material from depths of 54.5-55.5 ft. and 59.5-61.5 ft. are quite similar so we feel justified in averaging the ^{90}Sr values and assuming that the material from these two depths contain about the same ^{90}Sr content. Further, we elected to estimate the ^{90}Sr content of the two larger size fractions by assuming that they would contain the same ratio of ^{90}Sr as the ratio for the <2-mm material from the averaged 54.5 to 61.5-ft sample to the ^{90}Sr content of the 51-52-ft. sample. The data and the calculation are shown in Table 4.1 . Using these assumptions, we could estimate the total ^{90}Sr content in each of the packed columns, and by measuring the ^{90}Sr content of each aliquot of effluent we could keep track of the cumulative amount leached at any given time, and by difference, the remaining ^{90}Sr content in the sediment. Further, by assuming that the column was a completely mixed and homogenous system, we could calculate a Kd value for ^{90}Sr for each effluent aliquot by using the relationship that the amount of ^{90}Sr per g remaining in the sediment divided by the amount of ^{90}Sr per ml of effluent is the Kd. The calculations and some of the pertinent raw data for the two leaching columns are shown in Tables 4.2 and 4.3.

Table 4.1. Column Test Details

Columns Packed With Borehole N-105A Sediment Depths 54.5-55.5 and 59.5-61.5 ft Mixed	
Particle Size (mm)	**% Wt.**
>13.2	36.68
2 to 13.2	21.48
<2	41.84

Available and Calculated Strontium-90 Content of Sediments					
Borehole (depth bgs in ft)	**Particle Size (mm)**	**^{90}Sr (pCi/kg)**	**Ave. (pCi/kg)**	**Ratio**	**Calculated ^{90}Sr (pCi/kg)**
N-105A (51-52)	<2 mm	431,024	467,236 ±36,000		
		503,034			
		467,650			
N-105A (51-52)	2 to 13.2	335,200			
N-105A (51-52)	>13.2	94,350			
N-105A (54.5-55.5)	<2	135,129	142,022 ±9750	0.304	
N-105A (59.5-61.5)	<2	148,915			
N-105A (54.5-61.5 mix)	2 to 13.2			0.304 x 335,200[a]	101,887
N-105A (54.5-61.5 mix)	>13.2			0.304 x 94,350[a]	28,679

[a] Assume ratio of ^{90}Sr for <2 mm material for 54.5-61.5 vs 51-52 ft is same for all sizes

Table 4.2. Data From Column #1 (Continual Flow)

Effluent	Solution Collect	Total Volume	Pore Volumes	^{90}Sr Effl.	pCi leached	Total pCi	Cum. %	Kd
#	(g)	(g ~ ml)		pCi/l	each	out	Removed	ml/g
1-1	313.71	313.71	0.98	10510	3298	3298	1.4	9
1-2	304.57	618.28	1.94	7710	2349	5647	2.4	12
1-3	291.05	909.33	2.85	7750	2255	7902	3.4	11
1-4	516.86	1426.19	4.48	6680	3452	11353	4.8	13
1-5	536.42	1962.61	6.16	5830	3127	14480	6.2	15
1-6	530.32	2492.93	7.82	4110	2177	16657	7.1	21
1-7	411.82	2904.75	9.12	5850	2410	19068	8.1	14
1-8	525.99	3430.74	10.77	4700	2474	21542	9.2	18
1-9	624.58	4055.32	12.73	5340	3334	24876	10.6	15
1-10	739.48	4794.80	15.05	4790	3544	28419	12.1	17
1-11	635.89	5430.69	17.04	5400	3431	31850	13.5	15
1-12	448.59	5879.28	18.45	4420	1984	33834	14.4	18
1-13	610.70	6489.98	20.37	4370	2667	36501	15.5	18
1-14	870.43	7360.41	23.10	4720	4106	40608	17.3	16
							Ave. Kd	14

Table 4.3. Data From Column #2 (Periodic Flow)

Effluent	Solution Collect	Total Volume	Pore Volumes	^{90}Sr Effl.	pCi leached	Total pCi	Cum. %	Kd
#	(g)	(g ~ ml)		pCi/l	each	out	Removed	ml/g
2-1	1494	1494	4.98	7110	10627	10607	4.4	12
2-2	1455	2949	9.83	6790	9882	20509	8.6	12
2-3	1472	4421	14.74	4030	5938	26447	11.0	20
2-4	563	4984	16.62	5270	2967	29414	12.3	15
2-5	598	5582	18.61	5800	3463	32878	13.7	14
2-6	600	6182	20.61	5170	3100	35978	15.0	15
2-7	593	6775	22.59	4880	2891	38870	16.2	16
2-8	570	7345	24.49	4370	2491	41361	17.2	17
							Ave. Kd	15

4.3 Results

Column #1 was run for a total of 23.1 pore volumes, and about 17.3% of the bound ^{90}Sr was removed (see Table 4.2.). The highest effluent concentration was observed in the first leachate, and there was a measurable concentration drop (from 10,510 to between 7,000 and 8,000 pCi/l) over the next four pore volumes. After about six pore volumes the effluent concentrations were rather constant at about 4,900 ± 600 pCi/l. Such a trend is partially consistent with a desorption mechanism. The more dramatic release in the first pore volume is often observed in leaching tests and has been called the "wash-off" effect. Once this most easily removable material is leached, the eluent data are consistent with the results one would expect if desorption controls the solution concentrations. The sequential effluents slowly show lower concentrations as the equilibrium desorption Kd (ratio of mass bound to soil to mass in effluent) redistributes the shrinking inventory between the sediment and the solution. The laboratory data show that the decrease is so slow that the variability in our ability to precisely measure ^{90}Sr is masking the trend. Because we have removed only 17% of the initial inventory, more pumping would be needed to corroborate the expected trend. A simple algorithm was prepared, and the expected results for column #1 are shown in the Appendix for a Kd value of 15 ml/g. The calculated Kd from the column #1 testing for each effluent aliquot shows that the initial Kd is slightly lower than the following values as a result of the "wash-off" phenomenon, after which the Kd becomes remarkably stable at a value of about 14 ml/g. This value can be compared to the in situ Kd values presented in Section 3.5, where we observed values of 18 and 21.7 (albeit for the finer grained fraction only), and to the size-corrected value 37.6 ml/g, calculated in Section 3.6. If we underestimated the amount of ^{90}Sr in the >2-mm material (recall that we did not have a direct measurement and resorted to the ratio assumptions presented in Table 4.1) packed into the columns (represents 58% of mass in columns), then the column Kd values would be biased low. Conversely, the ^{90}Sr Kd values measured for the borehole N-105A-51 to 52-ft.bgs sample (see Tables 3.5 and 3.6) are larger than the values for other boreholes such as N-103A, and N-93A through N-95A. Thus, the calculated size-normalized Kd value of 37.6 ml/g for ^{90}Sr discussed in Section 3.6 could be biased high.

The effluent data for column #2, using the "pulsed-pump" technique with fast pumping for a short time followed by a period of inactivity, are quite similar to the continual flow test results (column #1). After eight cycles, a total of 24.5 pore volumes of effluent were collected, and 17.3% of the initial inventory of ^{90}Sr was leached (see Table 4.3.). This is essentially the same as the leached quantity for the same amount of effluent collected in column #1. Thus, volumetric flow rates used in these two tests release the same amount of ^{90}Sr from the sediments. Using the calculated porosity of 0.28 for the sediment-packed columns, the column #1 pore water flow rate is 23 m/y and the two flow rates used in column #2 were 104 and 312 m/y. From the kinetic experiments described in Section 3.4 and these column tests, it would appear that as long as the flow rates were kept below a value that allows for at least 6 to 8 hours of contact time with the contaminated sediments, then desorption reaches equilibrium and the groundwater will gain close to a "full load" of leached ^{90}Sr The highest ^{90}Sr effluent concentration observed for column #2 is about 7,100 pCi/l at the very beginning, and then the effluents drop down to about 5,000 ± 600 pCi/l for the remaining cycles.

The calculated column #2 Kd is very similar to the value for column #1, 15 vs. 14 ml/g.

4.4 Discussion of Column Results

Using the spreadsheet values shown in the Appendix, based on equilibrium and reversible reaction for a stirred reactor filled with sediment with a constant Kd for ^{90}Sr of 15 ml/g, one finds that it would take 74 pore volumes of pumping uncontaminated groundwater through the sediment to remove 50% of the adsorbed ^{90}Sr. The calculations performed in the Appendix do not include natural radioactive decay because time is not a variable in the conceptual model. Table 4.4 shows the comparable pore volumes needed to remove various percentages of the ^{90}Sr, without considering radioactive decay. Once the pore volumes pumped are related to actual time for a given scenario, then decay could be included as will be shown in Section 5.0.

As shown in Table 4.4, the number of pore volumes needed to remove a 10% increment of the ^{90}Sr starts to increase, from about 12 pore volumes per 10%, after 20% of the ^{90}Sr is removed, to twice as many pore volumes (~25) once 50-60% of the ^{90}Sr is removed. This is because the amount of ^{90}Sr remaining on the sediment drops, the Kd ratio remains the same, and thus the amount of ^{90}Sr that can be desorbed into solution must drop accordingly. Thus, removal becomes less efficient as the desorption process continues.

Table 4.4. Calculated Pore Volumes Necessary to Remove Strontium-90 From 100-N Area Sediment

^{90}Sr Removal (%)	Pore Volumes
10	12
20	24
30	38
40	54
50	74
60	97
70	128
80	171
90	245
95	318
97.5	392

Data in Tables 4.2 and 4.3 that show the observed solution concentrations are compared to the calculated solution concentrations expected for the Kd = 15 case in Figure 4.1. It can be seen that calculated ^{90}Sr effluent drops off with the same relationship as the percent total ^{90}Sr removed. That is, after 10% of the ^{90}Sr has been removed, the effluent solution concentration is ~90% as high as in the first pore volume, and after 50% of the ^{90}Sr has been removed, the effluent solution concentration is 50% as high as that in the first pore volume. As stated previously, the experimental data show a slightly higher solution concentration at first, followed by a less pronounced drop as the experiment continued, although we only ran the columns until about 24 pore volumes were flushed through the sediment.

The calculated Kd values for the two column tests appear to be lower than the value calculated in Section 3.6, where we presented an approach to calculating the Kd for bulk sediment from knowing the Kd for three separate particle sizes of the sediment. Table 3.5 shows that it is possible that the ^{90}Sr desorption Kd values measured for sediment from borehole N-105A are higher than the Kd values for sediment from other boreholes. For instance, if the Kd values are adjusted to be similar to the borehole N-103A value (the value for the <2-mm-sized material is only 49% as large as the <2-mm borehole N-105A samples), the size-normalized Kd would be 17.2 ml/g. This value is very close to the values calculated for the two experimental columns. Without knowledge of the mineralogy of the material from boreholes N-103A and N-105A, and perhaps other characterization data, it is not possible to state whether the differences in Kd values are real or artificial. We do have enough data on borehole N-105A to suggest that precision for ^{90}Sr Kd desorption generally is much better than the nearly 50% difference for the <2-mm material between the two boreholes shown in Table 3.5. Conversely, our earlier work using sediments from along the Columbia River show quite large scatter for samples from different depths (but still within the Ringold Unit E) within the same borehole. Without a larger data base, it is difficult to state how precisely ^{90}Sr desorption Kd values can be measured.

If the Kd for ^{90}Sr was larger than the value of 15 ml/g used for the bulk sediment packed in the columns and in the Appendix calculations, then the removal of ^{90}Sr from the contaminated sediments would be

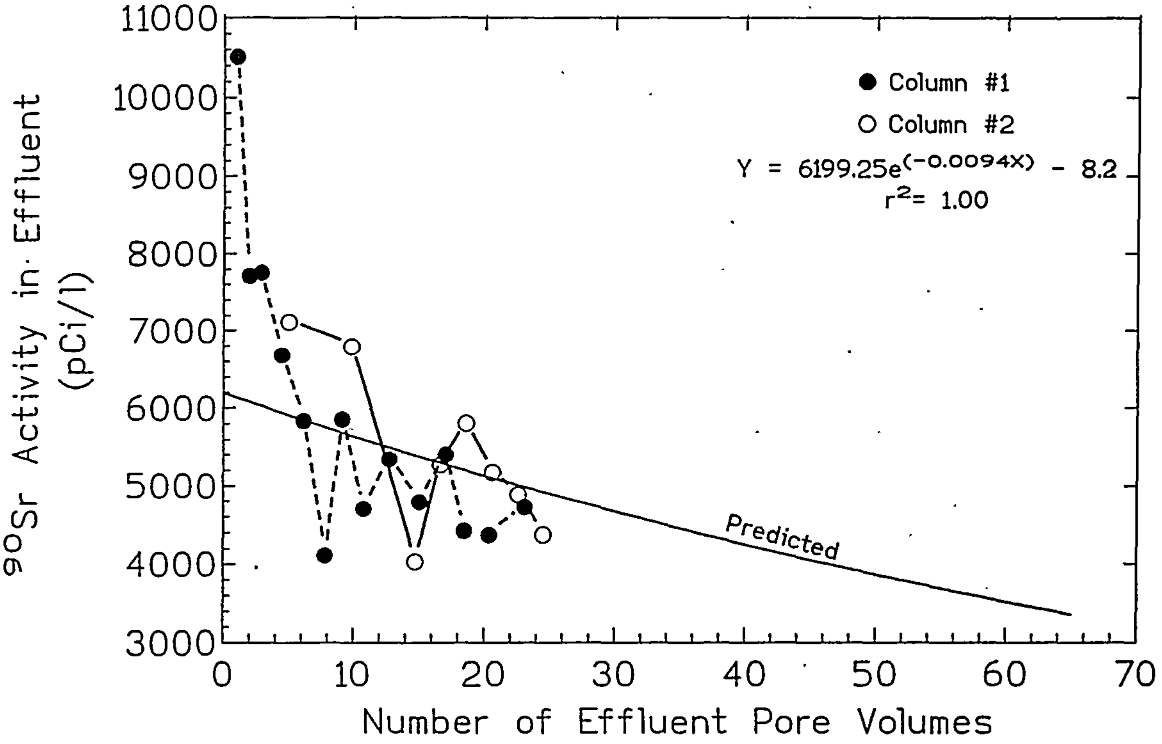

Figure 4.1. Observed and Calculated Effluent Concentrations of Strontium-90

correspondingly slower.

The column test data can be considered an ideal pump-and-treat simulation because the hydrologic flow is completely controlled such that uncontaminated water is forced to contact all of the contaminated sediment. In real life pump-and-treat operations, hydrologic control will not be complete, and some of the sediment may not be contacted with water that is also removed at the withdrawal wells. Further, the withdrawal wells may collect water from outside the zone of contaminated sediments, and thus the concentrations of ^{90}Sr in the water removed may be lower than observed in the lab tests for a sediment with about 92,000 pCi/kg. Further, the data shown in Section 2.5 suggest that the contaminated sediment is relatively "pancake" shaped, akin to a thin layer. The highest levels of ^{90}Sr also occur in a thin layer (5 to 10 ft.) for most of the boreholes (except perhaps N-106A) at a depth where the historically high water table was located during disposal operations. At several boreholes, these most contaminated sediments are now above the existing water table and thus are not available to current water that will be used to set up the hydrologic circuit during the pump-and-treat. Without careful control of the pump-and-treat hydrology, the withdrawal wells may be pumped too hard and a "cone-shaped" depression in the existing water table could further separate the active flow field from the contaminated sediments. If the withdrawal wells are not located within the more highly contaminated sediments, then some of the ^{90}Sr leached from the most contaminated regions will readsorb onto the less contaminated sediment between the most contaminated sediments and the withdrawal well until the sediments near the withdrawal well become the most contaminated sediments (i.e. move the zone of highest contamination to the proximity of the withdrawal well by reversible ion-exchange reactions). This adsorption-desorption process will follow the same mathematics as shown in the Appendix, and thus could take tens of years or longer to improve the ^{90}Sr removal efficiency.

Finally, the treated water that is reinjected upgradient from the withdrawal wells so that it can travel back through the contaminated sediments may not be as effective at removing additional ^{90}Sr after its first contact with the sediments. This is because the water will be processed by an ion-exchange process using the natural zeolite clinoptilolite. The clinoptilolite will remove stable strontium and some of the natural calcium and magnesium from the water as well as the ^{90}Sr. It is the dynamic equilibrium between the stable strontium, calcium, and magnesium that controls the ^{90}Sr Kd (given the assumption that all the contaminated sediment is fairly constant in chemical and mineralogical composition). The higher the concentration of stable strontium, calcium, and magnesium present in the water flowing through the sediment, the better the competition is for the exchange sites that bind ^{90}Sr, and thus the better the ^{90}Sr desorption (and the lower the Kd). In the laboratory, we fixed the strontium, calcium, and magnesium contents in the simulated groundwater. If these competing cations are removed from the water that percolates through the contaminated sediments, then the ^{90}Sr will not desorb as readily. It is thus useful to set up the pump-and-treat such that a much larger quantity of natural groundwater than recycled treated water is continually pulled through the contaminated sediments. Alternatively, divalent cations could be added to the recycled and/or natural groundwater to improve the desorption of bound ^{90}Sr through competitive exchange. Data on the Kd for strontium as a function of solution calcium and magnesium concentration has been presented in Appendix A of Alexander and Johnson (1993). A figure from this report is included here as Figure 4.2. The sediment used in Alexander and Johnson (1993) was from borehole N-75 from the 100-N Area. Calculations to quantify the impact of recycling water that has had significant portions of stable strontium, calcium, and magnesium removed during ex situ treatment are beyond the scope of this report but should be considered if pump-and-treat is continued for long time periods. Currently, the field demonstration (BHI 1995) is reinjecting treated water far upgradient from the withdrawal wells, and no impact is expected for several years.

If one added competing divalent cations (alkaline-earths strontium, calcium, and magnesium) to the recycled water or the natural groundwater, then ^{90}Sr desorption would be enhanced as shown in Figure 4.2. But as reported in Mattigod et al. (1995), the efficiency of ^{90}Sr removal onto the clinoptilolite would be diminished. This would require looking for a more selective exchange media or perhaps changing to another type of treatment such as ^{90}Sr chemical precipitation. These alternatives should be addressed in the final report on the field demonstration.

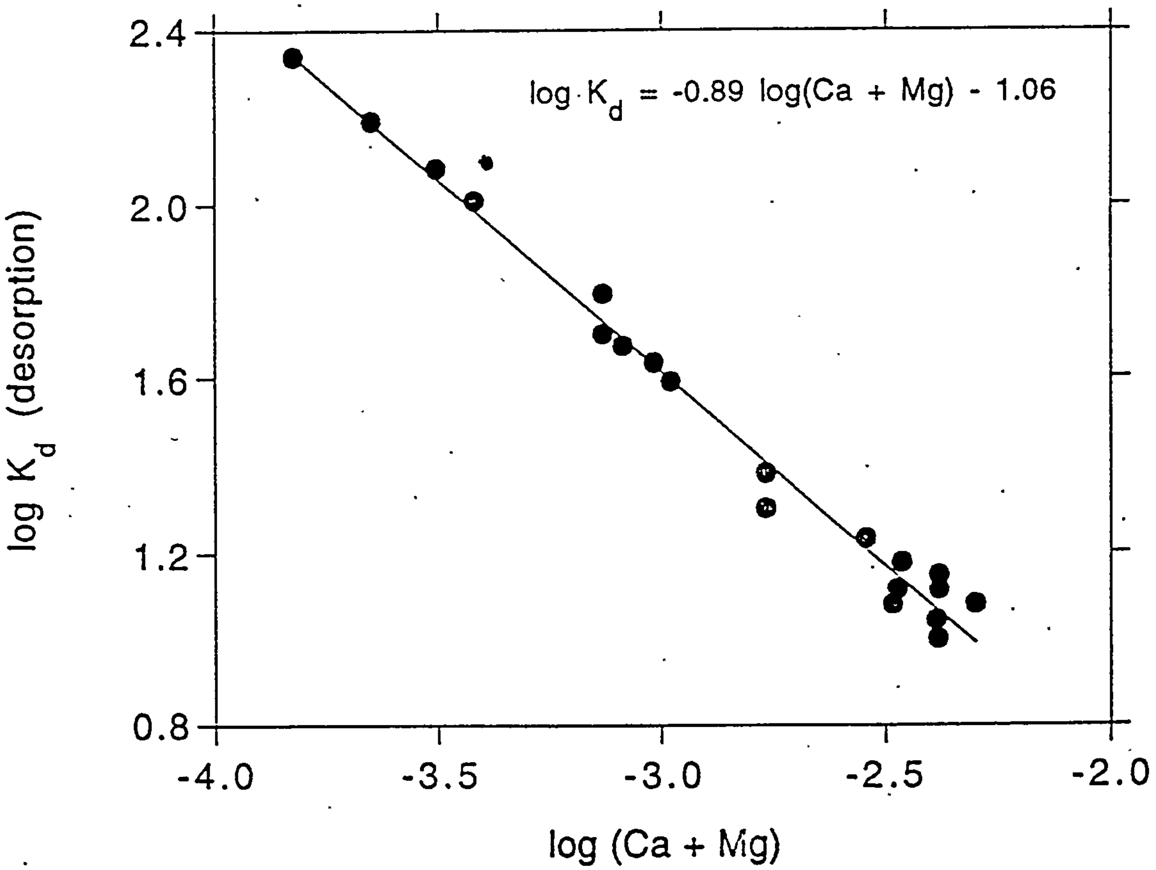

Figure 4.2. Sr Kd Values as a Function of the Sum of the Solution Concentration of Ca and Mg (in M)

5.0 Discussion on Laboratory Results Relevancy to Field Pump-and-Treat

In this section we will relate the results of the laboratory column studies described in Section 4.0 to the ongoing field demonstration pump-and-treat. The field demonstration currently is pumping water out of up to four wells, N-75, N-103A, N-105A, and N-106A (no more than three at any one time), with a cumulative rate of 50 gpm (189.27 l/min or 9.95 x 10^7 l per year). The pump-and-treat demonstration facility was designed for a maximum throughput of 180 gpm (681.37 l/min or 3.58 x 10^8 l per year) as described in BHI (1995).

From September 6 to November 27, 1995 the field demonstration extracted 1.73 x 10^7 l of groundwater, with an average ^{90}Sr content of about 1,000 pCi/l (personal communication from R. L. Jackson, BHI). The ^{90}Sr content of the water has remained fairly constant with time, and the bulk of the radionuclide appears to be coming out of well N-106A. If we assume that this concentration can be maintained for a very long time at either the 50 gpm or the 180 gpm rate, we can estimate the amount of ^{90}Sr that is removed from the aquifer. Further, if we can estimate the total ^{90}Sr content in the saturated sediments in the upper unconfined aquifer plume that is downgradient from the two LWDFs, we can make comparisons with the column tests described in Section 4.0.

WHC and BHI staff have been analyzing the 100-N Area ^{90}Sr groundwater plume for several years (Connelly et al. 1991, DOE/RL 1995). Mike Connelly has provided a spreadsheet that is summarized in Table 5.1. It includes the areas contained within ^{90}Sr isoconcentration contours (isopleths) for the 100-N Area groundwater ^{90}Sr plume. If we sum the areas for the isopleths for ^{90}Sr groundwater activities above 42 pCi/l, the total area is 5.155 x 10^5 m^2. If we assume that the depth of contaminated sediment existing within the current aquifer is 4 m (based on the thin pancake conceptual model discussed in Section 2.0 after analyzing the available data), that the ^{90}Sr distribution coefficient between sediment and groundwater is 15 ml/g from the column leaching data in Section 4.0, and that the sediment dry bulk density is 2.0 g/cm^3 as found in the column tests and from cores of coarse Hanford sediments from the proposed grout facility (Rockhold et al. 1993), then we can estimate the ^{90}Sr distributed in the contaminated sediments and their pore waters (the groundwater plume itself). Using the particle density of 2.78 g/cm^3 for Hanford sediments (Serne et al. 1993) and the assumed dry bulk density of 2.0 g/cm^3 yields a porosity of 0.28. As shown in Table 5.1, the calculated amount of ^{90}Sr within the plume (defined as ^{90}Sr concentrations above the 42 pCi/l maximum permissible concentration) is 88.8 curies, with 88 curies bound on the sediment and 0.8 curies in the groundwater. This estimate can be compared to values of 75.5 total curies with 75 bound to the sediments and 0.5 curies in the groundwater obtained by DOE/RL (1994).

The pore volume of this contaminated plume at the 100-N Area would be 5.77 x 10^8 liters based on the assumed porosity of 0.28 and the plume volume of 2.06 x 10^9 l. Given this pore volume and the pump rates mentioned above, the existing pump rate (50 gpm) is removing one pore volume every 5.8 years, while the higher pump rate (the system's maximum design rate is 180 gpm) would require 1.6 years to remove a pore volume. If we take the data from Table 4.4 and attach a time to pump a pore volume, we can calculate the time required to remove a certain proportion of the bound ^{90}Sr, assuming that the

Table 5.1 Strontium-90 Plume Estimates for Several Isopleth Values

Conc. pCi/l	Area of Plume Greater than Conc. (m^2)	Conc. Limits for Area pCi/l	Area of Plume between Conc. Limits (m^2)	Conc. used to Compute Mass pCi/l	Mass of ^{90}Sr in Soil (Ci)	Mass of ^{90}Sr in Water (Ci)
8	695788.5	8<n<42	180240.39	25	0.54	0.005
42	515548.11	42<n<400	223987.73	221	5.94	0.05
400	291560.38	400<n<1000	65896.91	700	5.5	0.05
1000	225663.47	1000<n<3000	131705.07	2000	31.6	0.27
3000	93958.4	3000<n<4000	52765.6	3500	22.2	0.19
4000	41192.8	n>4000	41192.8	4500	22.2	0.19

efficiency of the field pumping matches the laboratory column work, which as discussed in Section 4.0, is not likely. The calculations are shown the Table 5.2. We have also included radioactive decay in the calculations. Radioactive decay alone, without any pumping, will "remove" ^{90}Sr at rates shown in the last column of Table 5.2.

Table 5.2. Calculated Times Necessary to Remove Strontium-90 From 100-N Area Sediment

^{90}Sr Removal (%)	Pore Volumes	Time (yr) for 50 gpm	Time (yr) for 180 gpm	Time (yr) for nat. decay
10	12	4.1	3.5	4.5
20	24	8.6	7.3	9.2
30	38	13.8	11.7	15
40	54	19.7	16.8	21
50	74	26.8	22.8	29
60	97	35.4	30.1	38
70	128	46.5	39.5	50
80	171	62.1	52.9	67
90	245	88.9	75.6	95
95	318	115.7	98.4	123
97.5	392	142.4	121.2	152

To obtain 90% ^{90}Sr removal from the existing plume beneath the 100-N Area with concentrations above the 42 pCi/l limit would take 89 years for a pump rate of 50 gpm and 76 years for a pump rate of 180 gpm. Natural decay will "remove" the ^{90}Sr in slightly longer times than the combined decay with pump-and-treat as shown in the last column of Table 5.2 and in Figure 5.1. Recall that the pump-and-treat calculations assume the efficiency in the field will be as good as that found in the lab column tests (discussed in Section 4.0), which is a highly unlikely assumption. The analyses presented in DOE/RL (1995) also suggest that the pump-and-treat will do very little in lowering the release of ^{90}Sr to the Columbia River compared to inserting a vertical sheet pile along the River that is buried into the underlying low hydraulic conductivity Upper Mud Unit of the Ringold Formation. There is one further observation that can be made from the data that were provided via personal communication with BHI staff who are performing the field demonstration. The ^{90}Sr content in the sediment in borehole N-106A, which is clearly the most productive extraction well among the four being used, is 52,000 pCi/kg at the depths where groundwater is present. The average concentration of the groundwater being consistently withdrawn from this well is 2,890 pCi/l of ^{90}Sr. From these two values, one can calculate the effective Kd by dividing the soil concentration by the groundwater concentration. The value is 18 ml/g, which is very

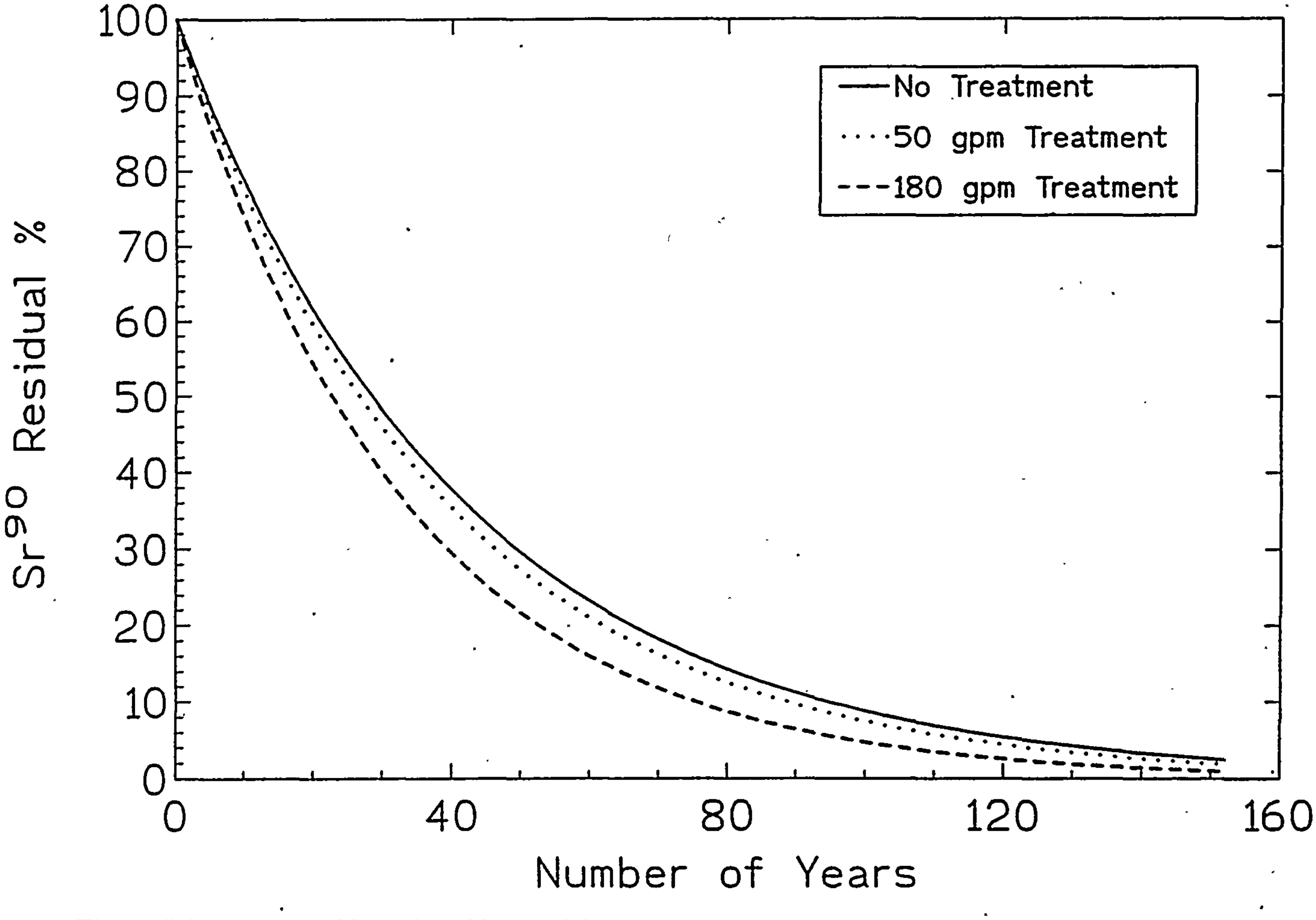

Figure 5.1. Amount of Strontium-90 Remaining in the Aquifer as a Function of Time for Two Pump Rates with Natural Decay and for Natural Decay Only

close to the value of 15 ml/g chosen for all the calculations in Section 5.0 and the value chosen from analyses of the bench-scale column experiments presented in Section 4.0.

The concentrations of ^{90}Sr being withdrawn in the other three wells being used in the field demonstration are much lower and have shown further decreases with continued pumping. Well N-75 yielded water with 900 pCi/l ^{90}Sr in the beginning but the value dropped to 400 pCi/l within about one month of pumping. Well N-105A yielded water that originally contained 300 pCi/l ^{90}Sr, but after 40 days the concentration dropped off to about 150 pCi/l. Sediments in this borehole at shallower depths above the existing water table contain the highest ^{90}Sr contents measured in any of the boreholes for which data are currently available (see Table 2.5). Therefore, this well is not producing extractable ^{90}Sr with much efficiency, likely because the water table is now below the zone of highest contamination. Well N-103A has never yielded groundwater with ^{90}Sr concentrations above 20 pCi/l despite having relatively high ^{90}Sr contents in the zone between 65 and 72 ft. below the surface (see Table 2.5). Again, this suggests that the ^{90}Sr contamination is now above the water table.

The 75 to 88 curies of ^{90}Sr calculated to exist in the aquifer represents only a small fraction of the ^{90}Sr inventory calculated to exist within the vadose zone sediments and inactive LWDFs above the existing plume. DOE/RL(1995) calculates the inventory in the vadose zone and LWDFs at ~1800 curies. However, as presented in Alexander and Johnson (1993), this inventory should decay essentially in place and contribute insignificant amounts of ^{90}Sr to the existing aquifer under natural conditions (i.e., no anthropogenic induced higher recharge rates).

Finally, the algorithm presented in the Appendix can be approximated by an exponential decay curve just as radioactive decay can be. Using the Kd for Sr of 15 ml/g and the estimated volume of the existing ^{90}Sr plume, we calculate that one would need to pump the contaminated aquifer at a rate of ~760 gpm to remove ^{90}Sr at the same rate that natural radioactive decay "removes" the ^{90}Sr. That is, if pump-and-treat could be performed at the ideal efficiency found in the bench-scale tests (see Section 4.0), it would take a pump rate of 760 gpm to remove ^{90}Sr as fast as natural decay. When pump-and-treat removal equals natural decay this would effectively double the rate of removal of ^{90}Sr shown in the last column of Table 5.2. It would likely require pump rates much higher than 760 gpm to get the efficiency of the pump-and-treat technique to reach the ^{90}Sr removal rate provided by natural radioactive decay.

6.0 Conclusions

The characterization data presented in Section 2.0 for 12 new boreholes (eight near the Columbia River, where the sheet pile barrier wall was to be emplaced and four inland) to better define the areal extent of contamination downgradient from the 1301-N LWDF suggest that the ^{90}Sr contamination resides in a relatively thin layer in the Ringold Unit E and in the Hanford-Ringold E interface along the Columbia River. Further, the most contaminated sediments are at a depth that corresponds with the estimated historically high water table formed during the active disposal phase. It appears that the cooling water containing ^{90}Sr "floated on top of the natural groundwater" and interacted with the sediments in a narrow band often as thin as 10 to 20 ft. or, near the river, as thin as 5 to 10 ft. The highest activity of ^{90}Sr found in the borehole sediments analyzed occurs in borehole N-105A downgradient from the 1301-N trench. At a depth of 51 to 52 ft. from ground surface the ^{90}Sr activity is ~460,000 pCi/kg, yet a sample at 45 ft. shows no ^{90}Sr. At depths of 55-75 ft. the ^{90}Sr activity slowly drops from 140,000 to 70,000 pCi/kg. At 80 ft. the activity is ~10,000 pci/kg, and by 86 ft. it is only 2,000 pci/kg. Thus, the whole zone of contamination is only about 40 ft. thick. At the other boreholes, except N-106A, with lower activities of ^{90}Sr the contamination zone is generally no thicker than 20 ft. Considerable amounts of the adsorbed ^{90}Sr appear to be above the current water table and thus are not available to interact with water injected and withdrawn during pump-and-treat remediation. This fact should be considered in determining the efficacy of pump-and-treat remediation if removal of all the ^{90}Sr, both that adsorbed on the aquifer sediments and that already in the groundwater, is the goal.

The adsorption-desorption data for strontium were evaluated using several techniques including adsorption of ^{85}Sr (a convenient surrogate for ^{90}Sr because it emits an easily measured gamma ray) onto uncontaminated sediments from depths above and below the zone of contamination; desorption experiments of ^{85}Sr and ^{90}Sr from laboratory-contaminated sediments and actual field samples from the zone of contamination, respectively; and flow-through column desorption tests on actual contaminated sediment from borehole N-105A.

Several geochemical issues were addressed using the various test methodologies. Issues included the reversibility of adsorption-desorption, linearity of the strontium Kd as a function of contaminant concentration, the possibility that "aging" could make desorption more difficult, the effect of particle size on Kd, and the effect of contact time on strontium adsorption and desorption (kinetics). About 80 individual samples were studied, which represents one of the largest data bases ever generated for one contaminant with sediment from one area at the Hanford Site.

Results discussed in Sections 3.0 and 4.0 lead to the following conclusions. Strontium-90 that was present in the cooling waters disposed to the two LWDFs in the 100-N Area adsorbed moderately to the relatively coarse-grained sediments in the upper unconfined aquifer. The ^{90}Sr is well-behaved in regard to geochemical traits such as adsorption-desorption reversibility, linearity, and aging. The kinetic studies also suggest ^{90}Sr adsorption-desorption reactions come to equilibrium quite rapidly (within 8 hours and perhaps within 2 hours,) which would indicate simple surface adsorption processes. These laboratory tests and other studies referenced in the main text also suggest that the ^{90}Sr is adsorbing via simple ion-exchange reactions, where other divalent cations naturally present in the groundwater can readily compete for sorption sites and cause desorption. All the data suggest that ^{90}Sr is behaving as one would expect for an ideal trace constituent that is controlled by simple ion-exchange reactions. The use of the Kd construct (Serne and Muller 1987, Serne 1992) thus appears fully justified. This should allow simple fate and transport calculations as generally performed for radionuclides to yield accurate predictions. Some examples of this approach specific to the N-Springs "issue" can be found in Knepp et al. (1995), Connelly et al. (1991), and DOE/RL (1995).

Kd values for ^{85}Sr for the adsorption direction for the <2-mm-size fraction of the coarse-grained sediments in the Hanford and Upper Ringold Unit E formations and an actual 100-N area groundwater sample were found to be about 28 ±7 ml/g, regardless of the concentration of ^{85}Sr used (as long as it was very low compared to the stable strontium naturally present). Using the same sediment samples, the previously adsorbed ^{85}Sr was desorbed into another batch of groundwater with a Kd of 32 ±7 ml/g. These values are statistically equivalent and support reversible ion exchange as the controlling mechanism. Using contaminated sediments from the same boreholes that are also from the Ringold Unit E, the desorption of ^{90}Sr was found to be 40 ±13 ml/g for the <2-mm fraction. This suggests that the ^{90}Sr is well-behaved and not showing significant aging effects in which desorption becomes less and less possible with time since disposal. For the boreholes farther inland and nearer to the LWDFs, the ^{90}Sr desorption Kd for <2-mm fractions of the Ringold Unite E were 38 ±17 for a small data set of three.

Strontium-90 desorption Kd values also were measured on various size fractions of one borehole sample, N-105A, and there was a distinctly different Kd for the three size fractions. The Kd for the <2-mm fraction averaged 58 ±10 ml/g, the 2 to 13.2-mm-size fraction yielded a Kd value of 39 ml/g, and the >13.2-mm-size fraction yielded a value of 8 ± 1 ml/g. The lower Kd with increasing particle size likely reflects the fact that finer grained material has more adsorption sites, and some of them have a higher selectivity for trace contaminants than do coarser materials.

Fine-grained material in the Upper Ringold Mud Unit yielded Kd values as high as 250 ml/g, but no ^{90}Sr has been found to have reached this layer situated under the Ringold E Unit, and thus this sediment has little importance to the "N-Spring" issue.

One sample from borehole N-103A contained in a split spoon steell liner (likely not significantly disturbed during collection and shipment to the lab) was used to squeeze out the native pore water and to calculate an in situ Kd based on the ratio of the ^{90}Sr in the sediment divided by the ^{90}Sr content in the extracted pore water. The results for two aliquots of sediment (~<2-mm fraction) were 20 ±3 ml/g versus a value of 17 ml/g calculated from using Kd versus particle size relationships found for borehole N-105 and ratioed for the differences in the Kds for the <2-mm material for both boreholes. These values are considered to be quite comparable. Finally, two columns were packed with the whole sediment from borehole N-105A that included >13.2-mm, from 2 to 13.2- mm, and <2 -m fractions in the exact proportions found in the split spoon liner sent from the field. We elected to use the "bulk" sediment in the columns because this simulated actual field conditions. The columns were contacted with the simulated groundwater using two common pumping regimes (continual slow flow and pulsed-pump).

Results of the two flow-through column leach tests suggest that the desorption of ^{90}Sr reaches equilibrium within 6 to 8 hours and that the Kd for desorption of the "bulk" sediment is about 15 ml/g. A calculation of the "bulk" Kd, based on results of batch testing the individual size fractions, yields a value of 37.6 ml/g. The agreement is not as good as we would like, and we have no explanation. After about 24 pore volumes of effluent was collected out of each column, only 17% of the total ^{90}Sr had been eluted. Thus pump-and-treat will require long time periods and large volumes of solution to be extracted to remove significant amounts of ^{90}Sr. The two pumping scenarios both resulted in the same performance because the desorption kinetics were fast enough for equilibrium to be reached as long as the flow rates were kept below 300 m/y (or residence time is kept above 6 hours in the contaminated zone).

An algorithm that assumes complete reversibility, rapid kinetics, and linear adsorption-desorption as a function of contaminant concentration (constant Kd provision) was generated to allow predictions of contaminant reduction via groundwater extraction. This algorithm should prove useful in interpreting field demonstration data and making simple predictions on the long-term efficacy of scaling up the demonstrated technology to full scale remediation. More sophisticated calculation could be made using transport codes such as described in Connelly et al. (1991) and DOE/RL (1995). Using the simple algorithm based on the laboratory column data, the following predictions are obtained. For a desorption Kd of 15 ml/g and ignoring radioactive decay, it will take 24 pore volumes to remove 20% of the ^{90}Sr, 74 pore volumes to remove 50% of the ^{90}Sr, and 245 pore volumes to remove 90% of the adsorbed ^{90}Sr. This assumes that the ex situ treatment removes all of the extracted ^{90}Sr before the water is reinjected into the aquifer or that only "fresh/clean" groundwater is forced into the contaminated zone.

There are many complicating real world events that will likely occur in the field that will make removal of the ^{90}Sr from the contaminated sediments underlying the 100-N Area less efficient than predictions based on the laboratory results and the simple algorithm. Such events include less efficient flushing of the thin layer of contaminated sediment because complete or optimum hydrologic control in the three-dimensional real world aquifer will not be possible, the withdrawal wells not being located right within the most contaminated sediments such that leached ^{90}Sr may readsorb on lesser contaminated sediments until the contaminants are drawn to the vicinity of the withdrawal wells by the sequential desorption-adsorption dynamic process, and the reinjected treated water not having as high a concentration of competing divalent cations because the clinoptilolite exchange resin will remove stable strontium and some calcium and magnesium. If the recirculated water has less of these competing ions, then the strontium Kd value will increase, and desorption will take longer to occur.

Based on the algorithm presented in the Appendix, the estimates of the size of the existing ^{90}Sr plume presented in Section 5.0 and natural radioactive decay, it would take 75 to 90 years to remove 90% of the ^{90}Sr in the existing aquifer at pump rates from 50 to 180 gpm. The Tri-Party Agreement goal is set at 90% removal. Natural radioactive decay will "remove" 90% of the ^{90}Sr in 95 years without any groundwater extraction. Thus, the efficacy of pump-and-treat deserves careful scrutiny to evaluate its usefulness and cost-effectiveness as a remediation process at the 100-N Area.

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PNL ANALYTICAL PROCEDURES

PNL-ALO-106(Rev. 0) "Acid Digestion for Preparation of Samples for Radiochemical Analysis."

PNL-ALO-418 "Tritium Determination in Soil and Water Using Lachat Micro-Distillation System."

PNL-ALO-441 " Radionuclide Separation and Analyses Procedure for Tritium."

PNL-ALO-443 " Liquid Scintillation Counting Procedure for Tritium."

PNL-ALO-464 " Procedure for Gamma Counting and Data Reduction in the Low-Level Counting Room."

PNL-ALO-476 " Strontium Determination Using Sr-SPEC Procedures."

Appendix

Spreadsheet Calculations of Strontium-90 Leaching from Contaminated Sediments

Appendix

Spreadsheet Calculations of Strontium-90 Leaching from Contaminated Sediments

The following is the output from an EXCEL spreadsheet that was generated to make calculations for the desorption of ^{90}Sr from contaminated soil. Pertinent assumptions include using an uncontaminated groundwater as the leaching fluid, the column is equivalent to a stirred reactor (one homogeneous cell), that the desorption kinetics are fast relative to the flow rate of the groundwater (equilibrium is maintained at all times), and that the Kd remains constant during the entire calculation.

The specific case shown uses a fixed Kd of 15 ml/g, an initial ^{90}Sr activity of 92,000 pCi/kg in the sediment, a dry bulk density of 2.0 g/cm^3, a particle density of 2.78 g/cm^3, and thus a porosity of 0.28 and a total column volume of 1280 cm^3.

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
Start	92000.00	235520.00	0.00	0.00	0.00	0.00
1	91137.50	233312.00	2208.00	2208.00	6133.33	0.94
2	90283.09	231124.70	2187.30	4395.30	6075.83	1.87
3	89436.68	228957.91	2166.79	6562.09	6018.87	2.79
4	88598.21	226811.43	2146.48	8708.57	5962.45	3.70
5	87767.60	224685.07	2126.36	10834.93	5906.55	4.60
6	86944.78	222578.65	2106.42	12941.35	5851.17	5.49
7	86129.68	220491.97	2086.67	15028.03	5796.32	6.38
8	85322.21	218424.86	2067.11	17095.14	5741.98	7.26
9	84522.31	216377.13	2047.73	19142.87	5688.15	8.13
10	83729.92	214348.59	2028.54	21171.41	5634.82	8.99
11	82944.95	212339.07	2009.52	23180.93	5581.99	9.84
12	82167.34	210348.39	1990.68	25171.61	5529.66	10.69
13	81397.02	208376.38	1972.02	27143.62	5477.82	11.52
14	80633.93	206422.85	1953.53	29097.15	5426.47	12.35
15	79877.98	204487.63	1935.21	31032.37	5375.60	13.18
16	79129.13	202570.56	1917.07	32949.44	5325.20	13.99
17	78387.29	200671.46	1899.10	34848.54	5275.28	14.80
18	77652.41	198790.17	1881.29	36729.83	5225.82	15.60
19	76924.42	196926.51	1863.66	38593.49	5176.83	16.39
20	76203.25	195080.33	1846.19	40439.67	5128.29	17.17
21	75488.85	193251.45	1828.88	42268.55	5080.22	17.95
22	74781.14	191439.71	1811.73	44080.29	5032.59	18.72
23	74080.07	189644.97	1794.75	45875.03	4985.41	19.48
24	73385.56	187867.05	1777.92	47652.95	4938.67	20.23
25	72697.58	186105.79	1761.25	49414.21	4892.37	20.98
26	72016.04	184361.05	1744.74	51158.95	4846.51	21.72
27	71340.89	182632.67	1728.38	52887.33	4801.07	22.46
28	70672.06	180920.48	1712.18	54599.52	4756.06	23.18
29	70009.51	179224.35	1696.13	56295.65	4711.47	23.90
30	69353.17	177544.13	1680.23	57975.87	4667.30	24.62
31	68702.99	175879.65	1664.48	59640.35	4623.54	25.32
32	68058.90	174230.78	1648.87	61289.22	4580.20	26.02
33	67420.85	172597.37	1633.41	62922.63	4537.26	26.72
34	66788.78	170979.26	1618.10	64540.74	4494.72	27.40
35	66162.63	169376.33	1602.93	66143.67	4452.59	28.08
36	65542.36	167788.43	1587.90	67731.57	4410.84	28.76
37	64927.90	166215.41	1573.02	69304.59	4369.49	29.43
38	64319.20	164657.14	1558.27	70862.86	4328.53	30.09
39	63716.20	163113.48	1543.66	72406.52	4287.95	30.74
40	63118.87	161584.30	1529.19	73935.70	4247.75	31.39
41	62527.13	160069.44	1514.85	75450.56	4207.92	32.04
42	61940.93	158568.79	1500.65	76951.21	4168.48	32.67
43	61360.24	157082.21	1486.58	78437.79	4129.40	33.30
44	60784.99	155609.56	1472.65	79910.44	4090.68	33.93
45	60215.13	154150.72	1458.84	81369.28	4052.33	34.55
46	59650.61	152705.56	1445.16	82814.44	4014.34	35.16
47	59091.39	151273.95	1431.61	84246.05	3976.71	35.77
48	58537.40	149855.75	1418.19	85664.25	3939.43	36.37
49	57988.62	148450.86	1404.90	87069.14	3902.49	36.97

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
50	57444.97	147059.13	1391.73	88460.87	3865.91	37.56
51	56906.43	145680.45	1378.68	89839.55	3829.66	38.15
52	56372.93	144314.69	1365.75	91205.31	3793.76	38.73
53	55844.43	142961.74	1352.95	92558.26	3758.20	39.30
54	55320.89	141621.48	1340.27	93898.52	3722.96	39.87
55	54802.26	140293.78	1327.70	95226.22	3688.06	40.43
56	54288.49	138978.52	1315.25	96541.48	3653.48	40.99
57	53779.53	137675.60	1302.92	97844.40	3619.23	41.54
58	53275.35	136384.89	1290.71	99135.11	3585.30	42.09
59	52775.89	135106.28	1278.61	100413.72	3551.69	42.63
60	52281.12	133839.66	1266.62	101680.34	3518.39	43.17
61	51790.98	132584.91	1254.75	102935.09	3485.41	43.71
62	51305.44	131341.93	1242.98	104178.07	3452.73	44.23
63	50824.45	130110.60	1231.33	105409.40	3420.36	44.76
64	50347.97	128890.81	1219.79	106629.19	3388.30	45.27
65	49875.96	127682.46	1208.35	107837.54	3356.53	45.79
66	49408.37	126485.44	1197.02	109034.56	3325.06	46.30
67	48945.17	125299.64	1185.80	110220.36	3293.89	46.80
68	48486.31	124124.95	1174.68	111395.05	3263.01	47.30
69	48031.75	122961.28	1163.67	112558.72	3232.42	47.79
70	47581.45	121808.52	1152.76	113711.48	3202.12	48.28
71	47135.38	120666.56	1141.95	114853.44	3172.10	48.77
72	46693.48	119535.32	1131.25	115984.68	3142.36	49.25
73	46255.73	118414.67	1120.64	117105.33	3112.90	49.72
74	45822.08	117304.53	1110.14	118215.47	3083.72	50.19
75	45392.50	116204.80	1099.73	119315.20	3054.81	50.66
76	44966.95	115115.38	1089.42	120404.62	3026.17	51.12
77	44545.38	114036.18	1079.21	121483.82	2997.80	51.58
78	44127.77	112967.09	1069.09	122552.91	2969.69	52.04
79	43714.07	111908.02	1059.07	123611.98	2941.85	52.48
80	43304.25	110858.88	1049.14	124661.12	2914.27	52.93
81	42898.27	109819.58	1039.30	125700.42	2886.95	53.37
82	42496.10	108790.02	1029.56	126729.98	2859.88	53.81
83	42097.70	107770.12	1019.91	127749.88	2833.07	54.24
84	41703.04	106759.77	1010.34	128760.23	2806.51	54.67
85	41312.07	105758.90	1000.87	129761.10	2780.20	55.10
86	40924.77	104767.41	991.49	130752.59	2754.14	55.52
87	40541.10	103785.22	982.19	131734.78	2728.32	55.93
88	40161.03	102812.23	972.99	132707.77	2702.74	56.35
89	39784.52	101848.36	963.86	133671.64	2677.40	56.76
90	39411.54	100893.54	954.83	134626.46	2652.30	57.16
91	39042.05	99947.66	945.88	135572.34	2627.44	57.56
92	38676.04	99010.65	937.01	136509.35	2602.80	57.96
93	38313.45	98082.43	928.22	137437.57	2578.40	58.35
94	37954.26	97162.90	919.52	138357.10	2554.23	58.75
95	37598.44	96252.00	910.90	139268.00	2530.28	59.13
96	37245.95	95349.64	902.36	140170.36	2506.56	59.52
97	36896.77	94455.73	893.90	141064.27	2483.06	59.89
98	36550.86	93570.21	885.52	141949.79	2459.78	60.27
99	36208.20	92692.99	877.22	142827.01	2436.72	60.64

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
100	35868.75	91823.99	869.00	143696.01	2413.88	61.01
101	35532.48	90963.14	860.85	144556.86	2391.25	61.38
102	35199.36	90110.37	852.78	145409.63	2368.83	61.74
103	34869.37	89265.58	844.78	146254.42	2346.62	62.10
104	34542.47	88428.72	836.86	147091.28	2324.62	62.45
105	34218.63	87599.70	829.02	147920.30	2302.83	62.81
106	33897.83	86778.45	821.25	148741.55	2281.24	63.15
107	33580.04	85964.90	813.55	149555.10	2259.86	63.50
108	33265.23	85158.98	805.92	150361.02	2238.67	63.84
109	32953.37	84360.62	798.37	151159.38	2217.68	64.18
110	32644.43	83569.73	790.88	151950.27	2196.89	64.52
111	32338.39	82786.27	783.47	152733.73	2176.30	64.85
112	32035.21	82010.15	776.12	153509.85	2155.89	65.18
113	31734.88	81241.30	768.85	154278.70	2135.68	65.51
114	31437.37	80479.66	761.64	155040.34	2115.66	65.83
115	31142.64	79725.17	754.50	155794.83	2095.82	66.15
116	30850.68	78977.74	747.42	156542.26	2076.18	66.47
117	30561.46	78237.33	740.42	157282.67	2056.71	66.78
118	30274.94	77503.85	733.47	158016.15	2037.43	67.09
119	29991.11	76777.25	726.60	158742.75	2018.33	67.40
120	29709.95	76057.47	719.79	159462.53	1999.41	67.71
121	29431.42	75344.43	713.04	160175.57	1980.66	68.01
122	29155.50	74638.07	706.35	160881.93	1962.09	68.31
123	28882.17	73938.34	699.73	161581.66	1943.70	68.61
124	28611.39	73245.17	693.17	162274.83	1925.48	68.90
125	28343.16	72558.50	686.67	162961.50	1907.43	69.19
126	28077.45	71878.26	680.24	163641.74	1889.54	69.48
127	27814.22	71204.40	673.86	164315.60	1871.83	69.77
128	27553.46	70536.86	667.54	164983.14	1854.28	70.05
129	27295.15	69875.58	661.28	165644.42	1836.90	70.33
130	27039.26	69220.49	655.08	166299.51	1819.68	70.61
131	26785.76	68571.55	648.94	166948.45	1802.62	70.89
132	26534.65	67928.69	642.86	167591.31	1785.72	71.16
133	26285.88	67291.86	636.83	168228.14	1768.98	71.43
134	26039.45	66661.00	630.86	168859.00	1752.39	71.70
135	25795.33	66036.05	624.95	169483.95	1735.96	71.96
136	25553.50	65416.97	619.09	170103.03	1719.69	72.22
137	25313.94	64803.68	613.28	170716.32	1703.57	72.48
138	25076.62	64196.15	607.53	171323.85	1687.60	72.74
139	24841.53	63594.31	601.84	171925.69	1671.77	73.00
140	24608.64	62998.11	596.20	172521.89	1656.10	73.25
141	24377.93	62407.51	590.61	173112.49	1640.58	73.50
142	24149.39	61822.43	585.07	173697.57	1625.20	73.75
143	23922.99	61242.85	579.59	174277.15	1609.96	74.00
144	23698.71	60668.70	574.15	174851.30	1594.87	74.24
145	23476.53	60099.93	568.77	175420.07	1579.91	74.48
146	23256.44	59536.49	563.44	175983.51	1565.10	74.72
147	23038.41	58978.34	558.15	176541.66	1550.43	74.96
148	22822.43	58425.42	552.92	177094.58	1535.89	75.19
149	22608.47	57877.68	547.74	177642.32	1521.50	75.43

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
150	22396.51	57335.07	542.60	178184.93	1507.23	75.66
151	22186.55	56797.56	537.52	178722.44	1493.10	75.88
152	21978.55	56265.08	532.48	179254.92	1479.10	76.11
153	21772.50	55737.60	527.49	179782.40	1465.24	76.33
154	21568.38	55215.06	522.54	180304.94	1451.50	76.56
155	21366.18	54697.41	517.64	180822.59	1437.89	76.78
156	21165.87	54184.63	512.79	181335.37	1424.41	76.99
157	20967.44	53676.65	507.98	181843.35	1411.06	77.21
158	20770.87	53173.43	503.22	182346.57	1397.83	77.42
159	20576.14	52674.93	498.50	182845.07	1384.72	77.63
160	20383.24	52181.10	493.83	183338.90	1371.74	77.84
161	20192.15	51691.90	489.20	183828.10	1358.88	78.05
162	20002.85	51207.29	484.61	184312.71	1346.14	78.26
163	19815.32	50727.22	480.07	184792.78	1333.52	78.46
164	19629.55	50251.65	475.57	185268.35	1321.02	78.66
165	19445.52	49780.54	471.11	185739.46	1308.64	78.86
166	19263.22	49313.85	466.69	186206.15	1296.37	79.06
167	19082.63	48851.53	462.32	186668.47	1284.21	79.26
168	18903.73	48393.55	457.98	187126.45	1272.18	79.45
169	18726.51	47939.86	453.69	187580.14	1260.25	79.65
170	18550.95	47490.42	449.44	188029.58	1248.43	79.84
171	18377.03	47045.20	445.22	188474.80	1236.73	80.02
172	18204.75	46604.15	441.05	188915.85	1225.14	80.21
173	18034.08	46167.24	436.91	189352.76	1213.65	80.40
174	17865.01	45734.42	432.82	189785.58	1202.27	80.58
175	17697.52	45305.66	428.76	190214.34	1191.00	80.76
176	17531.61	44880.92	424.74	190639.08	1179.83	80.94
177	17367.25	44460.16	420.76	191059.84	1168.77	81.12
178	17204.43	44043.35	416.81	191476.65	1157.82	81.30
179	17043.14	43630.44	412.91	191889.56	1146.96	81.47
180	16883.36	43221.41	409.04	192298.59	1136.21	81.65
181	16725.08	42816.21	405.20	192703.79	1125.56	81.82
182	16568.28	42414.80	401.40	193105.20	1115.01	81.99
183	16412.96	42017.16	397.64	193502.84	1104.55	82.16
184	16259.08	41623.25	393.91	193896.75	1094.20	82.33
185	16106.65	41233.04	390.22	194286.96	1083.94	82.49
186	15955.65	40846.48	386.56	194673.52	1073.78	82.66
187	15806.07	40463.54	382.94	195056.46	1063.71	82.82
188	15657.89	40084.19	379.35	195435.81	1053.74	82.98
189	15511.10	39708.41	375.79	195811.59	1043.86	83.14
190	15365.68	39336.14	372.27	196183.86	1034.07	83.30
191	15221.63	38967.36	368.78	196552.64	1024.38	83.45
192	15078.92	38602.04	365.32	196917.96	1014.78	83.61
193	14937.56	38240.15	361.89	197279.85	1005.26	83.76
194	14797.52	37881.65	358.50	197638.35	995.84	83.92
195	14658.79	37526.51	355.14	197993.49	986.50	84.07
196	14521.37	37174.70	351.81	198345.30	977.25	84.22
197	14385.23	36826.18	348.51	198693.82	968.09	84.36
198	14250.37	36480.94	345.25	199039.06	959.02	84.51
199	14116.77	36138.93	342.01	199381.07	950.02	84.66

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
200	13984.42	35800.13	338.80	199719.87	941.12	84.80
201	13853.32	35464.50	335.63	200055.50	932.29	84.94
202	13723.45	35132.02	332.48	200387.98	923.55	85.08
203	13594.79	34802.66	329.36	200717.34	914.90	85.22
204	13467.34	34476.38	326.27	201043.62	906.32	85.36
205	13341.08	34153.17	323.22	201366.83	897.82	85.50
206	13216.01	33832.98	320.19	201687.02	889.41	85.63
207	13092.11	33515.80	317.18	202004.20	881.07	85.77
208	12969.37	33201.59	314.21	202318.41	872.81	85.90
209	12847.78	32890.32	311.26	202629.68	864.62	86.04
210	12727.33	32581.98	308.35	202938.02	856.52	86.17
211	12608.02	32276.52	305.46	203243.48	848.49	86.30
212	12489.82	31973.93	302.59	203546.07	840.53	86.42
213	12372.72	31674.17	299.76	203845.83	832.65	86.55
214	12256.73	31377.23	296.95	204142.77	824.85	86.68
215	12141.82	31083.06	294.16	204436.94	817.12	86.80
216	12027.99	30791.66	291.40	204728.34	809.45	86.93
217	11915.23	30502.99	288.67	205017.01	801.87	87.05
218	11803.52	30217.02	285.97	205302.98	794.35	87.17
219	11692.87	29933.74	283.28	205586.26	786.90	87.29
220	11583.25	29653.11	280.63	205866.89	779.52	87.41
221	11474.65	29375.11	278.00	206144.89	772.22	87.53
222	11367.08	29099.72	275.39	206420.28	764.98	87.64
223	11260.51	28826.91	272.81	206693.09	757.81	87.76
224	11154.94	28556.66	270.25	206963.34	750.70	87.88
225	11050.37	28288.94	267.72	207231.06	743.66	87.99
226	10946.77	28023.73	265.21	207496.27	736.69	88.10
227	10844.14	27761.01	262.72	207758.99	729.78	88.21
228	10742.48	27500.75	260.26	208019.25	722.94	88.32
229	10641.77	27242.93	257.82	208277.07	716.17	88.43
230	10542.00	26987.53	255.40	208532.47	709.45	88.54
231	10443.17	26734.52	253.01	208785.48	702.80	88.65
232	10345.27	26483.88	250.64	209036.12	696.21	88.76
233	10248.28	26235.60	248.29	209284.40	689.68	88.86
234	10152.20	25989.64	245.96	209530.36	683.22	88.96
235	10057.03	25745.98	243.65	209774.02	676.81	89.07
236	9962.74	25504.62	241.37	210015.38	670.47	89.17
237	9869.34	25265.51	239.11	210254.49	664.18	89.27
238	9776.81	25028.65	236.86	210491.35	657.96	89.37
239	9685.16	24794.00	234.64	210726.00	651.79	89.47
240	9594.36	24561.56	232.44	210958.44	645.68	89.57
241	9504.41	24331.29	230.26	211188.71	639.62	89.67
242	9415.31	24103.19	228.11	211416.81	633.63	89.77
243	9327.04	23877.22	225.97	211642.78	627.69	89.86
244	9239.60	23653.37	223.85	211866.63	621.80	89.96
245	9152.98	23431.62	221.75	212088.38	615.97	90.05
246	9067.17	23211.95	219.67	212308.05	610.20	90.14
247	8982.16	22994.34	217.61	212525.66	604.48	90.24
248	8897.96	22778.77	215.57	212741.23	598.81	90.33
249	8814.54	22565.22	213.55	212954.78	593.20	90.42

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
250	8731.90	22353.67	211.55	213166.33	587.64	90.51
251	8650.04	22144.10	209.57	213375.90	582.13	90.60
252	8568.95	21936.50	207.60	213583.50	576.67	90.69
253	8488.61	21730.85	205.65	213789.15	571.26	90.77
254	8409.03	21527.12	203.73	213992.88	565.91	90.86
255	8330.20	21325.30	201.82	214194.70	560.60	90.95
256	8252.10	21125.38	199.92	214394.62	555.35	91.03
257	8174.74	20927.33	198.05	214592.67	550.14	91.11
258	8098.10	20731.13	196.19	214788.87	544.98	91.20
259	8022.18	20536.78	194.35	214983.22	539.87	91.28
260	7946.97	20344.25	192.53	215175.75	534.81	91.36
261	7872.47	20153.52	190.73	215366.48	529.80	91.44
262	7798.66	19964.58	188.94	215555.42	524.83	91.52
263	7725.55	19777.41	187.17	215742.59	519.91	91.60
264	7653.12	19592.00	185.41	215928.00	515.04	91.68
265	7581.38	19408.32	183.67	216111.68	510.21	91.76
266	7510.30	19226.37	181.95	216293.63	505.43	91.84
267	7439.89	19046.12	180.25	216473.88	500.69	91.91
268	7370.14	18867.57	178.56	216652.43	495.99	91.99
269	7301.05	18690.68	176.88	216829.32	491.34	92.06
270	7232.60	18515.46	175.23	217004.54	486.74	92.14
271	7164.79	18341.87	173.58	217178.13	482.17	92.21
272	7097.62	18169.92	171.96	217350.08	477.65	92.29
273	7031.08	17999.58	170.34	217520.42	473.17	92.36
274	6965.17	17830.83	168.75	217689.17	468.74	92.43
275	6899.87	17663.67	167.16	217856.33	464.34	92.50
276	6835.18	17498.07	165.60	218021.93	459.99	92.57
277	6771.10	17334.03	164.04	218185.97	455.68	92.64
278	6707.62	17171.52	162.51	218348.48	451.41	92.71
279	6644.74	17010.54	160.98	218509.46	447.17	92.78
280	6582.45	16851.06	159.47	218668.94	442.98	92.85
281	6520.74	16693.08	157.98	218826.92	438.83	92.91
282	6459.60	16536.59	156.50	218983.41	434.72	92.98
283	6399.05	16381.56	155.03	219138.44	430.64	93.04
284	6339.05	16227.98	153.58	219292.02	426.60	93.11
285	6279.63	16075.84	152.14	219444.16	422.60	93.17
286	6220.75	15925.13	150.71	219594.87	418.64	93.24
287	6162.43	15775.83	149.30	219744.17	414.72	93.30
288	6104.66	15627.93	147.90	219892.07	410.83	93.36
289	6047.43	15481.42	146.51	220038.58	406.98	93.43
290	5990.74	15336.28	145.14	220183.72	403.16	93.49
291	5934.57	15192.51	143.78	220327.49	399.38	93.55
292	5878.94	15050.08	142.43	220469.92	395.64	93.61
293	5823.82	14908.98	141.09	220611.02	391.93	93.67
294	5769.22	14769.21	139.77	220750.79	388.25	93.73
295	5715.14	14630.75	138.46	220889.25	384.61	93.79
296	5661.56	14493.59	137.16	221026.41	381.01	93.85
297	5608.48	14357.71	135.88	221162.29	377.44	93.90
298	5555.90	14223.10	134.60	221296.90	373.90	93.96
299	5503.81	14089.76	133.34	221430.24	370.39	94.02

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
300	5452.22	13957.67	132.09	221562.33	366.92	94.07
301	5401.10	13826.82	130.85	221693.18	363.48	94.13
302	5350.47	13697.19	129.63	221822.81	360.07	94.18
303	5300.30	13568.78	128.41	221951.22	356.70	94.24
304	5250.61	13441.57	127.21	222078.43	353.35	94.29
305	5201.39	13315.56	126.01	222204.44	350.04	94.35
306	5152.63	13190.72	124.83	222329.28	346.76	94.40
307	5104.32	13067.06	123.66	222452.94	343.51	94.45
308	5056.47	12944.56	122.50	222575.44	340.29	94.50
309	5009.06	12823.20	121.36	222696.80	337.10	94.56
310	4962.10	12702.99	120.22	222817.01	333.94	94.61
311	4915.58	12583.89	119.09	222936.11	330.81	94.66
312	4869.50	12465.92	117.97	223054.08	327.71	94.71
313	4823.85	12349.05	116.87	223170.95	324.63	94.76
314	4778.63	12233.28	115.77	223286.72	321.59	94.81
315	4733.83	12118.59	114.69	223401.41	318.58	94.85
316	4689.45	12004.98	113.61	223515.02	315.59	94.90
317	4645.48	11892.44	112.55	223627.56	312.63	94.95
318	4601.93	11780.94	111.49	223739.06	309.70	95.00
319	4558.79	11670.50	110.45	223849.50	306.80	95.04
320	4516.05	11561.09	109.41	223958.91	303.92	95.09
321	4473.71	11452.70	108.39	224067.30	301.07	95.14
322	4431.77	11345.33	107.37	224174.67	298.25	95.18
323	4390.22	11238.97	106.36	224281.03	295.45	95.23
324	4349.06	11133.60	105.37	224386.40	292.68	95.27
325	4308.29	11029.23	104.38	224490.77	289.94	95.32
326	4267.90	10925.83	103.40	224594.17	287.22	95.36
327	4227.89	10823.40	102.43	224696.60	284.53	95.40
328	4188.25	10721.93	101.47	224798.07	281.86	95.45
329	4148.99	10621.41	100.52	224898.59	279.22	95.49
330	4110.09	10521.83	99.58	224998.17	276.60	95.53
331	4071.56	10423.19	98.64	225096.81	274.01	95.57
332	4033.39	10325.48	97.72	225194.52	271.44	95.62
333	3995.58	10228.67	96.80	225291.33	268.89	95.66
334	3958.12	10132.78	95.89	225387.22	266.37	95.70
335	3921.01	10037.79	94.99	225482.21	263.87	95.74
336	3884.25	9943.68	94.10	225576.32	261.40	95.78
337	3847.84	9850.46	93.22	225669.54	258.95	95.82
338	3811.76	9758.11	92.35	225761.89	256.52	95.86
339	3776.03	9666.63	91.48	225853.37	254.12	95.90
340	3740.63	9576.00	90.62	225944.00	251.74	95.93
341	3705.56	9486.23	89.78	226033.77	249.38	95.97
342	3670.82	9397.30	88.93	226122.70	247.04	96.01
343	3636.40	9309.20	88.10	226210.80	244.72	96.05
344	3602.31	9221.92	87.27	226298.08	242.43	96.08
345	3568.54	9135.47	86.46	226384.53	240.15	96.12
346	3535.09	9049.82	85.65	226470.18	237.90	96.16
347	3501.95	8964.98	84.84	226555.02	235.67	96.19
348	3469.11	8880.93	84.05	226639.07	233.46	96.23
349	3436.59	8797.67	83.26	226722.33	231.27	96.26

Leach Curve Kd=15

Pore volumes	Sediment Conc.	Tot. pCi Sed	pCi Leached	Cum Leached	Solution Conc	% Leached
350	3404.37	8715.20	82.48	226804.80	229.11	96.30
351	3372.46	8633.49	81.70	226886.51	226.96	96.33
352	3340.84	8552.55	80.94	226967.45	224.83	96.37
353	3309.52	8472.37	80.18	227047.63	222.72	96.40
354	3278.49	8392.94	79.43	227127.06	220.63	96.44
355	3247.76	8314.26	78.68	227205.74	218.57	96.47
356	3217.31	8236.31	77.95	227283.69	216.52	96.50
357	3187.15	8159.10	77.22	227360.90	214.49	96.54
358	3157.27	8082.61	76.49	227437.39	212.48	96.57
359	3127.67	8006.83	75.77	227513.17	210.48	96.60
360	3098.35	7931.77	75.06	227588.23	208.51	96.63
361	3069.30	7857.41	74.36	227662.59	206.56	96.66
362	3040.53	7783.74	73.66	227736.26	204.62	96.70
363	3012.02	7710.77	72.97	227809.23	202.70	96.73
364	2983.78	7638.48	72.29	227881.52	200.80	96.76
365	2955.81	7566.87	71.61	227953.13	198.92	96.79
366	2928.10	7495.93	70.94	228024.07	197.05	96.82
367	2900.65	7425.66	70.27	228094.34	195.21	96.85
368	2873.45	7356.04	69.62	228163.96	193.38	96.88
369	2846.52	7287.08	68.96	228232.92	191.56	96.91
370	2819.83	7218.76	68.32	228301.24	189.77	96.93
371	2793.39	7151.09	67.68	228368.91	187.99	96.96
372	2767.21	7084.05	67.04	228435.95	186.23	96.99
373	2741.26	7017.63	66.41	228502.37	184.48	97.02
374	2715.56	6951.84	65.79	228568.16	182.75	97.05
375	2690.11	6886.67	65.17	228633.33	181.04	97.08
376	2664.89	6822.11	64.56	228697.89	179.34	97.10
377	2639.90	6758.15	63.96	228761.85	177.66	97.13
378	2615.15	6694.79	63.36	228825.21	175.99	97.16
379	2590.64	6632.03	62.76	228887.97	174.34	97.18
380	2566.35	6569.85	62.18	228950.15	172.71	97.21
381	2542.29	6508.26	61.59	229011.74	171.09	97.24
382	2518.46	6447.25	61.01	229072.75	169.49	97.26
383	2494.84	6386.80	60.44	229133.20	167.90	97.29
384	2471.46	6326.93	59.88	229193.07	166.32	97.31
385	2448.29	6267.61	59.31	229252.39	164.76	97.34
386	2425.33	6208.85	58.76	229311.15	163.22	97.36
387	2402.60	6150.64	58.21	229369.36	161.69	97.39
388	2380.07	6092.98	57.66	229427.02	160.17	97.41
389	2357.76	6035.86	57.12	229484.14	158.67	97.44
390	2335.65	5979.27	56.59	229540.73	157.18	97.46
391	2313.76	5923.22	56.06	229596.78	155.71	97.49
392	2292.07	5867.69	55.53	229652.31	154.25	97.51
393	2270.58	5812.68	55.01	229707.32	152.80	97.53
394	2249.29	5758.19	54.49	229761.81	151.37	97.56
395	2228.20	5704.20	53.98	229815.80	149.95	97.58
396	2207.31	5650.73	53.48	229869.27	148.55	97.60
397	2186.62	5597.75	52.98	229922.25	147.15	97.62
398	2166.12	5545.27	52.48	229974.73	145.77	97.65

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