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Evaluation of a Permeable Reactive Barrier Technology for Use at Rocky Flats Environmental Technology Site (RFETS)

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ADVANCED SUBSURFACE CONTAINMENT SYSTEMS
DESIGN AND PERFORMANCE EVALUATION OF REACTIVE MEDIA
TECHNICAL TASK PLAN NO. AL-28-SS-40

EVALUATION OF A PERMEABLE REACTIVE BARRIER TECHNOLOGY FOR USE AT ROCKY FLATS ENVIRONMENTAL TECHONOLOGY SITE (RFETS)

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ABSTRACT

Three reactive materials were evaluated at laboratory scale to identify the optimum treatment reagent for use in a Permeable Reactive Barrier Treatment System at Rocky Flats Environmental Technology Site (RFETS). The contaminants of concern (COCs) are uranium, TCE, PCE, carbon tetrachloride, americium, and vinyl chloride. The three reactive media evaluated included high carbon steel iron filings, an iron-silica alloy in the form of a foam aggregate, and a pellicular humic acid based sorbant (Humasorb from Arctech) mixed with sand. Each material was tested in the laboratory at column scale using simulated site water. All three materials showed promise for the 903 Mound Site; however, the iron filings were determined to be the least expensive media. In order to validate the laboratory results, the iron filings were further tested at a pilot scale (field columns) using actual site water. Pilot test results were similar to laboratory results; consequently, the iron filings were chosen for the full-scale demonstration of this reactive barrier technology. Additional design parameters including saturated hydraulic conductivity, treatment residence time, and head loss across the media were also determined and provided to the design team in support of the final design. The final design was completed by the Corps of Engineers in 1997 and the system was constructed in the summer of 1998. The treatment system began full operation in December, 1998 and despite a few problems has been operational since. Results to date are consistent with the lab and pilot scale findings, i.e., complete removal of the contaminants of concern (COCs) prior to discharge to meet RFETS cleanup requirements. Furthermore, it is fair to say at this point in time that laboratory developed design parameters for the reactive barrier technology are sufficient for full scale design; however, the treatment system longevity and the long-term fate of the contaminants are questions that remain unanswered. This project along with others such as the Durango, CO and Monticello, UT reactive barriers will provide the data to determine the long-term effectiveness and return on investment (ROI) for this technology for comparison to the baseline 'pump and treat'.

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1. INTRODUCTION

The primary objectives of this project were to: (1) identify the optimum treatment media (reagent) for the 903 Mound Site at Rocky Flats Environmental Technology Site (RFETS) proposed reactive barrier installation; and (2) conduct laboratory, pilot and full scale performance evaluation of the technology. The evaluation is divided into three parts: (1) a laboratory scale optimization of three potential reagents; and (2) a pilot-scale, field column study to verify laboratory results; and (3) performance monitoring and evaluation of the full scale reactive barrier. A secondary objective was to provide necessary design parameters to the design team for incorporation into the full-scale reactive barrier design. The required design parameters are: saturated hydraulic conductivity (Ks), required residence time for contaminant removal (tr), and the head loss across the media per unit length (hL).

The DOE employed quite a team on the 903 Mound Reactive Barrier project including MSE Technology Applications, Inc. (MSE), Corps of Engineers, EnviroMetal Technologies Inc. (ETI), U.S. Environmental Protection Agency (EPA), and Sandia National Laboratories (SNL). SNL is responsible for laboratory, pilot and full scale testing and evaluation for the entire waste stream, ETI was responsible for laboratory optimization of the media to treat the organic contaminants, MSE and the Corps of Engineers were responsible for the design and construction, and the EPA was responsible for providing an independent assessment of the treatment system performance for the first year of operation – FY 1999.

2. BACKGROUND

SITE DESCRIPTION

The 903 Mound Site was the location of a subsurface disposal cell consisting of approximately 1400 unconfined drums. The drums contained depleted uranium and beryllium contaminated lathe coolant – high in solvent content; enriched uranium and plutonium and tetrachloroethene (PCE). Although the contamination source was removed in 1970, the groundwater in the area shows residual concentration of TCE; carbon tetrachloride mixed with uranium and minor amounts of plutonium and americium. In FY 1998 a reactive barrier was constructed at the 903 Mound Site. The system is designed to passively remediate the site in situ. This is only the second reactive barrier installation in the country for remediation of mixed waste contamination. The U.S. Department of Energy (DOE) primary objectives are to: (1) meet Rocky Flats Site cleanup goals; (2) show demonstrated cost savings and return on investment over baseline; and (3) assist with transfer of technology for deployment at other sites and subsequent commercialization. In order to meet the stated objectives the treatment system effectiveness and longevity of the barrier will be closely monitored and reported.

SITE GEOLOGY

The Mound Site is located on relatively level ground along the southern edge of South Walnut Creek. The ground surface slopes to the north from the Mound Site. The surface deposits consist of approximately 12 ft. of Rocky Flats Alluvium, colluvium and slump deposits along with artificial fill, and undisturbed soil. Bedrock consisting of weathered claystone and minor sandstones of the Cretaceous Arapaho and Laramie Formations undulate approximately 15 to 20 ft. beneath the surface. The depth to groundwater is approximately 12 ft. (RMRS, 1997)

CONTAMINANT DESCRIPTION

Prior to installation of the 903 Mound Site reactive barrier treatment system, investigations in the vicinity indicated that 400 to 1,000 cubic yards of soil have residual volatile organic compounds (VOCs) contamination above Tier I Subsurface Soil Action Levels specified in the Rocky Flats Cleanup Agreement (RFCA) (DOE, 1996). For this reason the contamination has been termed the Mound Site Plume. Although the Mound Site Plume area has been well characterized, the boundaries of the plume are still not well defined (RMRS, 1997). Before construction of the treatment system to capture the Mound Site Plume, the groundwater was discharged as surface seeps and subsurface flow into South Walnut Creek Drainage. Total groundwater flow in the vicinity was estimated to range from 0.1 to 2 gpm. Groundwater samples for the plume are collected at monitoring location 10797. Results from one grab sample are shown in Table 1. In addition radioactive contaminants have been found above Colorado Water Quality Standards.

Table 1. VOC concentrations in grab groundwater collected at monitoring location 10797.

Contaminant	Minimum (*ug*/l)	Maximum (*ug*/l)	Average (*ug*/l)	Number of Defections	Colorado Water Quality Standard (*ug*/l)
Vinyl Chloride	nd	55.0	13.0	5	2
1,1-Dichloroethene	nd	94.2	18	8	7
Cis-1,2-Dichloroethene	nd	808.0	169.0	9	70
Carbon tetrachloride	nd	6.6	0.8	1	5
Trichloroethene	nd	844	195	9	5
Tetrachloroethene	nd	261	66	8	5
Dichloromethane	NA	NA	NA	NA	5
Trichloromethane	nd	177	17	6	8
1,1,1-Trichloroethane	NA	NA	NA	NA	200

Notes:

ug/l Micrograms per liter
NA Not Analyzed
nd Nondetect
Colorado Water Quality Standards for Segment 5 of Big Dry Creek required by the Rocky Flats Cleanup Agreement (DOE, 1996)
Source: RMRS 1997

The RFETS personnel determined that the following COCs were of primary concern for the 903 Mound Site study (Table 2). Additional contaminants were given consideration in order to enhance the technological application for other sites.

Table 2. 903 Mound Site COCs

Contaminants	Parts/Billion in 903 Mound Site Groundwater	Action Level (parts/billion)
Carbon Tetrachloride	1004	5
Tetrachloroethene	5496	5
Trichloroethene	5250	5
Vinyl Chloride	102	2
Uranium	3.4 pCi/L	3 pCi/L
Americium	0.25 pCi./L	0.15 pCi/L

Note: Contaminant concentrations are highest expected concentrations.

TECHNOLOGY DESCRIPTION

The 903 Mound Site reactive barrier system is essentially a funnel and gate concept, consisting of HDPE impermeable funnel sections that direct the water into the gate which is a collection sump that overflows via gravity to baffled plug flow reactors with iron filings as the treatment media. The entire system is passive in nature (gravity flow) and constructed in situ.

Critical system performance parameters that need to be evaluated over time are: (1) contaminant treatment effectiveness; (2) changes in hydraulic conductivity (head loss) across the treatment media; (3) longevity of iron media (biological/precipitation fouling and/or passivation are potential problems); and (4) contaminant fate (can the contaminant re-mobilize).

To date, six commercial reactive barriers have been installed at various sites but only one is being used to treat an inorganic compound (chromium) while the other five are treating organic contaminants. The Rocky Flats Environmental Technology Center has already begun construction of another reactive barrier at the East Trenches Site and has identified six additional sites that reactive barrier technology is being considered as the remedial method, contingent upon the effectiveness at the 903 Mound Site. Consequently, future deployments and subsequent commercialization of this technology hinges on data collection at the 903 Mound Site.

TREATMENT SYSTEM CHEMISTRY

The removal mechanisms for the VOCs and the inorganic compounds vary and are briefly described in the following sections:

Inorganic Compound Removal

The inorganic compounds (metals and radionuclides) present in the 903 Mound Site Plume are removed by reductive precipitation. The treatment reagent/media – iron filings (zero valent iron-ZVI) creates a reducing environment where the inorganic contaminants form insoluble phases.

These reactions are all pH dependent. Uranium precipitates as uraninite if the oxidation state is low enough. The concentration of carbonates, calcium, magnesium, dissolved oxygen and others in the groundwater system have an impact on what complexes or precipitates will form. It is essential that preliminary studies on the geochemistry of the groundwater system are evaluated to determine whether the potential formation of these mineral complex precipitates will adversely affect the performance of the reactive barrier by plugging off the porosity. Currently it is felt that creating a gradual or tapered reducing zone can help eliminate the potential clogging at the interface between the reactive media and the indigenous soil. This can be achieved by placing a porous material such as pea gravel upgradient of the reactive barrier. ZVI is gradually mixed with in an increasing percentage to cause a gradual-reducing zone with high porosity for precipitate formation.

Organic Compound Removal

The granular ZVI oxidizes as groundwater flows past, releasing electrons creating a reducing environment. The hydrocarbon-chloride bonds in the chlorinated contaminants become unstable and break apart. The breakdown is sequential, i.e., forming less chlorinated compounds and releasing chloride ions in the groundwater. The rate of the reaction depends primarily on the surface area of the iron or its abundance in the permeable reactive media (Gillham, 1997).

The dechlorination reaction is generally accompanied by a decrease in redox potential (Eh) a decrease in total dissolved solids (TDS), and an increase in pH for the groundwater system.

3. LABORATORY STUDY

The objective of the laboratory studies were to evaluate the contaminant removal effectiveness and hydraulic flow characteristics of the three potential treatment reagents. Results would identify the optimum material for the full-scale demonstration of reactive barrier technology.

Column Packings

Three solid sorbants or solid reducing reagents that were potential treatment reagents for use in a reactive barrier at the 903 Mound Site, located on RFETS were examined in column tests. A literature search identified three reagents that had the potential to remove the contaminants of concern (COCs) from the 903 Mound Site groundwater plume. The proposed sorbants or reagents included high carbon steel iron filings, an iron-silica alloy in the form of a foam aggregate, and a pellicular humic acid based sorbant (Humasorb from Arctech) mixed with sand. These three materials were packed into plexiglass columns (2.54 cm ID x 12.7 cm Long) manufactured by Soil Measurement Systems. Figure 1 displays the laboratory column setup.

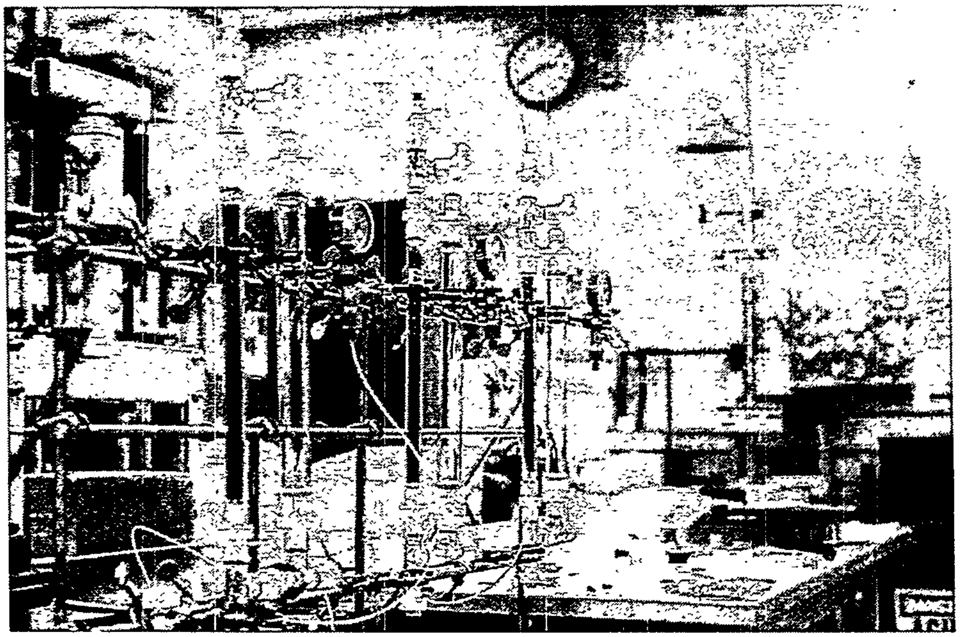


Figure 1. Laboratory Column Testing.

Flow Rates

The initial flow rate of influent through the column was chosen to reflect a contaminant resident time of approximately two hours. Based on measurements made for a set of two columns, Table 3 gives the average ratio of pore space to the total volume of the column packing. For columns of this size and type, a flow rate of 14-21 mL/hr is roughly equivalent to a residence time of two hours. A flow rate in this range, 17.5 mL/hr, was chosen for start up.

Table 3. Density and Pore Space Data for Column Packings to Be Used in Column Tests.

Sorbant or Reagent	Pore Space (%)	Bulk Density (g/mL)	Material Density (g/mL)
Iron Filings	65.5	2.74	7.97
Iron-Silica Alloy	69.8	2.18	7.25
Humasorb/sand	43.5	1.43	2.52

The specific objective of these experiments was to determine breakthrough concentrations of contaminants through the column at various flow rates. For the concentrations of contaminants used in this experiment it was assumed that the column capacity is many times greater than the amount of contaminant pumped through the column. Thus, breakthrough occurs because there is insufficient residence time for complete reduction or sorption of the metal contaminant rather than insufficient capacity.

Initially, the columns were washed with 500 mL of deionized water at a flow rate of 230-250 mL/hr. The deionized water rinse was used to strip loosely sorbed ions from the column packings and to remove air bubbles before the synthetic ground water samples were pumped through the columns. After the rinse was completed the columns were removed from the assembly and weighed, taking care not to siphon water from the columns.

The columns were incorporated once again into the column assembly and influent lines were connected to the influent reservoir containing the Rocky Flats synthetic water sample. The peristaltic pump was set to deliver influent at a rate of 17.5 mL/hr. The system was permitted to equilibrate at this initial flow rate for 12 hours before the first sample was taken. The first sample was taken after the equilibration step. To retrieve a 500-mL or larger sample, effluents were collected over a 32-hour period. Flow rates were increased over the course of the experiment several times. Each time, an equilibration step was used before taking a sample. The sampling schedule for column FE-1 is given in Table 4. Sampling the effluents of other columns was performed in a similar manner.

Table 4. Sample and Flow Rate Schedule for the First Run with Influents Containing Antimony, Thallium and Manganese.

Line Number	Action	Time from Start (hr)	Flow Rate (mL/hr)	Sample Size (mL)	Cumulative Volume (mL)
1	Equilibration 1	00:00-14:00	17.3	243	243
2	Sample 1	14:00-46:00	17.0	543	786
3	Equilibration 2	46:00-51:00	47.8	239	1025
4	Sample 2	51:00-63:00	48.2	579	1604
5	Equilibration 3	63:00-66:00	85.2	255	1859
6	Sample 3	66:00-72:00	84.2	505	2364
7	Equilibration 4	72:00-74:00	120	239	2603
8	Sample 4	74:00-78:30	120	540	3143
9	Equilibration 5	78:30-80:30	147	294	3437
10	Sample 5	80:30-84:00	152	533	3970
11	Equilibration 6	84:00-84:30	182	273	4243
12	Sample 6	84:30-87:30	184	552	4795
13	Equilibration 7	87:30-88:45	217	272	5067
14	Sample 7	88:45-91:15	215	539	5606

Contaminants

Radionuclides which were measured at levels exceeding the Rocky Flats Tier II action levels were the focus of our investigation. These include uranium 238, americium 241, and plutonium 239. The Tier II action levels and the starting concentrations of these metals in the column influents are listed in Tables 5 and 6. A single sample solution of these three species was prepared by Lovelace Biomedical and Environmental Research Institute and delivered in a 100-mL polypropylene bottle. It was prepared in concentrated form and added to 20 liters of the synthetic Rocky Flats ground water to produced 20 liters of sample influent that meets the concentration criteria indicated in Table 6. The pH of the synthetic Rocky Flats ground water was measured before and after addition of the sample concentrate to insure that the buffering capacity of the ground water was sufficient to absorb acid from the sample and maintain a neutral pH. No additional pH adjustment of the sample was necessary since the final pH was between 7.3 and 7.9.

The synthetic ground water was prepared from various inorganic salts to produce a background matrix for the metal sample solution similar to ground waters in the 903 Mound Site at Rocky Flats. Tables 7 and 8 give the make-up of the background electrolytes that were used for all column influents.

In addition to the three radionuclides mentioned, non-radioactive metals in concentrations exceeding the Tier II action levels were used in separate column studies. These included manganese, antimony, and thallium. A single eluent with these three metals was made from purchased and prepared 1000-ppm standards in dilute nitric or hydrochloric acid. The same background matrix composition as the eluents containing the radionuclides was used (Tables 7 and 8).

Table 5. Action Levels for Metal Contaminants to Be Used in Column Experiments and Highest Reported Concentrations in the Ground Waters at the Rocky Flats Site.

Metal Contaminant	Highest Reported Activity	Highest Reported Conc	Tier II Action Level Activities	Tier II Action Level Conc
Americium				
241	0.25 pCi/L	0.072 pg/L	0.145 pCi/L	0.042 pg/L
Plutonium				
239	0.18 pCi/L	2.90 pg/L	0.151 pCi/L	2.43 pg/L
240	0.18 pCi/L	0.79 pg/L	0.151 pCi/L	0.659 pg/L
Uranium				
238	3.02 pCi/L	8.96 μg/L	0.768 pCi/L	2.28 μg/L
233	3.40 pCi/L	0.348 μg/L	2.98 pCi/L	0.305 ng/L
234	3.40 pCi/L	0.543 μg/L	2.98 pCi/L	0.476 ng/L
Antimony		16.0 μg/L		6 μg/L
Manganese		339.2 μg/L		183 μg/L
Thallium		4.6 μg/L		2 μg/L

Table 6. Initial Concentrations to Be Used in Column Experiments.

Metal Contaminant	Conc of Column Influent	Activity of Column Influent	Target Conc of Column Effluent	Target Activity of Column Effluent
Americium 241	5 pg/L	17.4 pCi/L	0.042	0.145 pCi/L
Plutonium 239	50 pg/L	3.11 pCi/L	2.43 pg/L	0.151 pCi/L
Uranium 238	50 µg/L	16.7 pCi/L	2.28 µg/L	0.768 pCi/L
Antimony	100 µg/L		6 µg/L	
Manganese	500 µg/L		183 µg/L	
Thallium	50 µg/L		2 µg/L	

Table 7. The Make-up of the Background Matrix for Column Influents by Salt Type.

Electrolyte Salt	Molecular Weight	Concentration (M)	Grams/20-Liter
$NaHCO_3$	84.01	3.00 x 10-3	5.041
$MgCO_3$	84.32	1.00 x 10-3	1.686
$CaSO_4$-$2H_20$	172.10	1.20 x 10-3	4.130
$CaCl_2$-$2H_20$	147.02	1.00 x 10-3	2.940
KCl	74.56	0.05 x 10-3	0.0746
HCl (36-37%)	36.46	1.00 x 10-3	1.967

Table 8. The Make-up of the Background Matrix for Column Influents b.

Cations	F. Wt.	ppm	Anions	F. Wt.	Ppm
Ca^{2+}	40.08	88.2	$S0_4^{2-}$	96.06	115.3
Mg^{2+}	24.31	24.3	Cl^-	35.45	108.1
Na^+	22.99	69.0	HCO_3^-	61.02	244.1
K^+	39.10	2.0			

Procedure

Columns manufactured by Soil Measurement systems were used. All columns were dry packed. The column material was compressed by lightly tapping the column on a rigid surface for several minutes until no additional compacting was observed. Sufficient material was added to completely fill a 1 x 5-inch column without leaving void space between the bed support and the column packing. The columns were weighed before and after packing. Teflon filters (10 µm, manufactured by MSI) were installed between the packing support and the packing material. Figure 2 shows the loaded columns.

Three columns, one of each material, were run simultaneously. The sample influent for a given run was stored in a 20-L polyethylene carboy with faucet. The intake tubing for all three columns was placed through the lid of the container so that the ends rested on the bottom of the carboy. The tubing leading to and from the column, and the fittings were made of Teflon; however, silicon peristaltic tubing was used. The influents were pumped through the column from bottom to top with a Rainin (Rabbit model) peristaltic pump. Peristaltic tubing was used which was capable of delivering flow rates of 5 to 250 mL/hour. The reservoir, tubing and fittings were pre-soaked with 0.10 N HCI to remove adsorbed ions, then rinsed several times with deionized water. After rinsing with deionized water, the tubing was fit to the column and 500 mL of deionized water was pumped through the column at a high flow rate. The deionized water was replaced by the metal-ion influent and pumped through the column at an initial flow rate of about 17.5 mL/hr.

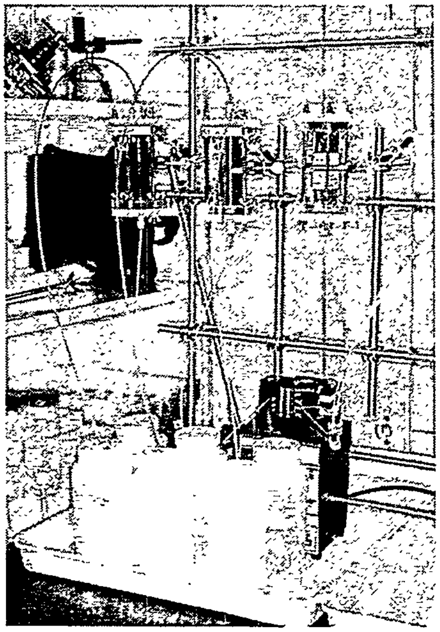


Figure 2. Laboratory column setup.

The effluents were collected in 1000-mL polypropylene sample bottles over concentrated nitric acid. A 2-mL aliquot of Fisher optima grade nitric acid was placed into the empty sample bottle and the bottle was weighed before collecting the sample. After the sample was collected, the bottles were weighed once again. Seven effluent samples were taken for each column. Each consecutive sample was collected at a progressively higher flow rate. Influent samples were collected concurrently with the effluent samples. Effluents from column studies with non-radioactive metals were analyzed by ICP mass spectroscopy at Sandia National Laboratories. Effluents from column studies that contained radionuclides were analyzed by alpha spectrometry by Lovelace Biomedical and Environmental Research Institute.

Results and Discussion

The results are summarized in Appendix A in eight tables (Tables A-1, A-2, A-3, A-4, A-5, A-6, A-7, and A-8) and three charts (Figures 3, 4, and 5) following this section of the report. The data are grouped by run number with four tables presented for each run. The first table in each group gives concentration values for influent samples. The remaining three tables in each group, one table for each of the reagents, contain data related to the concentration of metals in the effluents. The influent of run 1 was spiked with antimony, manganese, and thallium; and that for run 2 was spiked with americium, plutonium and uranium.

The concentrations of antimony, manganese, and thallium remain fairly stable throughout the run; however, there is some loss of the metal spike likely due to sorption on the walls of the influent reservoir. Sorption of metal ions is generally a problem in basic solutions; thus the loss of nearly 25 percent of the initial antimony spike is credible.

For a given metal and column, a percentage breakthrough was calculated based on the ratio of the effluent concentration to the ratio of the average influent concentration. The percentages are plotted versus residence time. All three reagents, Connelly iron fillings, iron-silica form, and Humasorb reduced thallium concentrations to well below action levels in a short residence time. Antimony was effectively eliminated only by the Connelly iron. The Humasorb and iron silica foam performed poorly for sorbtion of antimony. There is some evidence that the iron-silica foam contains a small percentage of antimony that elutes as the material oxidizes. The most effective reagent for the extraction of manganese is Humasorb that eliminates nearly all the metal from the influent in a residence time of 15 minutes. Both iron reagents appear to contain large amounts of manganese. The manganese elutes as the iron oxidizes resulting in as much as a 5-fold increase in the manganese concentration in the effluent rather than a decrease.

In separate column studies, the influent was spiked with uranium, americium, and plutonium. It was decided after viewing the results that the plutonium numbers could not be trusted. Control samples associated with the these results showed elevated levels of plutonium indicating there was some contamination which occurred during analysis. However, the uranium and americium numbers should be valid as the controls indicate. In the influent, the concentration of uranium is constant during much of the run, but increases slightly for the last few samples. The americium concentration decreased rapidly during the first 48 hours of the run and then levels off at about 25 percent of the initial concentration. Americium tends to sorb on surfaces at neutral to high pH according to experts at Sandia who work with americium on a regular basis. The plutonium results were difficult to interpret; consequently, little may be inferred from these numbers, nonetheless, this concentration also appears to drop with increasing time. The decrease is most certainly due to sorption of the metals on the influent reservoir surface. Both americium and plutonium are present in amounts in the parts per quadrillion range; consequently, a small amount of surface sorption results in a large decrease in the concentration of these analytes.

Uranium is removed by both iron reagents even at very high flow rates. On the other hand, Humasorb is almost ineffective at sorption of uranium. At low flow rates, a residence time of 85 minutes, about 50 percent of the uranium is removed. At a residence time of 33 minutes or less, uranium passes through the column too quickly for an appreciable decrease in the metal concentration to occur. For sorption of americium, all three reagents are effective. Little or no americium was detected in the influents even at high flow rates. As for plutonium, the values follow no evident trend. Some values are below the action level, other values are much higher than the action level. Based on ten blanks, the average amount of plutonium contamination was 0.09 pCi/L per sample. However, the error was not systematic. Same blanks were highly contaminated; whereas, others were completely clean.

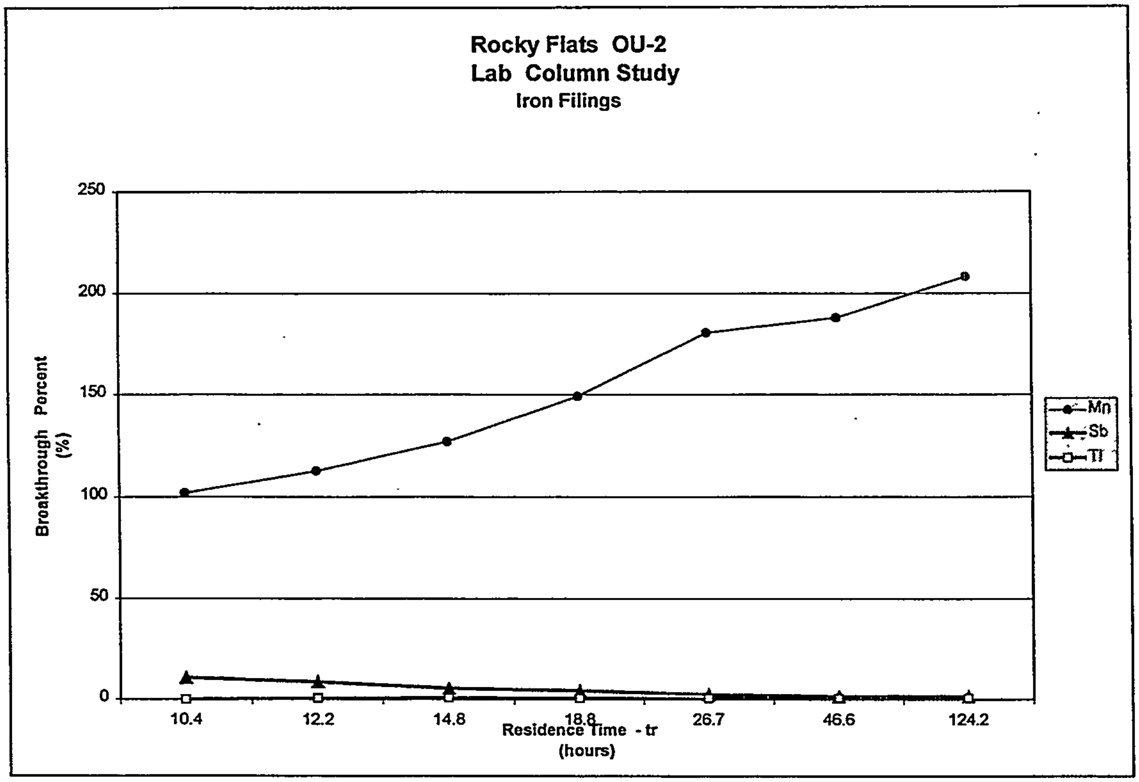


Figure 3. Iron Filings Lab Column Results.

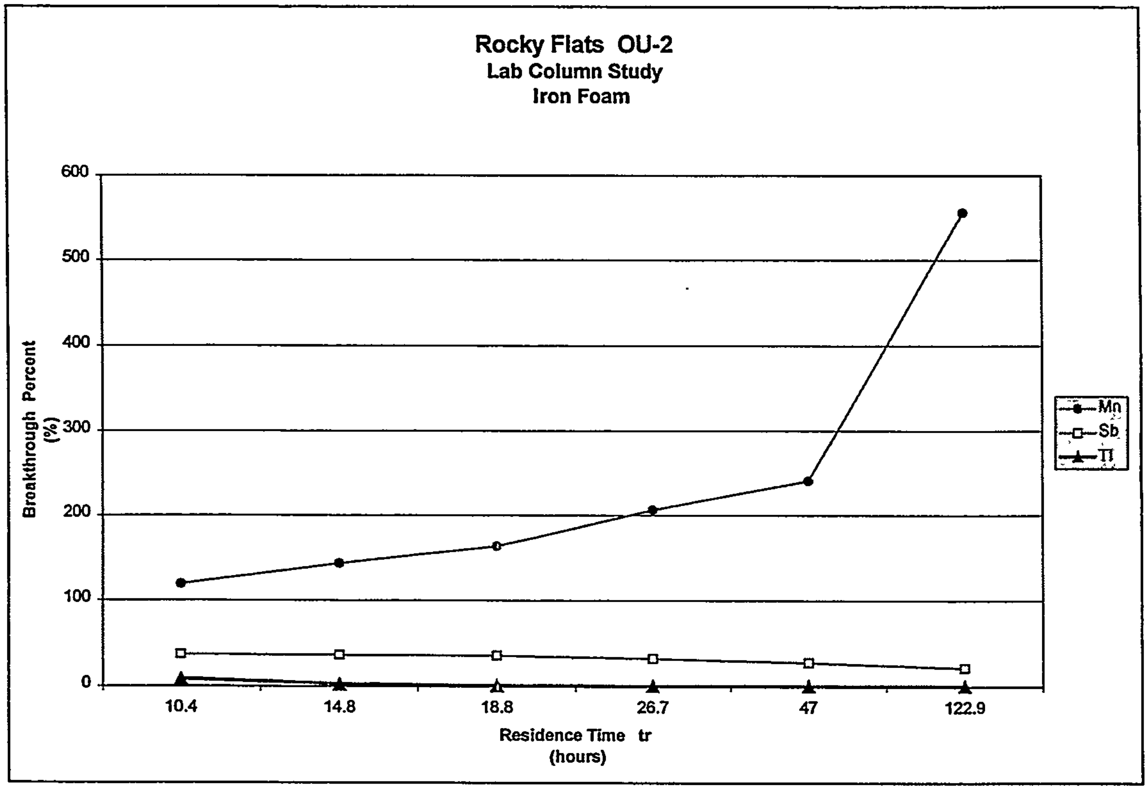


Figure 4. Iron Foam Lab Column Results.

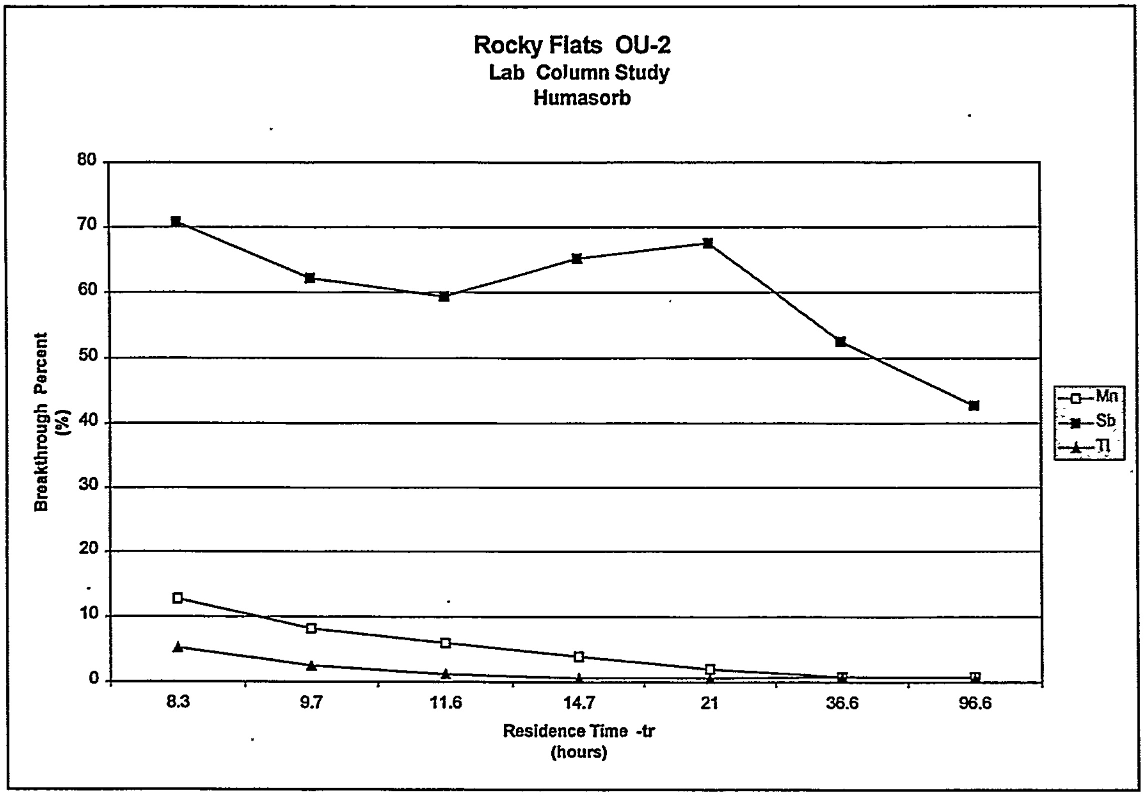


Figure 5. Humasorb Lab Column Results.

Conclusions

Individual columns containing each potential reagent were evaluated to determine their effectiveness in the reduction of americium, plutonium, and uranium from synthetic ground waters at various flow rates and residence times. In very low concentrations americium and uranium are removed by columns containing either the clean iron fillings or the iron-silica foam when residence times exceed 15 minutes. It is likely that plutonium is also removed by both of these reagents, though this is not a certainty based on the results in this study. Humasorb, the third reagent investigated, does not appear to be effective for the removal of uranium when mixed with 80 percent sand (Arctech prepared the reagents with a 4 to 1 ratio of sand to Humasorb). In pure form, Humasorb may fair better and its cost is still quite low. When these same reagents were evaluated with influents containing antimony, manganese, and thallium, each showed some weakness. The iron reagents both contain high levels of manganese that is released as the iron oxidizes. The iron foam may contain a small amount of antimony that also shows up in the effluent. The Humasorb is excellent for sorption of manganese and thallium, but sorbs antimony at low efficiency. However, a solid bed of Humasorb may effectively remove all three heavy metals.

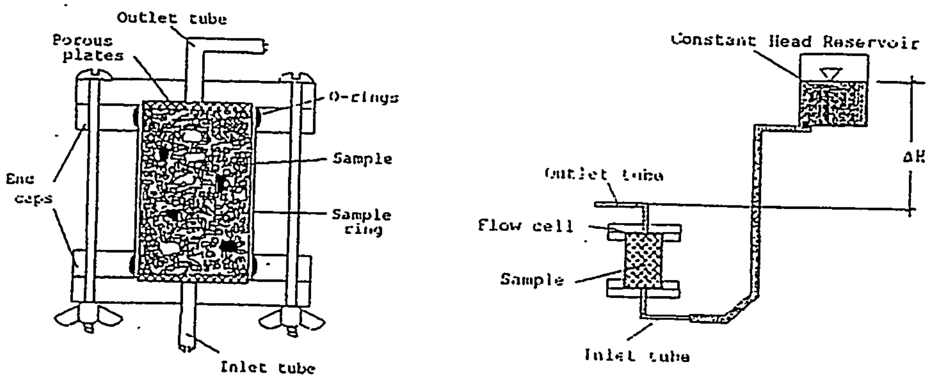
The primary COCs for the RFETS 903 Mound Site are U, PCE, TCE, and CCl_4. Both iron filings and foam were favorable to the Humasorb in the lab removal effectiveness study. Also the Ks for the three media were all within an acceptable range; consequently, the iron foam and filings were given further consideration. The remaining consideration was cost and availability.

Iron filings are less expensive and more readily available than the iron foam so the iron filings were chosen as the optimum media for further evaluation/validation in the pilot column-test study at the actual site.

Saturated Hydraulic Conductivity Determination

In a reactive barrier treatment system it is essential to understand the hydraulic flow characteristics of the treatment media. The media must have a higher saturated hydraulic conductivity (Ks) than the surrounding soil to avoid flow bypassing the system. Also the head loss across the media should be low enough to avoid unacceptable mounding of contaminated water upgradient of the treatment barrier.

The Ks for each media was determined using a constant head flow apparatus (Figure 6). Each media was tested at three bulk densities to simulate various field conditions: 1) the bulk density when the sample was poured into the flow cell; 2) the higher bulk density when the media was vibrated into the flow cell; and 3) the bulk density when the sample was packed as tightly as possible using vibration and a hand ram. Appendix B - Tables B-1, B-2, and B-3 present the results for the three media samples at each of the bulk densities tested.



Flow Cell

Constant Head Setup

Figure 6. Constant head and flow cell apparatus.

Tests on samples were begun after the samples were fully saturated and an apparent constant flow had been established. The tests were repeated after 12 hours (72 hours for the Humasorb-CS media). After the second test, Ks had decreased slightly, with the greatest decrease occurring at the higher bulk densities. The saturated hydraulic conductivity (Ks) was calculated using:

$$k_s = \frac{Q_{H_2O}}{A \cdot t} \cdot \frac{\Delta L}{\Delta H} = \frac{\text{mass}_{H_2O}}{A \cdot \rho_{H_2O}} \cdot \frac{\Delta L}{\Delta H} = \frac{(\text{outflow mass - tare})}{A \cdot \rho_{H_2O} \cdot t} \cdot \frac{\Delta L}{\Delta H}$$

where: outflow mass = mass of flow through cell + container mass
tare = mass of container
$\rho_{H_2O} = 0.9978\text{g/cm}^3$

A = area of the flow cell perpendicular to flow
ΔL = length of flow cell perpendicular to flow
ΔH = difference between inflow and outflow elevations

The flow medium used was a 0.0005M solution of CaSO4 in deionized water. This solution is used in most hydrologic testing of soils to minimized slaking and other effects. Its density is 0.9978 g/cc. This solution should not have an adverse effect on Ks for the purposes of this study.

Conclusions

The Ks for each respective media for design purposes was determined to be:

Iron foam	4×10^{-2} cm/s
Iron filings	3×10^{-2} cm/s
Humasorb-CS	1.5×10^{-2} cm/s

The higher the conductivity within a range, the better flow characteristics. A conductivity in the 10^{-1} cm/s range would present a problem with requiring a longer flow path to meet the required treatment residence time. There is an ideal balance between the Ks value of the media, and the required residence time (tr) because these values relate to the volume of media required, which is directly related to project costs. All three media were low enough not to result in an excessive flow path length, yet are high enough to avoid substantial mounding of upgradient groundwater. Consequently, this parameter provided no differentiation of the three media with respect to choosing an optimum material, i.e., all three materials would provide acceptable Ks and hL values for the full-scale demonstration.

4. PILOT FIELD COLUMN STUDY

Column Scale Field Validation

Upon completion of the laboratory study that identified ZVI (iron filings) as the optimum treatment media for the Mound Site Plume, field columns were set up at the Mound Site to verify the ZVI media performance using actual site water. In addition head loss, saturated hydraulic conductivity were monitored to ensure that the proper parameters were given to the design team at the Corps of Engineers.

Experimental

Reagents, Instruments, and Apparatus

The columns were packed with pre-cleaned 40 mesh iron filings supplied by Connelly GMP Inc. Ultra-pure concentrated hydrochloric acid and nitric acid for the preservation of water samples were supplied by the contract Lab (Core Labs) with the sample containers. Calibration standards for measuring pH were purchased from Fisher and standards for measuring dissolved oxygen were obtained from Corning. A Corning model Checkmate 90 was used to measure influent and effluent pH, dissolved oxygen, and conductivity. Mass measurements were made with Mettler scales models PM30-K and PM4800. Custom designed acrylic columns were made by Soil

Measurement Systems to various lengths. Teflon bed filters were purchased from Micron Separations (10 ±m pore size x 90 mm diameter disks). Influent water was pumped into columns with an eight channel Rainin peristaltic pump model Rabbit. All tubing was constructed of Teflon FEP (1/8" OD x 1/16" ID) and fittings were made of Teflon PTFE, PEEK and KYNAR. Bag filters which were used to prevent particles from entering the intake lines were purchased from Knight Corporation (10 ±m pore size x 7" diameter x 16" length). A support structure for the bag filters was constructed of polyethylene canvas purchased from Uniek (No 7 grid). The experimental setup and operation is shown in Figure 7.

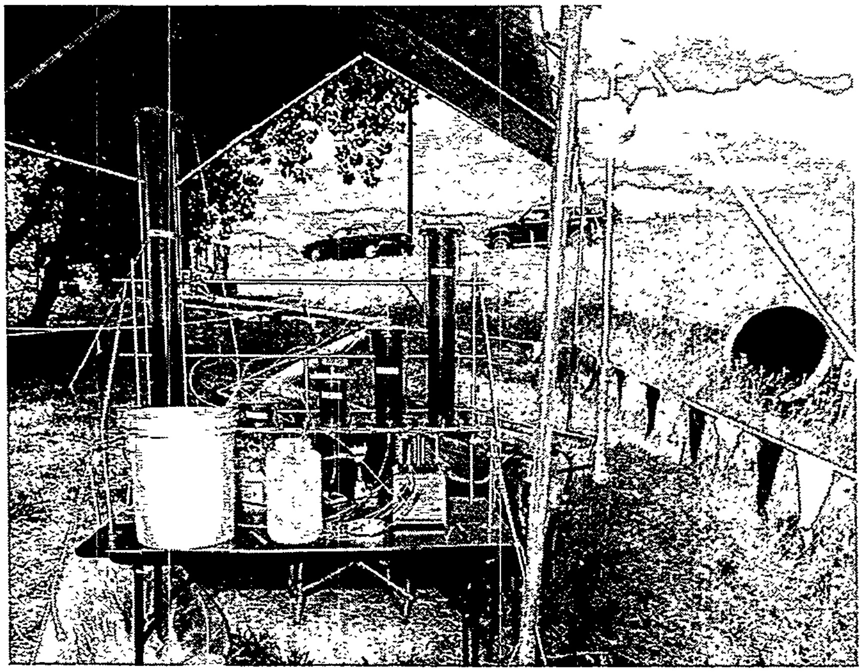


Figure 7. Pilot-scale field columns at RFETS 903 Mound Site.

Procedure

The columns were obtained from Soil Measurement systems in five lengths (3.0, 6.0, 12.0, 24.0, and 36.0 inches) each 3.0 inches wide. Each column was cleaned, dried, and assembled without packing and then its mass was measured and recorded. A Teflon bed filter was placed on one end of the column and the support end plates attached before the columns were packed. Iron filings were scooped into the columns with occasional light tapping. When the bed was filled completely, the top plates were attached with the supporting rods. The entire apparatus was tapped vigorously against a rubber surface for several minutes to increase the packing density. The top plates were removed and additional filings were added to the column. These steps were repeated several times until a packing density between 2.6 and 2.7 g/mL was obtained. At this density, very little additional settling of the bed occurs when the columns are jostled over time. After the packing was completed, the final mass of each column assembly was recorded. These results appear in Table 1. The columns were attached to a large aluminum lattice and bolted to a portable table that was positioned several feet from seep SWO50 at the Mound site. Pumps, tubing, valves, and fittings were fasten to the column assembly at the field site. The tubing ends that were placed in the seep collection sump well were covered with a bag filter. Bag filters were used because it was necessary to trap a large amount of suspended soil and organic matter without clogging the intake lines or causing a reduction in flow rates. To prevent the bag filter from collapsing on the intake lines, a cage-like supporting structure was constructed from polyethylene canvas and placed inside the bag filter. The intake lines were positioned inside the cage and the bag filter over the cage with the filter tightly gathered against the intake lines using cable ties.

A Teflon valve was installed between the pump and the column to prime the pump before filling the columns with influent from the seep. Flow rates were maximized (setting of 48.0) initially. The first effluent emerging from the largest column was sampled to determine the concentration of organic residues left from the cleaning process done by Connelly GMP. These same contaminants would be expected in the initial effluents emerging from the iron reactor during the field-scale project. With sight of the first effluent, the flow rate setting was reduced to a value of 12.0 and maintained for 16 hours. At that time, the pump was stopped. The columns were disconnected and plugged to prevent loss of the interstitial water. The entire column assemblies were weighted once again, then reconnected and the pumps started at the same flow rate setting.

After approximately 40 hours of operation, (the initial 16 hours plus an additional 24 hours to allow the columns to reach a steady state) the first set of samples were taken. For each set, six samples were collected, one effluent sample from each column and one influent sample. The configuration and length of the tubing used to sample the influent was identical to that for the columns except this line did not have a column attached to the end. Sample sets for three types of analysis were collected during the working hours. For volatile organic analysis, the samples were collected in 100-mL glass jars with Teflon liners. A 1/8" hole was drilled through the top into which the effluent line was placed. The jars were weighted before and after sampling and the starting and stopping times were recorded to determine the mass of sample and flow rates. After approximately 100 milliliters of sample was collected in each jar (this took about 45 minutes), the sample was quickly poured into two 40-mL glass VOA vials, sealed, labeled and refrigerated immediately. An HCl preservative was used for these samples. For heavy metal analysis, narrow-mouth 125-mL polyethylene bottles were used. A 1/8" hole was drilled through the top in which to place the effluent lines. Approximately 100 mL of sample was collected in a small amount of nitric acid preservative. The exact amount of sample was recorded by weighing the bottles before after sampling. Starting and stopping times were also recorded for the purpose of determining flow rates. When sampling was complete (about 45 minutes), the bottles were sealed with new tops, labeled and refrigerated immediately. Larger plastic bottles (1000-mL) were used to collect samples for the radioactive metals assay. However, the sampling procedure was identical to that for the heavy metal assay. Between sampling for heavy metals and radioactive metals, approximately 100 milliliters of the column effluents and the influent were collected in a 100-mL glass container for the purpose of measuring dissolved oxygen levels and pH. DO and pH levels were also measured directly on water that accumulated in the seep well.

On the afternoon of July 16, 1997, the pumps were started to begin the column studies. On the morning of July 18, about 40 hours later, the first set of samples was collected. Subsequent sets of samples were collected beginning on the mornings of July 22, July 23, and July 24.

Radioactive metals samples were collected on the 18th, 22nd, and 24th. Volatile organic and heavy metal samples were collected on each day samples were taken.

Results and Discussion

Tables C-1, C-2, and C-3 in Appendix C contain the data collection from the field columns. Figures 8, 9 and 10 below exemplify the removal of COCs for the 903 Mound Site using ZVI.

Americium and plutonium are at such low levels at the 903 Mound Site that a change in the effluent concentration is not apparent; however, uranium is significantly removed from the column over time. Antimony and thallium are negligible in the influent and subsequent effluent, while iron is released in a large pulse that slowly comes back down to near zero. Manganese appears to be released gradually and continuously from the treatment system. It is thought that the manganese is liberated from the iron filings. Finally, the organic compounds of primary concern – TCE, PCE, and carbon tetrachloride are removed quite rapidly from the system, with the appearance of no additional bad actors. It is critical with organics that the retention or residence time is adequate to allow for complete degradation to avoid releasing intermediate by-products downgradient. Environmental Technologies, Inc. (ETI) was responsible for determining the design residence time (tr) with respect to the organic COCs. They determined the tr to be a minimum of 15 hours. A treatment system design tr of 20 hours was used to ensure an adequate factor of safety (F.S.)

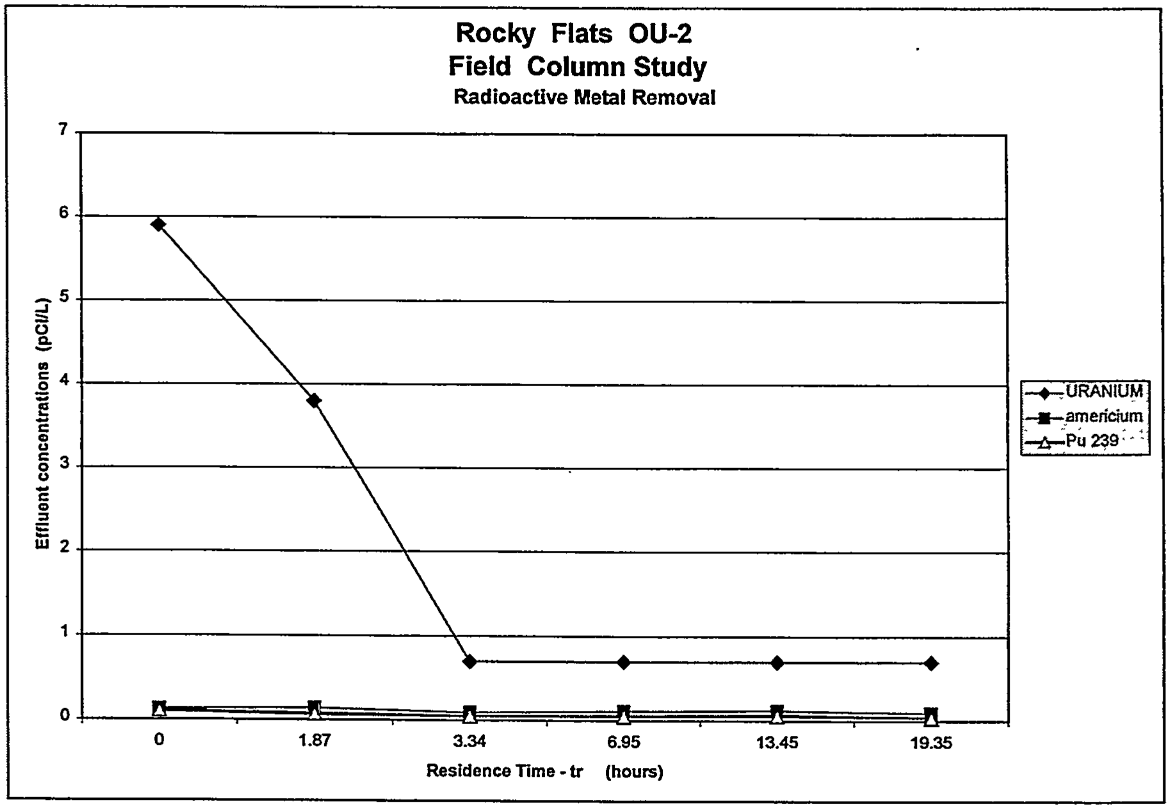


Figure 8. Radioactive Metals Removal.

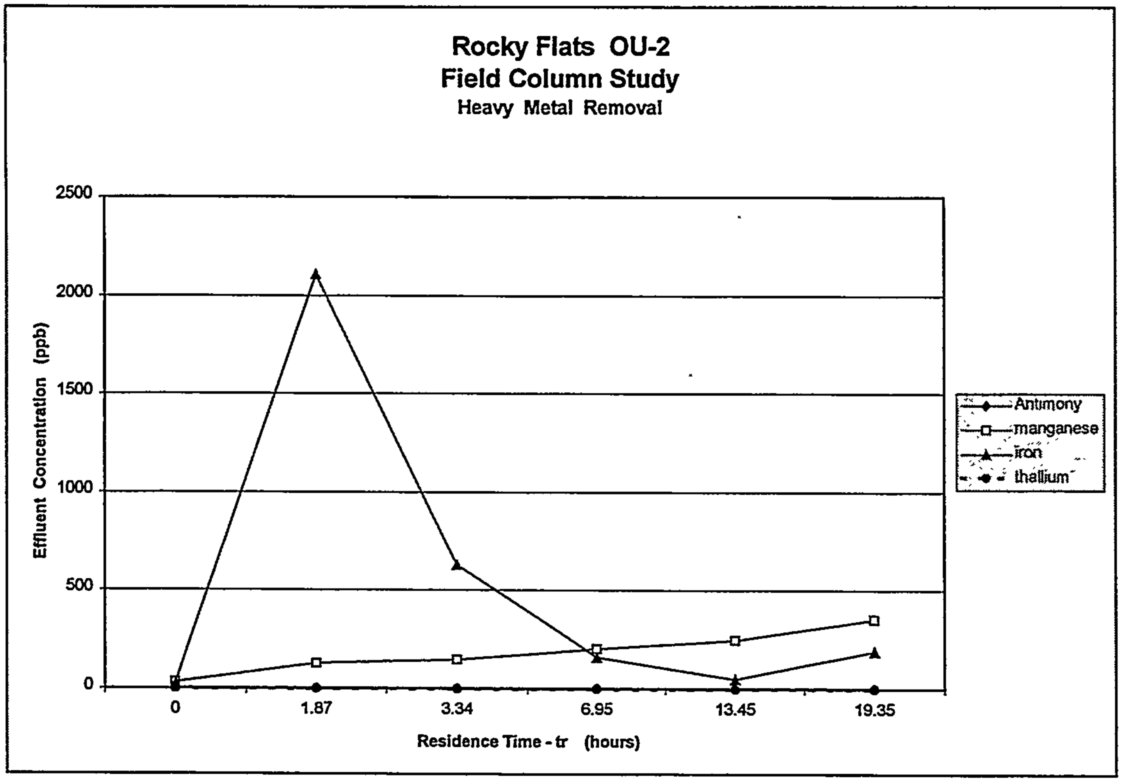


Figure 9. Heavy Metals Removal.

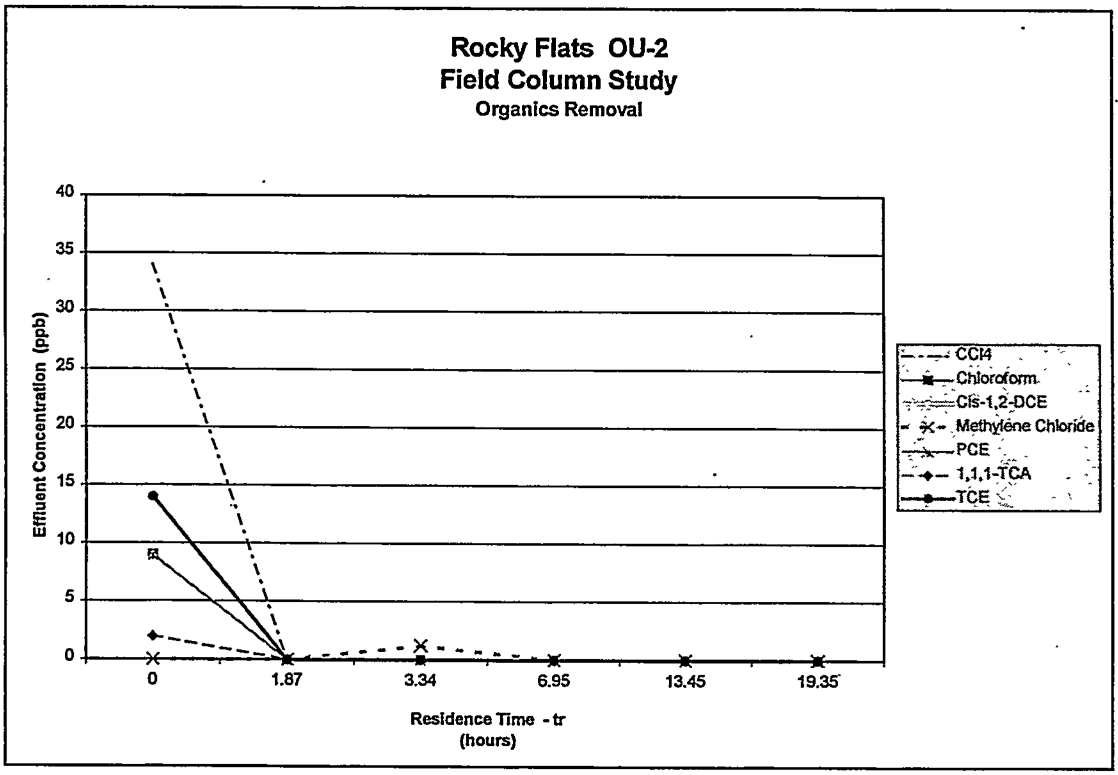


Figure 10. Organic Compounds Removal.

Conclusions

In the pilot-scale, field-column studies the primary COCs - uranium, TCE, PCE, and CCl4 were removed to regulatory acceptable levels in 3.5 hours or less. Results from the full-scale barrier installation will be compared to the lab and pilot-scale studies. It is anticipated that the comparison will show that lab/pilot testing can provide reliable design parameters to engineers for full-scale reactive barrier designs.

The full-scale demonstration of this technology is designed to have a minimum of 20 hours of residence at a flow rate of 2 gpm. Sample ports on the full-scale system allowed for sampling along the flow path to better clarify the actual required residence time (tr). A more reliable tr value allows reactive barrier engineers the confidence to decrease the design Factor of Safety (F.S.). A decrease in the F.S. translates directly into less treatment media required which results in immediate cost savings for a reactive barrier project.

5. FULL-SCALE REACTIVE BARRIER INSTALLATION

Reactive Barrier Concept

Conceptually reactive barriers are used to intercept and remove ground water contaminants before passing into the wider ecosystem. The barrier is constructed of benign reactive materials such as metallic iron that are used to breakdown or immobilize contaminants by redox reduction using ordinary chemical, physical, and/or biological means. Typically installations require a trench excavation below the depth of the aquifer, downstream from the plume; the trench is filled with the reactive media to form a treatment wall. Laboratory research has shown that iron filings appear to be the most economical viable treatment media that is technically adequate. After further review by interested parties, the 903 Mound Site conditions, reactive barrier technology was chosen as the remediation methodology for the 903 Mound Site Plume. The site is ideally suited as one for the investigation of a relatively new technology since contaminant levels are low and there is little or no risk to the environment if the technology proves to be inadequate. As mentioned, reactive barrier installations to date typically involve the subsurface placement of iron media to effectively intercept the contaminated groundwater. Subsurface placement; however, does not easily allow for performance interpretation because aquifer effluent samples are difficult to gather and the condition of the barrier material cannot be easily observed. Consequently, a reactive barrier design that assisted scientific investigation was chosen.

Reactive Barrier Design and Construction

MSE and the Corps of Engineers were in charge of the design and construction of the 903 Mound Reactive Barrier. Sandia National Laboratories, ETI, and the RFETS personnel provided input to aid in design and construction. MSE published a document summarizing the design and construction of the system (MSE, 1999)

The reactive barrier installation consists of a 230 ft. wide water collection wall made of an impermeable material (HDPE) that is approximately perpendicular (bisects) to the groundwater flow. The HDPE wall is keyed into the underlying aquitard with a bentonite seal. The wall acts as a funnel to direct the groundwater into a centrally located collection sump where it overflows to the treatment vessels containing the ZVI. The entire system is passive, i.e., gravity feed. Figure 11 shows a plan layout view of the treatment system.

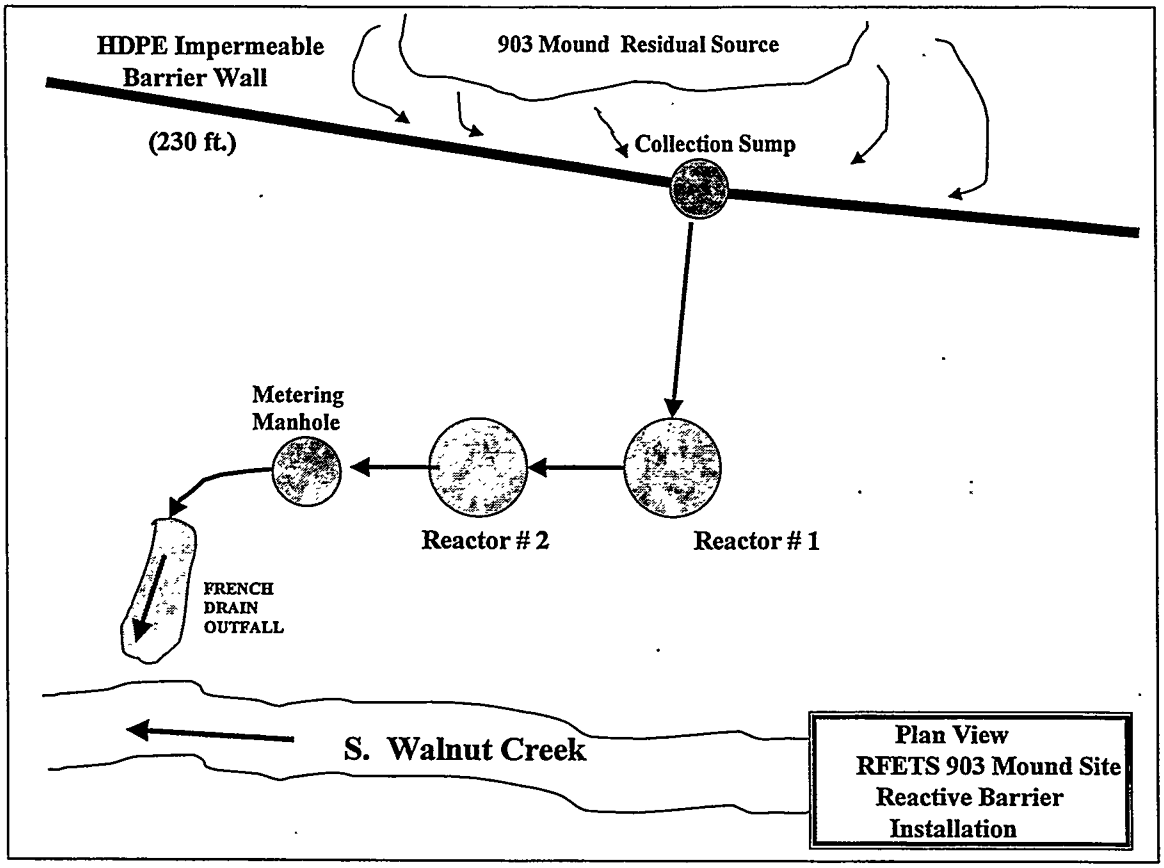


Figure 11. Schematic Plan View of 903 Mound Site Reactive Barrier Layout.

Treated effluent from the reactor vessels will be released into the stream at the bottom of the hill. Thus, the influents and effluents may be sampled directly. The reactor tanks have multiple sampling ports and top access that accommodate sampling. Figure 12 provides a profile view of the treatment system including sampling ports.

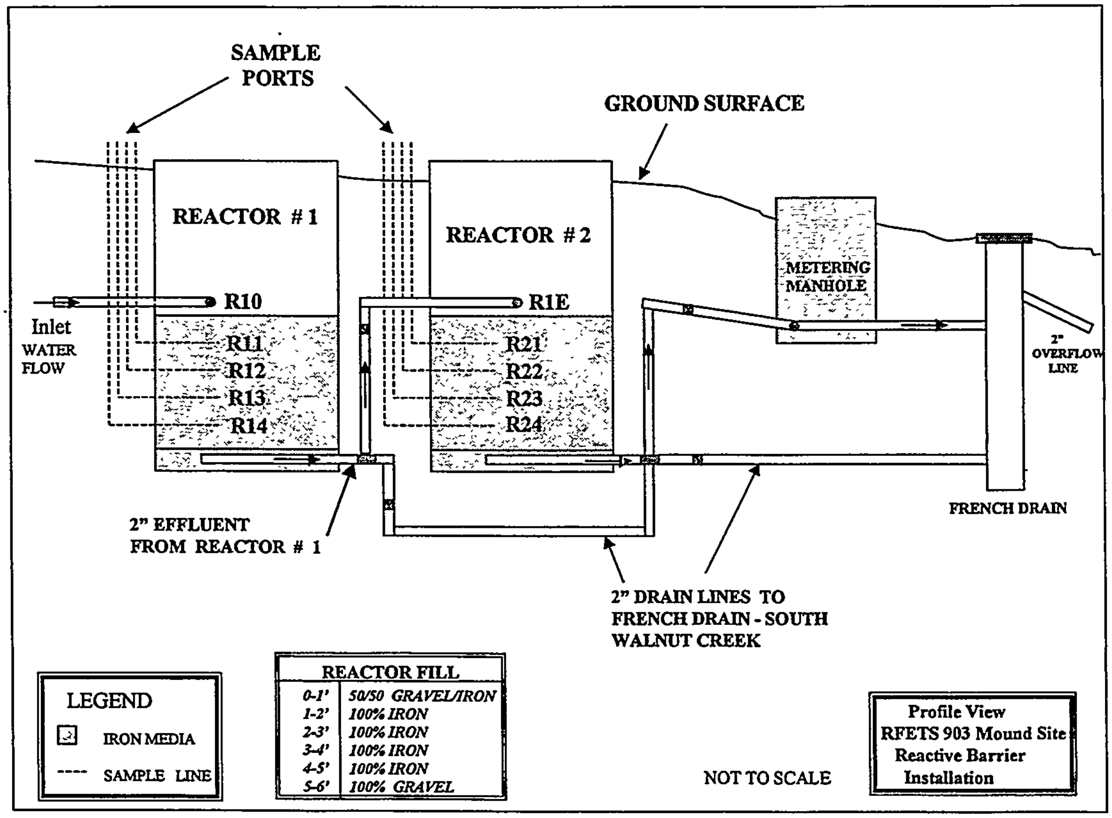


Figure 12. Schematic Profile View of 903 Mound Site Reactive Barrier Treatment System.

The reactors are cylindrical HDPE vessels with a 6 ft. by 6 ft. opening in the top. Each reactor has four sampling ports. The composition inside each reactor is as follows: the bottom foot is 100% pea gravel; covered by four ft. of 100% ZVI filings with sample ports every foot; topped off with a 50%/50%- iron/pea gravel mixture. The reactors are at atmospheric pressure and are essentially open air (aerobic). The reactors act as plug-flow vessels, i.e., water enters on top and pushes water out of the bottom; consequently the treatment media always has a minimum of six inches of water above the top layer. This design attempts to minimize surface oxidation. The vessels are plumbed so that either vessel or both can be operated in any possible sequence.

Each reactor contains 25 tons of 8X50 mesh ZVI provided by Connelly GPM, Inc. The system was designed so the iron media can be replaced in the future.

IT Corporation constructed the 903 Mound Site Reactive Barrier. The MSE report mentioned above documents details of the construction including as-built drawings and corresponding costs.

Figures 13, 14, 15, 16, and 17 show various construction stages.

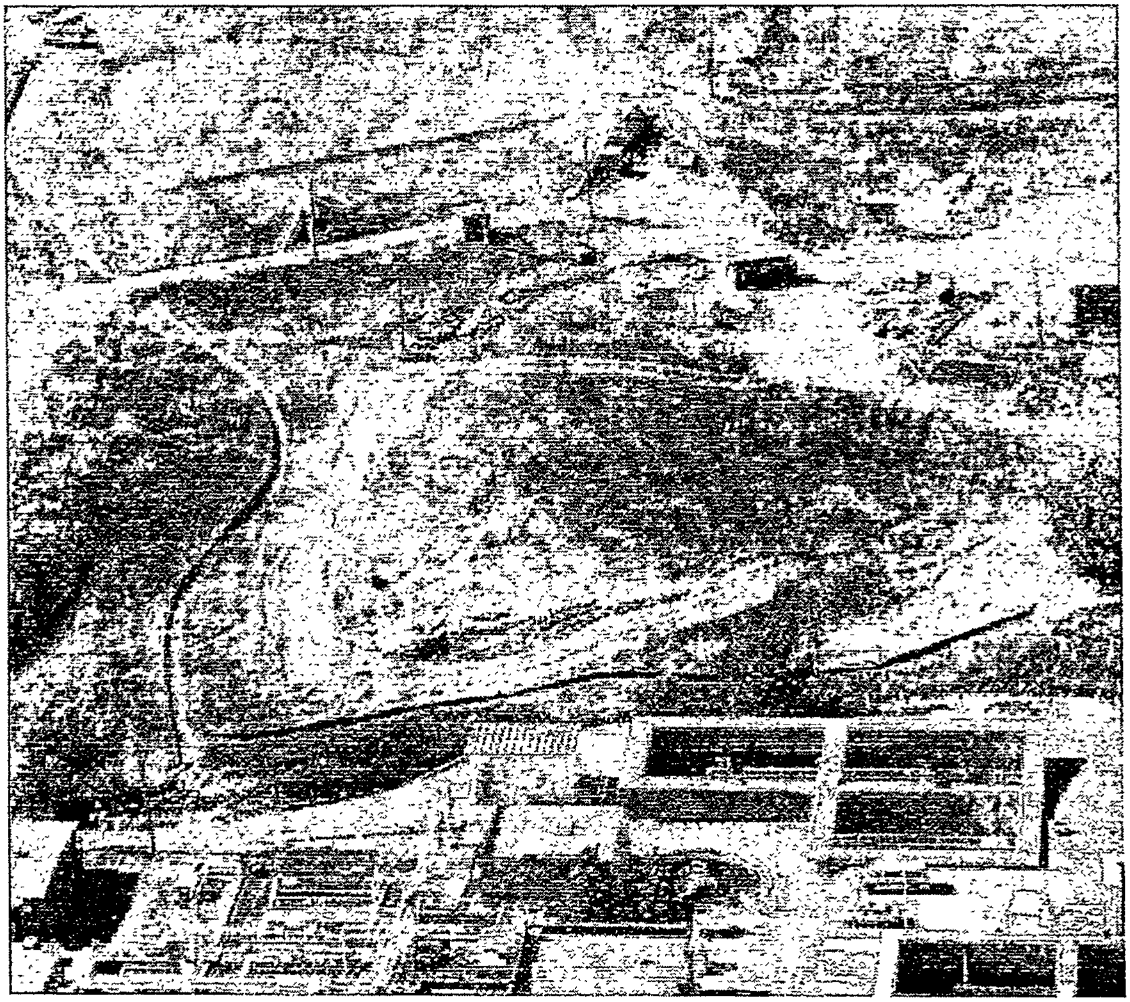


Figure 13. Plan view of 903 Mound Site. Early stages of grading.

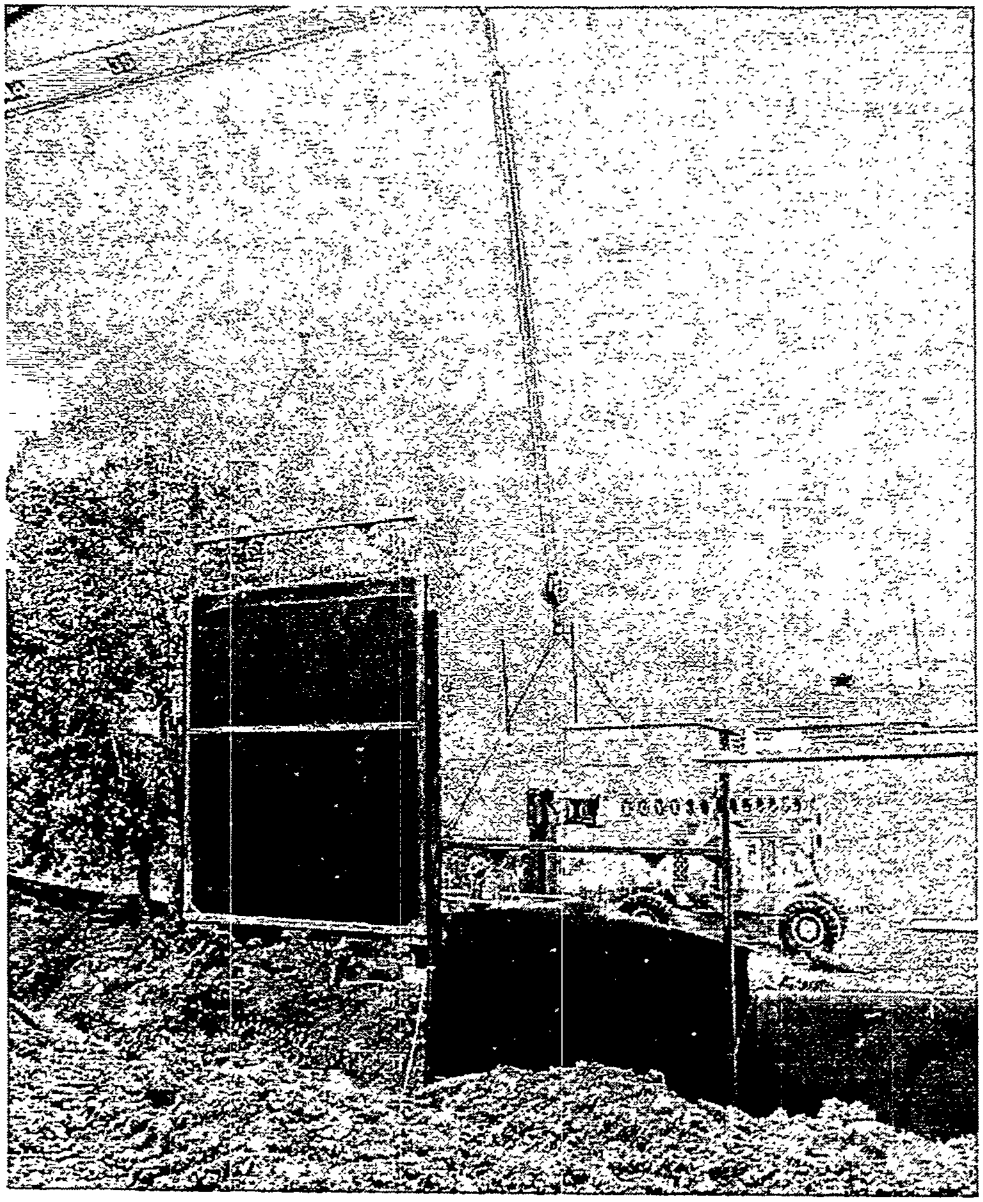


Figure 14. Installation of HDPE impermeable wall sections. Wall is composed of 10' wide interlocking panels with a hydrophilic seal in the joints.

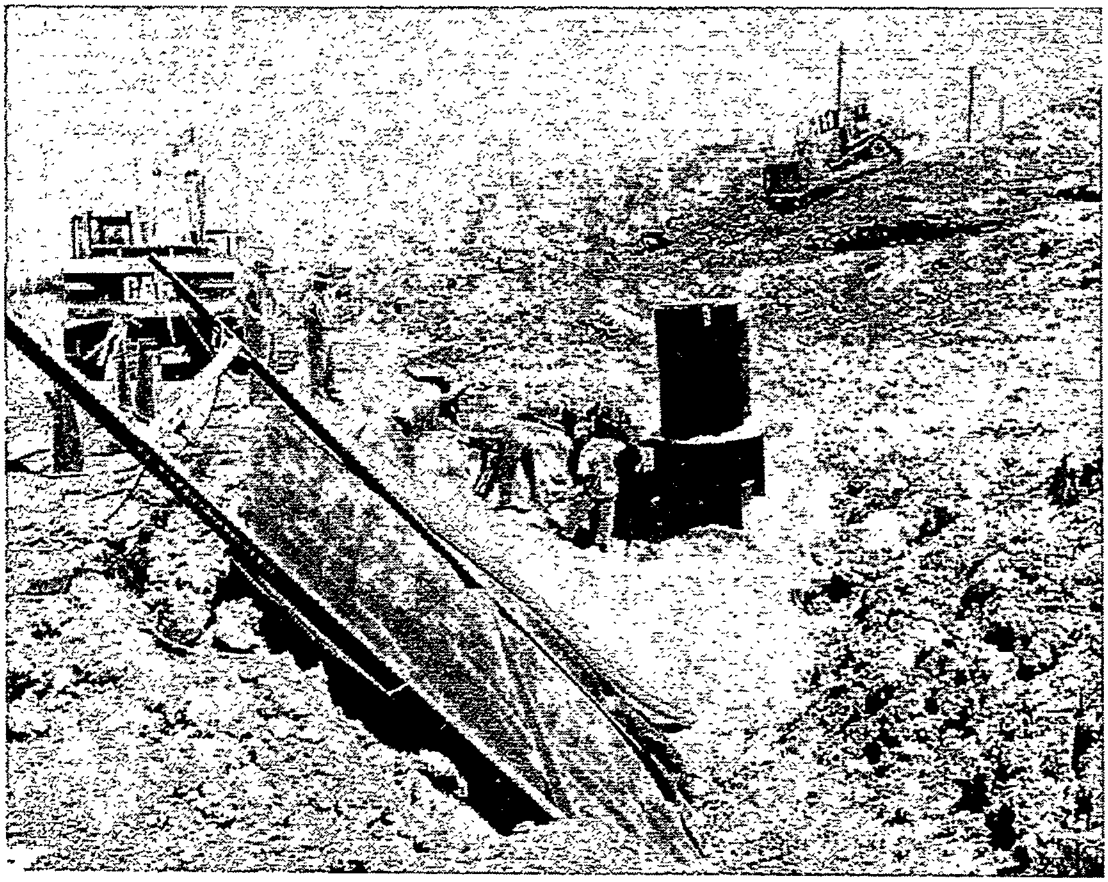


Figure 15. HDPE collection wall and sump. Low Cohesion (sloughing) soil conditions resulted in slanted installation of the HDPE in some areas of the wall.

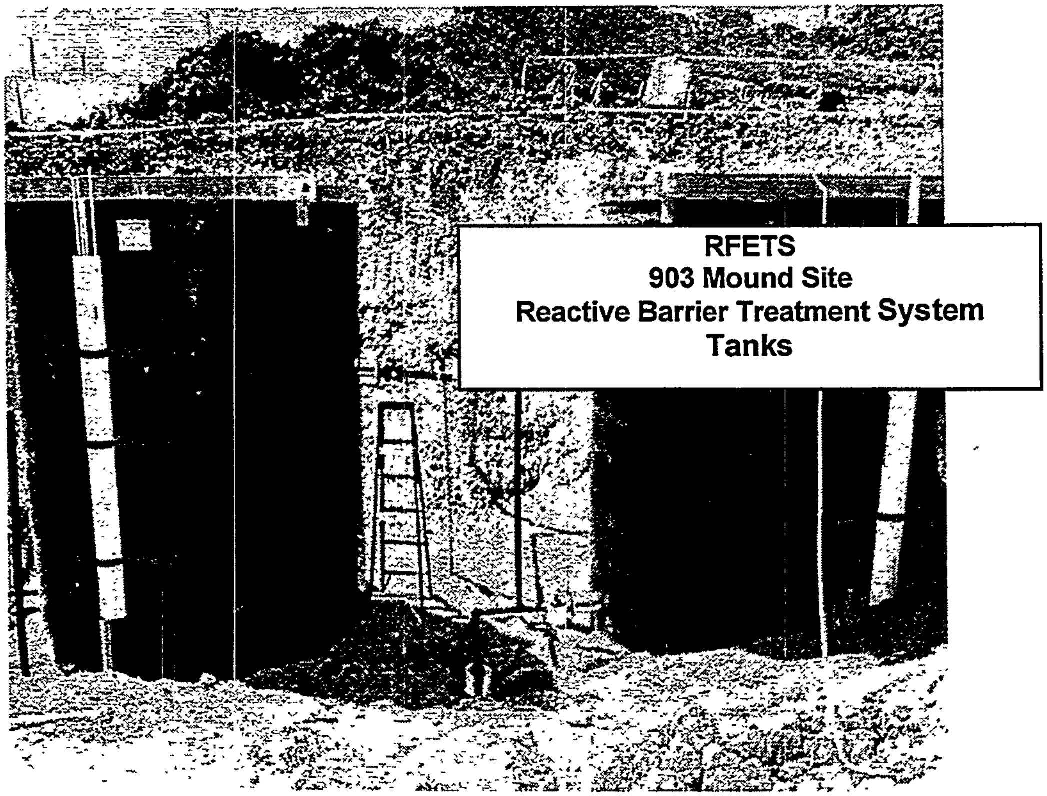


Figure 16. HDPE Reactor vessels. Dimensions are 11'-6" tall X 9'-10" in diameter.

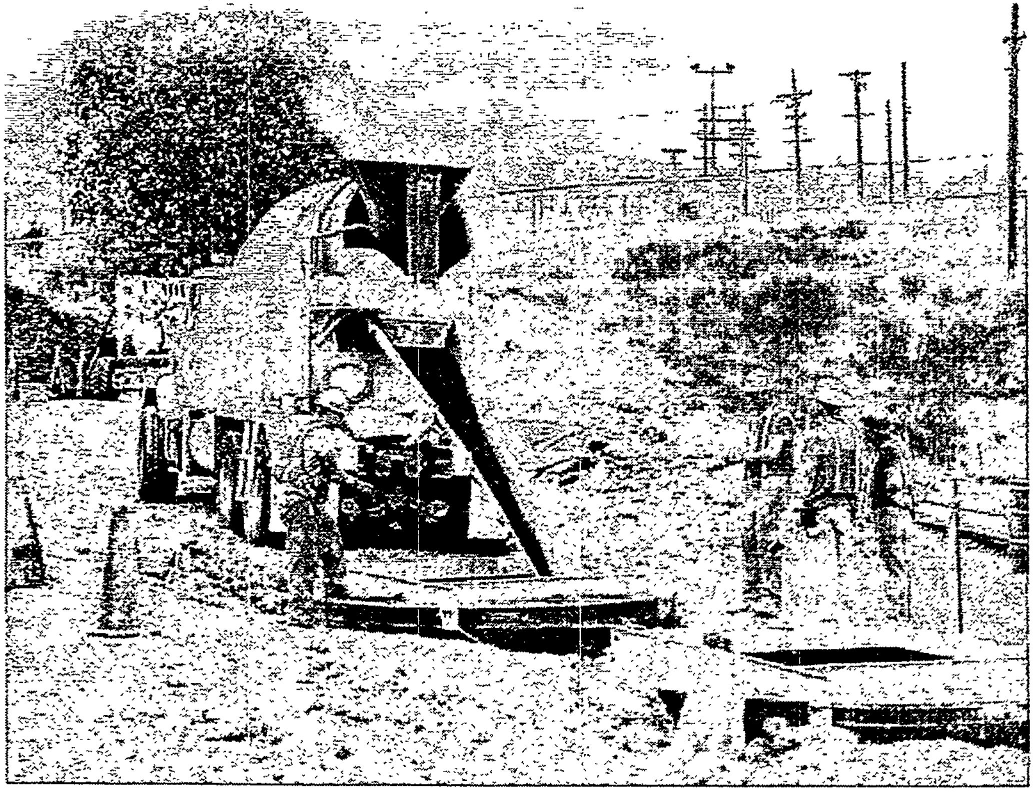


Figure 17. Reactor vessel loading.

Results and Discussion

This treatment system functions to remove the COCs by creating a reducing groundwater environment. Typical signs of reducing conditions are an increase in pH, and a decrease in redox conditions (Eh) as shown in Figures 18 and 19.

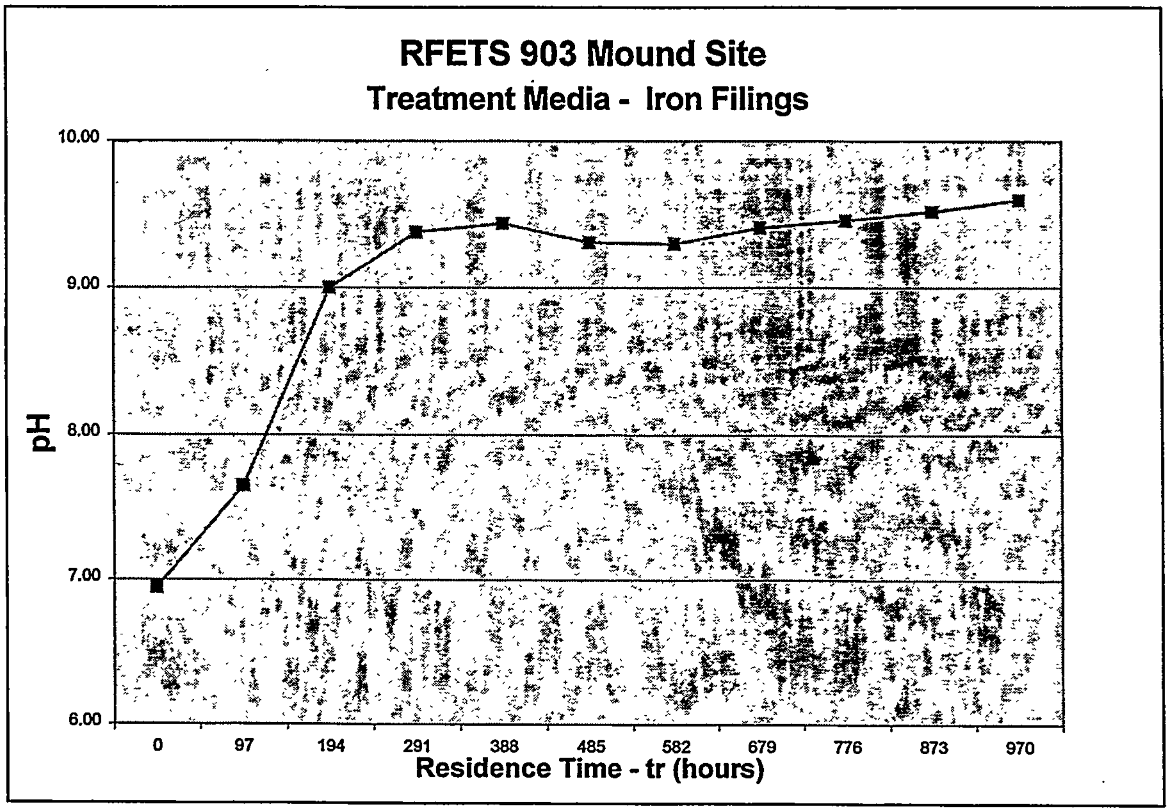


Figure 18. pH as a function of residence time (tr).

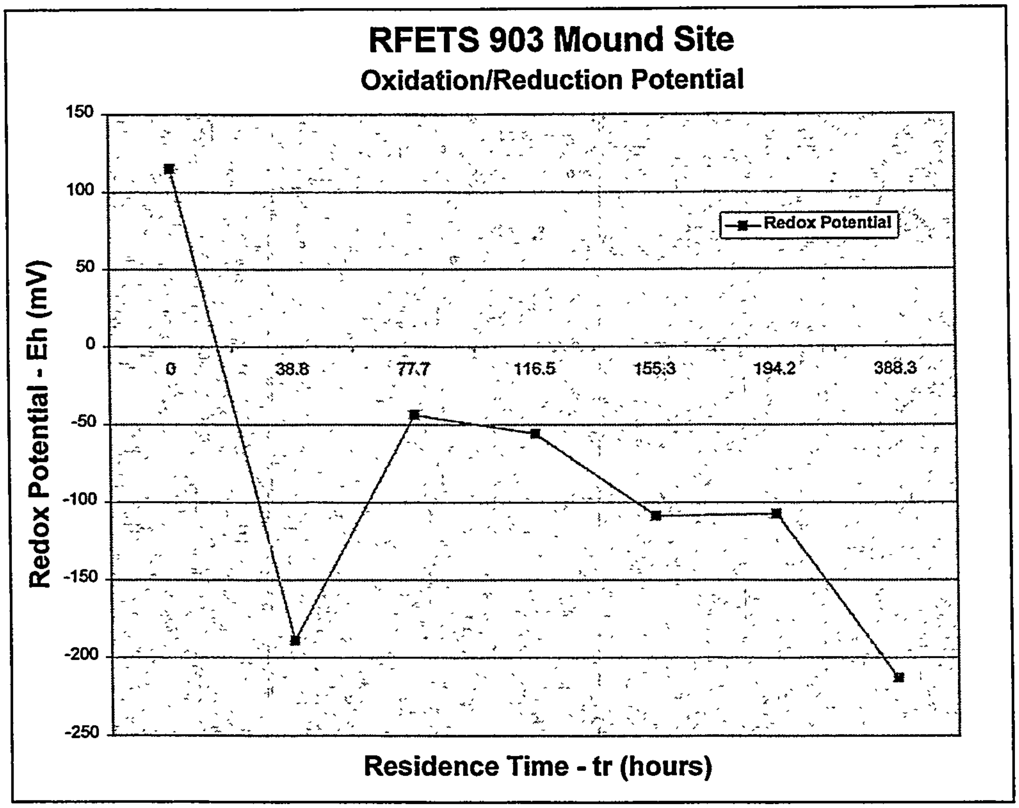


Figure 19. Eh as a function of residence time (tr).

The two figures are typical for all sampling events. The pH of the groundwater rises from near nuetral-7 to 9.5 as it flows through the system. The Eh also declines as expected; however it is not as textbook as the pH rise. Another very important parameter that is felt to be directly correlated to the performance longevity of a reactive barrier is the dissolved oxygen (DO). As the groundwater conditions become more reducing, i.e., less oxidizing, the DO should decline.

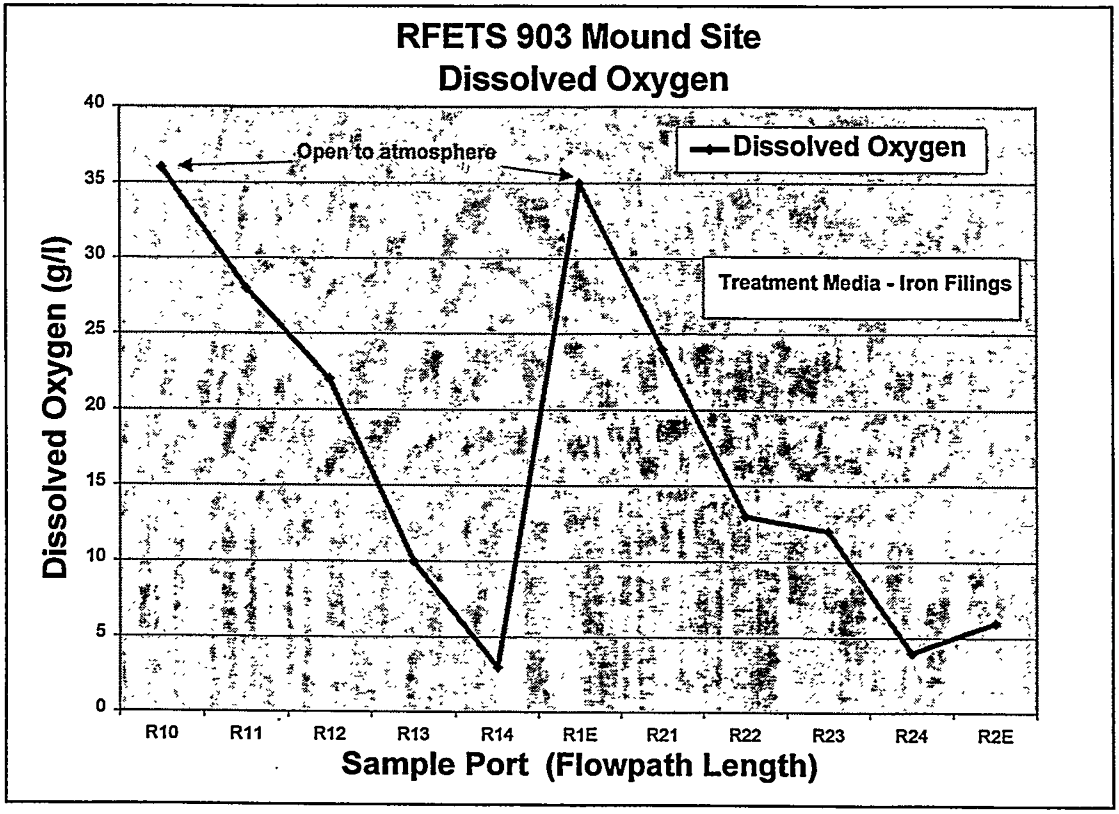


Figure 20. Dissolved Oxygen (DO) as a function of flowpath length.

Figure 20 charts the DO along the flowpath of the groundwater. The DO starts above 35 g/L at R10 which is open to the atmosphere, then falls to near zero at R14 which is the bottom of Reactor #1, then the water is routed to the top of Reactor #2. As expected the DO rises to 35 g/L because the water is exposed to atmospheric (oxygenated) conditions again, then DO declines as anaerobic conditions persist through Reactor #2.

The treatment system is designed to accommodate flow rates ranging from 0.1 gpm to 2 gpm. To date, the flowrate has averaged approximately 0.05 gpm, which is slower than expected. Recently (August, 1999) the flowrate was up around 1 gpm, showing signs of an anticipated equilibration. As a result of the low flow rate, the tr values appear very high. This is because the system operates as a plug flow reactor, i.e., untreated water must enter the system to flush the treated water from the system. Each tr value corresponds to a sample port. Refer to Figure 12 for the location of sampling ports, noting the sampling flowpath starts at R10 and ends at R2E.

Figure 21, 22, 23, and 24 show removal rates and RFETS Action Levels for the organic COCs. All the COCs are removed to well below the Action Levels prior to release; however the TCE and PCE removal is slower than expected.

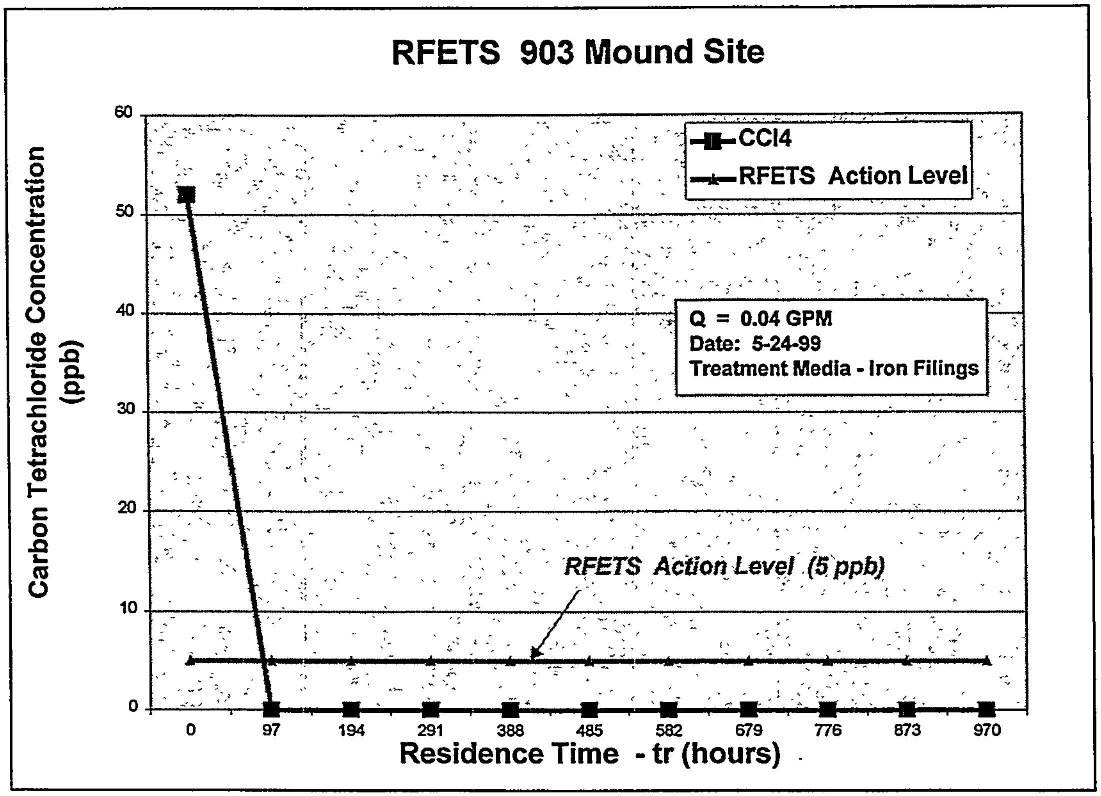


Figure 21. Carbon Tetrachloride Removal.

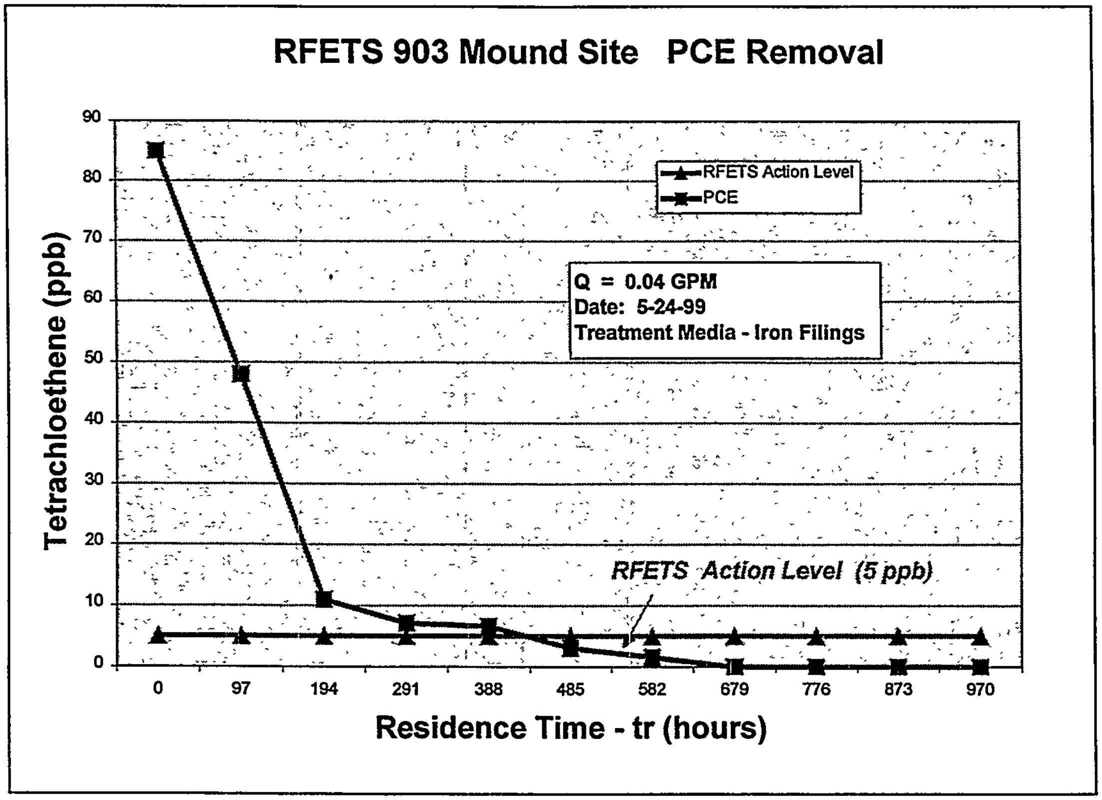


Figure 22. Tetrachloroethene Removal.

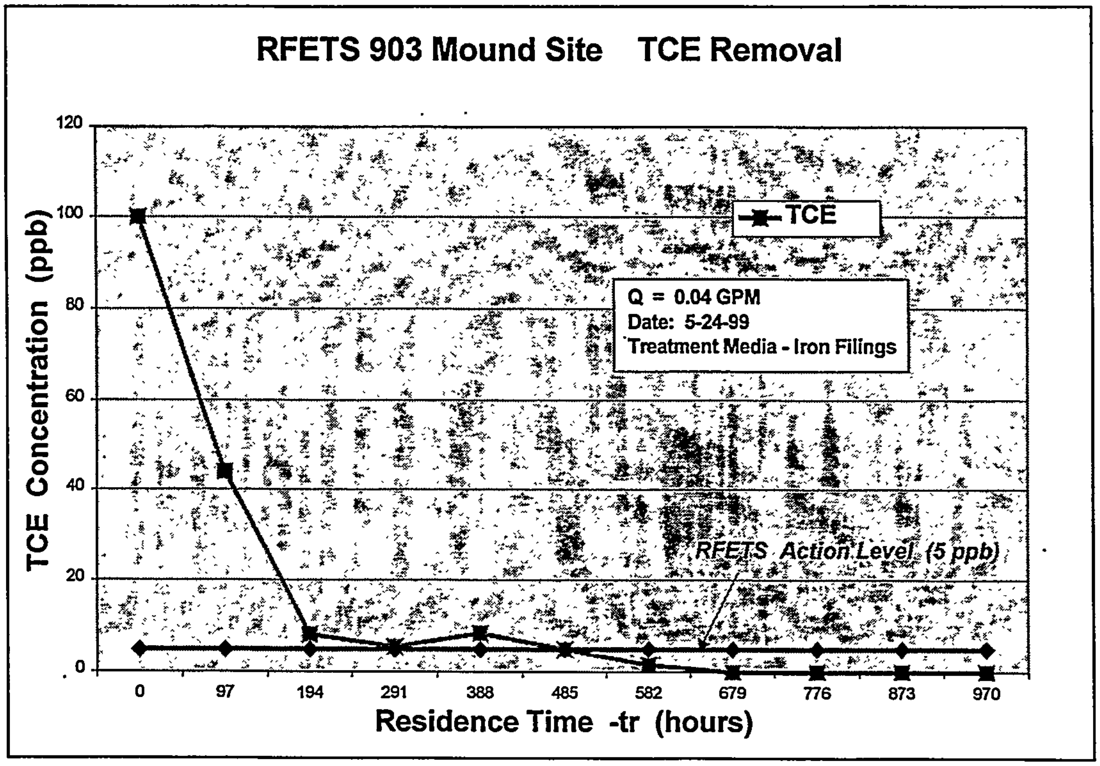


Figure 23. Trichloroethene Removal.

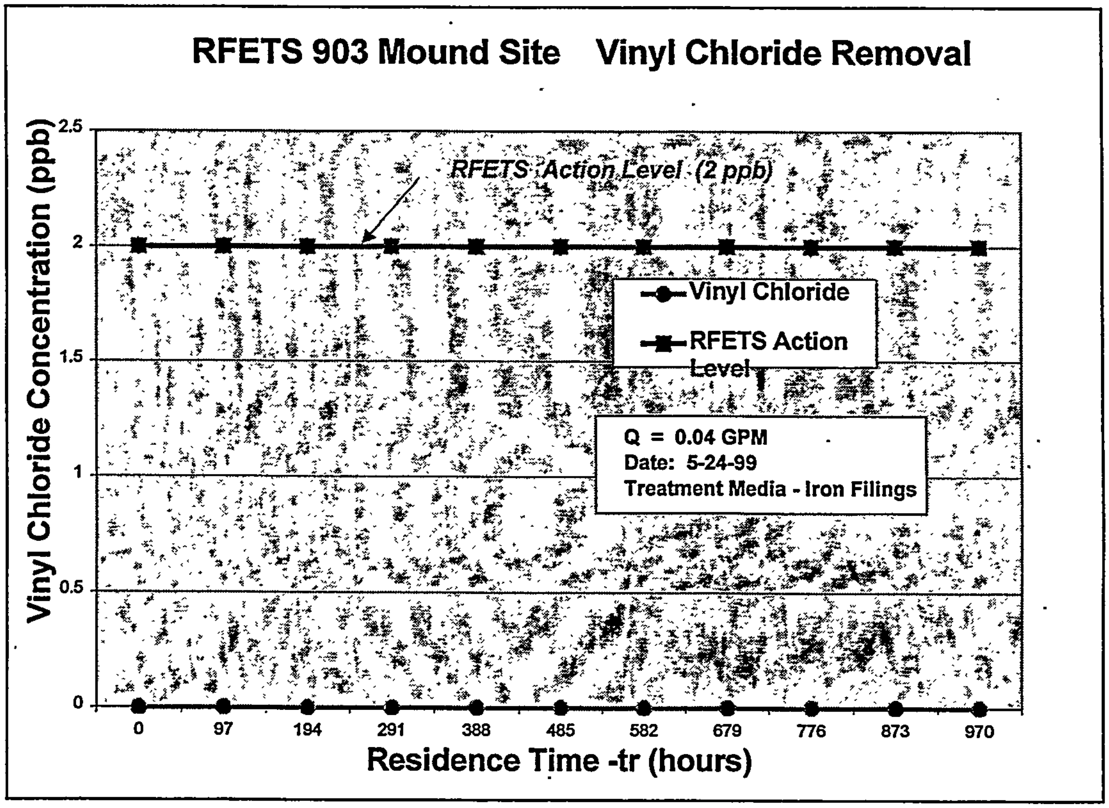


Figure 24. Vinyl Chloride Removal

Figures 25 and 26 show the radionuclide removal rates. Uranium is completely removed by the first sample port R11, which is the equivalent of passing one foot of the ZVI treatment media. Americium is essentially never present at a significant concentration. Finally, Figure 27 shows the iron and manganese levels. Iron is released, i.e., becomes mobile, initially within the first two feet of the reactor but is not present beyond the second sampling port R12. The presence of manganese, which is often released from the ZVI is negligible.

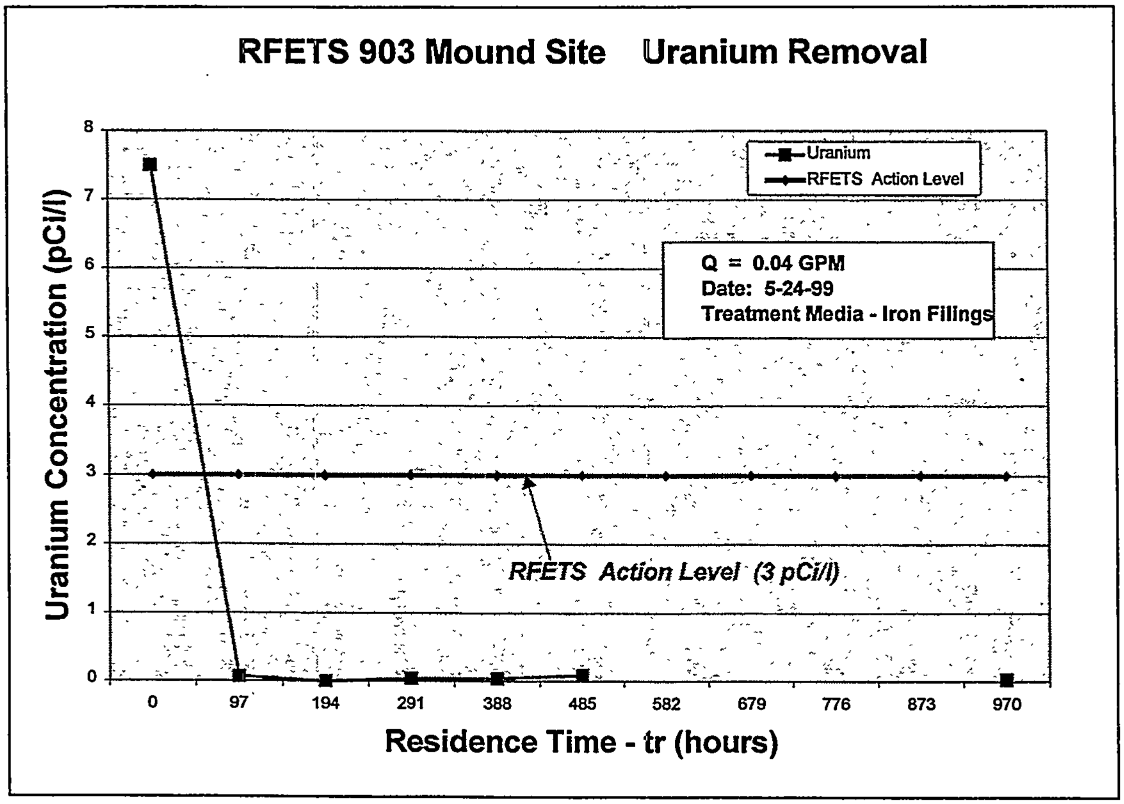


Figure 25. Uranium Removal.

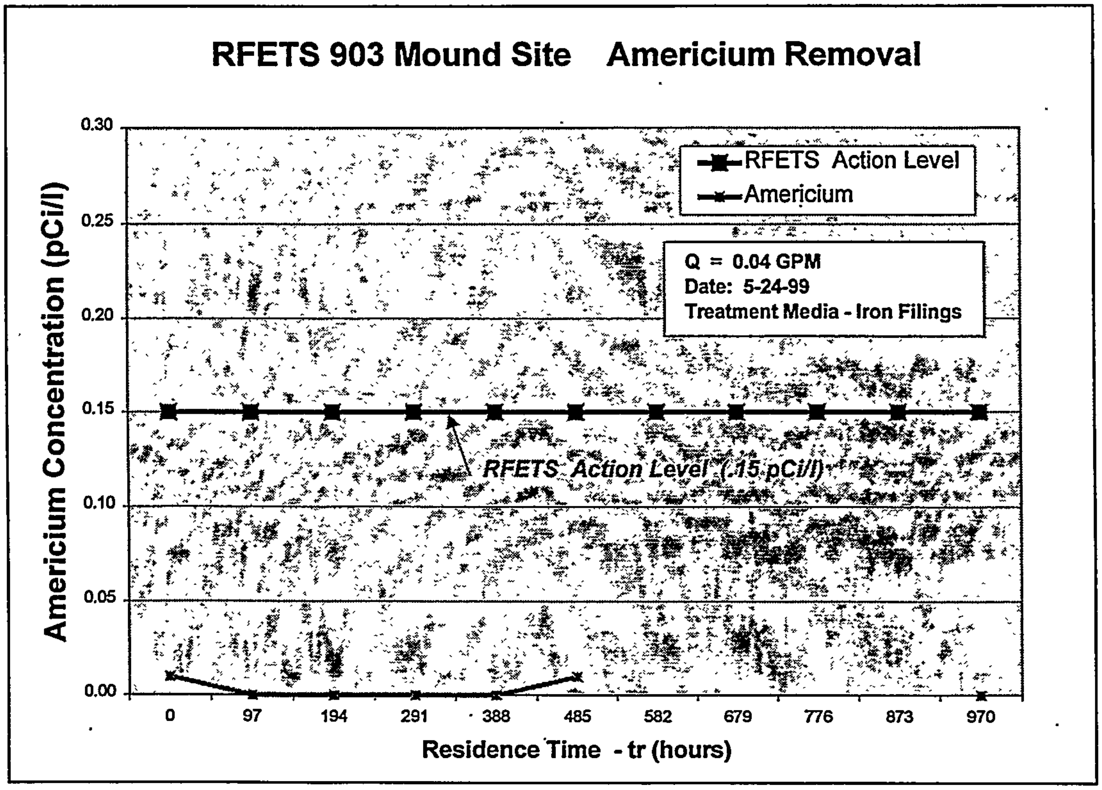


Figure 26. Americium Removal.

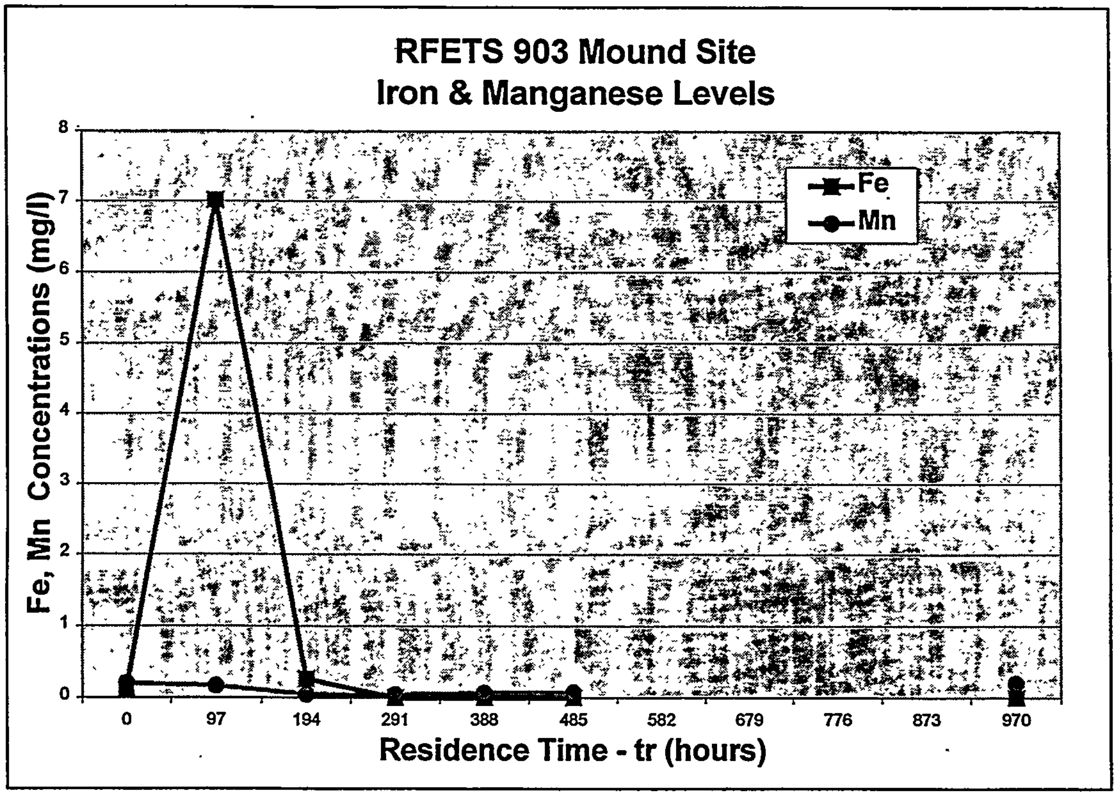


Figure 27. Iron and Manganese Removal.

APPENDIX A

Table A-1. Rocky Flats Barrier Materials Column Studies.

Influent Concentrations for All Columns Used in Run 1: Iron Filings, Iron-Silica Foam, and Humasorb-Sand								
Sample ID	Sample Description	Sample Volume	Influent Mn (ppb)	MDL Mn (ppb)	Influent Sb (ppb)	MDL Sb (ppb)	Influent Tl (ppb)	MDL Tl (ppb)
S-220	1st Fraction		429	0.7	67.0	0.4	43.4	0.3
S-230	2nd Fraction		510	0.7	81.1	0.4	50.8	0.3
S-240	3rd Fraction		497	0.7	80.4	0.4	51.5	0.3
S-250	4th Fraction		464	0.7	74.6	0.4	47.6	0.3
S-260	5th Fraction		479	0.7	76.7	0.4	49.2	0.3
S-270	6th Fraction		467	0.7	76,2	0.4	48.5	0.3
S-280	7th Fraction		459	0.7	74.0	0.4	47.9	0.3
Average			472		75.7		48.4	

Table A-2. Rocky Flats Barrier Materials Column Studies.

Effluents from the Connelly Iron Filings Column, Run 1

Column Volume (mL): 58.1
Pore Volume (%): 64.5
Pore Volume (mL): 37.5

Sample ID	Sample Description	Sample Volume	Effluent Mn (ppb)	MDL Mn (ppb)	Effluent Sb (ppb)	MDL Sb (ppb)	Effluent Tl (ppb)	MDL Tl (ppb)	Flow Rate (mL/Hr)	Res Time (min)	Breakthru Mn (%)	Breakthru Sb (%)	Breakthru Tl (%)
FE-111	DI Wash		1,743	0.7	0	0.4	0.4	0.3			369.2	0.0	0.8
FE-121	1st Fraction		984	0.7	1.2	0.4	0.3	0.3	18.1	124.2	208.4	1.6	0.6
FE-131	2nd Fraction		888	0.7	1.2	0.4	0.3	0.3	48.2	46.6	188.1	1.6	0.6
FE-141	3rd Fraction		853	0.7	1.8	0.4	0.3	0.3	84.2	26.7	180.7	2.4	0.6
FE-151	4th Fraction		705	0.7	3.3	0.4	0.3	0.3	119.9	18.8	149.3	4.4	0.6
FE-161	5th Fraction		599	0.7	4.2	0.4	0.4	0.3	152.3	14.8	126.9	5.5	0.8
FE-171	6th Fraction		532	0.7	6.6	0.4	0.3	0.3	184.1	12.2	112.7	8.7	0.6
FE-182	7th Fraction		481	0.7	8.2	0.4	LMDL	0.3	215.4	10.4	101.9	10.8	0.0

LMDL = lower than the material detection limit

Table A-3. Rocky Flats Barrier Materials Column Studies.

Effluents from the Iron-Silica Foam Column, Run 1

Column Volume (mL):	58.52
Pore Volume (%):	69.2
Pore Volume (mL):	40.5

Sample ID	Sample Description	Sample Volume	Effluent Mn (ppb)	MDL Mn (ppb)	Effluent Sb (ppb)	MDL Sb (ppb)	Effluent Tl (ppb)	MDL Tl (ppb)	Flow Rate (mL/Hr)	Res Time (min)	Breakthru Mn (%)	Breakthru Sb (%)	Breakthru Tl (%)
FESI-112	DI Wash		158	0.7	2.60	0.4	0.3	0.3			33.5	3.4	0.6
FESI-122	1st Fraction		2,626	0.7	16.50	0.4	0.3	0.3	18.3	122.9	556.2	21.8	0.6
FESI-132	2nd Fraction		1,138	0.7	21.10	0.4	0.4	0.3	47.8	47.0	241.0	27.9	0.8
FESI-142	3rd Fraction		975	0.7	24.70	0.4	0.3	0.3	84.2	26.7	206.5	32.6	0.6
FESI-152	4th Fraction		772	0.7	27.20	0.4	0.5	0.3	119.9	18.8	163.5	35.9	1.0
FESI-162	5th Fraction		677	0.7	27.60	0.4	1.4	0.3	152.3	14.8	143.4	36.5	2.9
FESI-182	7th Fraction		563	0.7	28.10	0.4	4.3	0.3	215.2	10.4	119.2	37.1	8.9

Note: the 6th fraction gave spurious results and was not included.

Table A-4. Rocky Flats Barrier Materials Column Studies.

Effluents from Humasorb-Sand Column, Run 1

Column Volume (mL):	69.82
Pore Volume (%):	42.2
Pore Volume (mL):	29.5

Sample ID	Sample Description	Sample Volume	Effluent Mn (ppb)	MDL Mn (ppb)	Effluent Sb (ppb)	MDL Sb (ppb)	Effluent Tl (ppb)	MDL Tl (ppb)	Flow Rate (mL/Hr)	Res Time (min)	Breakthru Mn (%)	Breakthru Sb (%)	Breakthru Tl (%)
H-113	DIWash		20.8	0.70	1.0	0.40	0.5	0.3			4.4	1.3	1.0
H-123	1st Fraction		4.0	0.70	32.3	0.40	0.3	0.3	18.3	96.6	0.8	42.7	0.6
H-133	2nd Fraction		3.7	0.70	39.8	0.40	0.4	0.3	48.3	36.6	0.8	52.6	0.8
H-143	3rd Fraction		9.3	0.70	51.2	0.40	0.3	0.3	84.1	21.0	2.0	67.6	0.6
H-153	4th Fraction		18.2	0.70	49.4	0.40	0.3	0.3	120.1	14.7	3.9	65.2	0.6
H-163	5th Fraction		28.5	0.70	45.0	0.40	0.6	0.3	151.8	11.6	6.0	59.4	1.2
H-173	6th Fraction		38.9	0.70	47.1	0.40	1.2	0.3	183.0	9.7	8.2	62.2	2.5
H-183	7th Fraction		60.0	0.70	53.6	0.40	2.5	0.3	213.20	8.3	12.7	70.8	5.2

Table A-5. Rocky Flats Barrier Materials Column Studies.

Influent Concentrations for All Columns Used in Run 2: Iron Filings, Iron-Silica Foam, and Humasorb-Sand

Sample ID	Sample Description	Sample Volume	Influent U238 (dpm)	MDA U238 (dpm)	Influent Pu239 (dpm)	MDA Pu239 (dpm)	Influent Am241 (dpm)	MDA Am241 (dpm)	Influent U238 (pCi/L)	MDL U238 (pCi/L)	Influent Pu239 (pCi/L)	MDL Pu239 (pCi/L)	Influent Am241 (pCi/L)	MDL Am241 (pCi/L)
S-220	1st Fraction	95.60	3.89	0.03	0.46	0.02	3.86	0.03	18.33	0.14	2.17	0.09	18.19	0.14
S-230	2nd Fraction	99.40	3.78	0.03	0.73	0.02	1.01	0.06	17.13	0.14	3.31	0.09	4.58	0.27
S-240	3rd Fraction	98.30	3.99	0.04	0.45	0.04	0.87	0.07	18.28	0.18	2.06	0.18	3.99	0.32
S-250	4th Fraction	95.10	3.45	0.03	0.59	0.05	0.86	0.08	16.53	0.14	2.79	0.24	4.07	0.38
S-260	5th Fraction	97.20	4.39	0.04	0.82	0.06	0.92	0.09	20.34	0.19	3.80	0.28	4.26	0.42
S-270	6th Fraction	100.50	4.77	0.03	0.63	0.03	0.84	0.08	21.38	0.13	2.82	0.13	3.76	0.36
S-280	7th Fraction	103.50	4.59	0.04	0.37	0.02	0.87	0.07	19.98	0.17	1.61	0.09	3.79	0.30
S-290	shut down	589.78	28.26	0.03	1.68	0.04	4.6	0.06	21.58	0.02	1.28	0.03	3.51	0.05

Table A-6. Rocky Flats Barrier Materials Column Studies.

Influent Concentrations for All Columns Used in Run 2: Iron Filings, Iron-Silica Foam, and Humasorb-Sand

Sample ID	Sample Description	Sample Volume	Influent U238 (dpm)	MDA U238 (dpm)	Influent Pu239 (dpm)	MDA Pu239 (dpm)	Influent Am241 (dpm)	MDA Am241 (dpm)	Influent U238 (pCi/L)	MDL U238 (pCi/L)	Influent Pu239 (pCi/L)	MDL Pu239 (pCi/L)	Influent Am241 (pCi/L)	MDL Am241 (pCi/L)
S-220	1st Fraction	95.60	3.89	0.03	0.46	0.02	3.86	0.03	18.33	0.14	2.17	0.09	18.19	0.14
S-230	2nd Fraction	99.40	3.78	0.03	0.73	0.02	1.01	0.06	17.13	0.14	3.31	0.09	4.58	0.27
S-240	3rd Fraction	98.30	3.99	0.04	0.45	0.04	0.87	0.07	18.28	0.18	2.06	0.18	3.99	0.32
S-250	4th Fraction	95.10	3.45	0.03	0.59	0.05	0.86	0.08	16.53	0.14	2.79	0.24	4.07	0.38
S-260	5th Fraction	97.20	4.39	0.04	0.82	0.06	0.92	0.09	20.34	0.19	3.80	0.28	4.26	0.42
S-270	6th Fraction	100.50	4.77	0.03	0.63	0.03	0.84	0.08	21.38	0.13	2.82	0.13	3.76	0.36
S-280	7th Fraction	103.50	4.59	0.04	0.37	0.02	0.87	0.07	19.98	0.17	1.61	0.09	3.79	0.30
S-290	shut down	589.78	28.26	0.03	1.68	0.04	4.6	0.06	21.58	0.02	1.28	0.03	3.51	0.05

Table A-7. Rocky Flats Barrier Materials Column Studies.

Effluents from the Iron-Silica Foam Column, Run 2

Column Volume (mL):	60.41
Pore Volume (%):	70.5
Pore Volume (mL):	42.6

Sample ID	Sample Description	Sample Volume	Effluent U238 (dpm)	MDA U238 (dpm)	Effluent Pu239 (dpm)	MDA Pu239 (dpm)	Effluent Am241 (dpm)	MDA Am241 (dpm)	Flow Rate mL/Hr	Res Time (min)	Effluent U238 (pCi/L)	MDL U238 (pCi/L)	Effluent Pu239 (pCi/L)	MDL Pu239 (pCi/L)	Influent Am241 (pCi/L)	MDL Am241 (pCi/L)
FESI-212	DI Wash	532.19	LMDA	0.04	0.22	0.05	LMDA	0.08	228.4	10.1	0	0.03	0.19	0.04	0	0.07
FESI-222	1st Fraction	546.57	0.08	0.03	0.46	0.04	LMDA	0.07	18.2	127.1	0.07	0.02	0.38	0.03	0	0.06
FESI-232	2nd Fraction	559.03	0.06	0.03	0.34	0.06	LMDA	0.08	46.6	49.6	0.05	0.02	0.27	0.05	0	0.06
FESI-242	3rd Fraction	488.04	LMDA	0.02	1.35	0.02	0.05	0.05	81.3	28.5	0	0.02	1.25	0.02	0.05	0.05
FESI-252	4th Fraction	593.96	LMDA	0.03	0.13	0.02	0.07	0.06	118.8	19.5	0	0.02	0.10	0.02	0.05	0.05
FESI-262	5th Fraction	519.68	LMDA	0.04	0.18	0.05	LMDA	0.09	148.5	15.6	0	0.03	0.16	0.04	0	0.08
FESI-272	6th Fraction	526.34	0.05	0.03	0.12	0.04	LMDA	0.06	175.4	13.2	0.04	0.03	0.10	0.03	0	0.05

LMDA = Lower than the MDA

Note: the 7th fraction was discarded due to experimental error

Table A-8. Rocky Flats Barrier Materials Column Studies.

Effluents from Humasorb-Sand Column, Run 2

Column Volume (Ml):	58.25
Pore Volume (%)	44.7
Pore Volume (Ml):	26.0

Sample ID	Sample Description	Sample Volume	Effluent U238 (dpm)	MDA U238 (dpm)	Effluent Pu239 (dpm)	MDA Pu239 (dpm)	Effluent Am241 (dpm)	MDA Am241 (dpm)	Flow Rate ML/Hr	Res Time (min)	Effluent U238 (pCi/L)	MDL U238 (pCi/L)	Effluent Pu239 (pCi/L)	MDL Pu239 (pCi/L)	Influent Am241 (pCi/L)	MDL Am241 (pCi/L)
H-213	DI Wash	538.24	0.10	0.02	0.21	0.03	LMDA	0.09	231.0	6.8	0.08	0.02	0.18	0.03	0	0.08
H-223	1st Fraction	548.51	11.70	0.04	1.61	0.05	LMDA	0.10	18.3	85.4	9.61	0.03	1.32	0.04	0	0.08
H-233	2nd Fraction	571.88	22.37	0.05	0.29	0.05	LMDA	0.08	47.7	32.8	17.62	0.04	0.23	0.04	0	0.06
H-243	3rd Fraction	489.06	16.38	0.02	0.57	0.03	LMDA	0.08	81.5	19.2	15.09	0.02	0.53	0.03	0	0.07
H-253	4th Fraction	598.08	23.12	0.02	0.15	0.01	LMDA	0.05	119.6	13.1	17.41	0.02	0.11	0.01	0	0.04
H-263	5th Fraction	523.29	21.83	0.02	0.20	0.04	LMDA	0.10	149.5	10.4	18.79	0.02	0.17	0.03	0	0.09
H-273	6th Fraction	527.55	20.38	0.02	0.19	0.03	LMDA	0.05	175.9	8.9	17.40	0.02	0.16	0.03	0	0.04

LMDA = Lower than the MDA

Note: the 7th fraction was discarded due to experimental error

APPENDIX B

Iron Foam Pellets 1

L (cm): 5.00
A (cm2): 17.72
Hc (cm): 36.50
Ho (cm): 23.60
Sample Mass (g): 180.92
Pb (g/cm^3): 2.04

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	180.98	59.84	8.85E-02
40	213.70	58.81	8.49E-02
40	213.65	58.70	8.49E-02
40	211.83	59.84	8.33E-02

Initial test + 12 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	171.91	59.84	8.19E-02
30	171.65	59.84	8.17E-02
30	171.95	58.81	8.27E-02

Iron Foam Pellets 2

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 23.70
Sample Mass (g): 188.58
Pb (g/cm^3): 2.13

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	168.92	59.84	8.37E-02
30	167.67	59.84	8.27E-02
30	166.61	58.81	8.27E-02
30	162.74	58.70	7.98E-02

Initial test + 12 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	155.70	59.88	7.35E-02
30	152.70	58.81	7.20E-02
30	152.31	58.70	7.18E-02

Iron Foam Pellets 3

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 22.40
Sample Mass (g): 199.89
Pb (g/cm^3): 2.26

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	139.66	58.70	5.64E-02
30	137.98	58.81	5.51E-02
30	135.15	59.84	5.25E-02
30	131.81	59.84	5.01E-02

Iron Foam Pellets 4

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 22.40
Sample Mass (g): 210.36
Pb (g/cm^3): 2.38

Initial test + 12 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	107.78	58.70	3.42E-02
30	116.12	58.81	3.99E-02
30	128.43	59.84	4.78E-02

Table B-1. Results of saturated hydraulic conductivity tests using Iron Foam Pellets media.

Connelly - GPM 1

L (cm): 5.00
A (cm2): 17.72
Hc (cm): 36.50
Ho (cm): 22.25
Sample Mass (g): 240.15
Pb (g/cm^3): 2.71

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	122.79	58.70	4.24E-02
30	111.57	58.81	3.49E-02
30	101.11	59.61	2.75E-02
30	91.39	59.88	2.08E-02

Initial test + 12 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	82.97	58.70	1.61E-02
30	82.35	58.81	1.56E-02
30	81.08	59.61	1.42E-02
30	80.81	59.88	1.38E-02

Connelly - GPM 2

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 22.30
Sample Mass (g): 250.74
Pb (g/cm^3): 2.83

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	159.67	58.70	6.98E-02
30	154.80	58.81	6.64E-02
30	141.13	59.61	5.64E-02
30	119.15	59.88	4.10E-02

Initial test + 12 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	102.13	58.70	3.00E-02
30	101.01	58.81	2.92E-02
30	97.44	59.61	2.62E-02
30	94.71	59.88	2.41E-02

Connelly - GPM 3

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 22.45
Sample Mass (g): 257.19
Pb (g/cm^3): 2.91

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	81.13	58.70	1.57E-02
30	96.53	58.81	2.64E-02
30	74.71	59.61	1.06E-02
30	71.52	59.88	8.14E-03

Initial test + 12 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	59.44	58.70	5.17E-04
30	59.48	58.81	4.68E-04
30	60.36	59.61	5.24E-04
30	60.53	59.88	4.54E-04

Table B-2. Results of saturated hydraulic conductivity tests using Iron Filings media.

Humasorb-CS 1

L (cm): 5.00
A (cm2): 17.72
Hc (cm): 36.50
Ho (cm): 23.00
Sample Mass (g): 79.21
Pb (g/cm^3): 0.89

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	168.51	58.70	7.67E-02
30	164.26	58.81	7.36E-02
30	161.64	59.61	7.12E-02
30	159.57	59.88	6.96E-02

Initial test + 72 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	76.68	58.70	1.26E-02
30	79.04	58.81	1.41E-02
30	79.06	59.61	1.36E-02
30	79.58	59.88	1.38E-02

Humasorb-CS 2

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 24.70
Sample Mass (g): 92.86
Pb (g/cm^3): 1.05

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	126.87	58.70	5.67E-02
30	119.34	58.81	5.04E-02
30	116.36	59.61	4.72E-02
30	121.67	59.88	5.14E-02

Initial test + 72 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	60.29	58.70	1.32E-03
30	60.50	58.81	1.41E-03
30	61.31	59.61	1.41E-03
30	61.51	59.88	1.36E-03

Humasorb-CS 3

L (cm): 5.10
A (cm2): 17.35
Hc (cm): 36.50
Ho (cm): 22.70
Sample Mass (g): 92.54
Pb (g/cm^3): 1.05

Initial test:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	108.38	58.70	3.54E-02
30	104.75	58.81	3.27E-02
30	100.03	59.61	2.88E-02
30	102.59	59.88	3.04E-03

Initial test + 72 hr.:

Outflow

Time (s)	Mass (g)	Tare (g)	Ks (cm/s)
30	60.78	58.70	1.48E-03
30	61.07	58.81	1.61E-03
30	61.85	59.61	1.59E-03
30	62.22	59.88	1.67E-03

Table B-3. Results of saturated hydraulic conductivity tests using Humasorb-CS media.

APPENDIX C

Table C-1. The Concentrations of Volatile Organic Species Present at Various Samplings of the Column Influents and Effluents.

Column Characteristics

Column Identification	Influent	FE3	FE6	FE12	FE24	FE36
Length of Column (inch)	0	3.00	6.00	12.00	24.00	36.00
Mass of Iron Filings (g)	0	905	1867	3687	7283	10951
Pore Volume (mL)	0	203	387	774	1545	2342

Day of 7/16/97 (initial plug of effluent)

SMO Sample Number						33823
Benzene						0.9
Chloromethane						1.2

Day of 7/18/97

SMO Sample Number	Average Influent	33825	33826	33827	33828	33824
Av Daily Flow Rate (mL/hr)	NA	122	122	121	124	128
Residence Time (hr)	0	1.66	3.16	6.39	12.46	18.24
Carbon Tetrachloride	34	*1*	*1*	*1*	*1*	*1*
Chloroform	9	4.4	*1*	*1*	*1*	*1*
Cis-1,2-Dichloroethene	9	2.8	1.1	*1*	*1*	*1*
Methylene Chloride	*1*	*1.5*	1.4	1.1	1.2	1
Metrachloroethane	9	*1*	*1*	*1*	*1*	*1*
1,1,1-Trichloroethane	2	*1*	*1*	*1*	*1*	*1*
Trichloroethene	14	*1*	*1*	*1*	*1*	*1*

Day of 7/22/98

SMO Sample Number	Average Influent	33765	33766	33767	33768	33764
Av Daily Flow Rate (mL/hr)	NA	114	120	116	119	134
Residence Time (hr)	0	1.78	3.22	6.68	12.94	17.50
Carbon Tetrachloride	34	*1*	*1*	*1*	*1*	*1*
Chloroform	9	*1.5*	*1*	*1*	*1*	*1*
Cis-1,2-Dichloroethene	9	*1*	*1*	*1*	*1*	*1*
Methylene Chloride	*1*	1.4	1.3	*1*	1.1	1.1
Tetrachloroethane	9	*1*	*1*	*1*	*1*	*1*
1,1,1-Trichloroethane	2	*1*	*1*	*1*	*1*	*1*
Trichloroethene	14	*1*	*1*	*1*	*1*	*1*

Day of 7/23/99

SMO Sample Number	Average Influent	33771	33772	33773	33774	33770
Av Daily Flow Rate (mL/hr)	NA	113	121	116	121	130
Residence Time (hr)	0	1.80	3.21	6.68	12.78	18.06
Carbon Tetrachloride	34	*1*	*1*	*1*	*1*	*1*
Chloroform	9	*1*	*1*	*1*	*1*	*1*
Cis-1,2-Dichloroethene	9	*1*	*1*	*1*	*1*	*1*
Methylene Chloride	1	1.6	*1.5*	1	*1*	*1*
Tetrachloroethane	9	*1*	*1*	*1*	*1*	*1*
1,1,1-Trichloroethane	2	*1*	*1*	*1*	*1*	*1*
Trichloroethene	14	*1*	*1*	*1*	*1*	*1*

Day of 7/24/100

SMO Sample Number	Average Influent	33802	33803	33804	33805	33801
Av Daily Flow Rate (mL/hr)	NA	109	116	111	*115*	121
Residence Time (hr)	0	1.87	3.34	6.95	13.45	19.35
Carbon Tetrachloride	34	*1*	*1*	*1*	*1*	*1*
Chloroform	9	*1*	*1*	*1*	*1*	*1*
Cis-1,2-Dichloroethene	9	*1*	*1*	*1*	*1*	*1*
Methylene Chloride	*1*	1.2	1.2	*1*	*1*	*1*
Tetrachloroethane	9	*1*	*1*	*1*	*1*	*1*
1,1,1-Trichloroethane	2	*1*	*1*	*1*	*1*	*1*
Trichloroethene	14	*1*	*1*	*1*	*1*	*1*

Notes: Numbers in italics are detection limits and indicate that the concentration of that species for that sample is below the detection limit. EPA method 8260 was used for the determination of aqueous phase volatile organic compounds which includes a screen for over 50 organic species. Only the compounds that were present in at least one sample were reported.

Table C-2. The Concentrations of Various Heavy Metal Species Present at Samplings of the Column Influents and Effluents.

Column Characteristics

Column Identification	Influent	FE3	FE6	FE12	FE24	FE36
Length of Column (inch)	0	3.00	6.00	12.00	24.00	36.00
Mass of Iron Filings (g)	0	905	1867	3687	7283	10951
Pore Volume (mL)	0	203	387	774	1545	2342

Day of 7/16/97 (initial plug of effluent)

SMO Sample Number						33788
Antimony (∓g/L)						*3*
Iron (∓g/L)						310000
Manganese (∓g/L)						34300
Thallium (∓g/L)						*1*

Day of 7/18/97

SMO Sample Number	Average Influent	33790	33791	33792	33793	33789
Av Daily Flow Rate (mL/hr)	NA	122	122	121	124	128
Residence Time (hr)	0	1.66	3.16	6.39	12.46	18.24
Antimony (∓g/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (∓g/L)	*30*	1280	2060	4880	1210	280
Manganese (∓g/L)	32	194	255	481	786	162
Thallium (∓g/L)	*1*	*1*	*1*	*1*	*1*	*1*

Day of 7/22/98

SMO Sample Number	Average Influent	33796	33797	3.3798	33799	33795
Av Daily Flow Rate (mL/hr)	NA	114	120	116	119	134
Residence Time (hr)	0	1.78	3.22	6.68	12.94	17.5 0
Antimony (∓g/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (∓g/L)	*30*	7680	*1510*	620	1280	790
Manganese (∓g/L)	32	210	195	198	1200	490
Thallium (∓g/L)	*1*	*1*	*1*	*1*	*1*	*1*

Day of 7/23/99

SMO Sample Number	Average Influent	33777	33778	33779	3.3780	33776
Av Daily Flow Rate (mL/hr)	NA	113	121	116	121	130
Residence Time (hr)	0	1.80	3.21	6.68	12.78	18.06
Antimony (∓g/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (∓g/L)	*30*	1100	430	140	90	370
Manganese (∓g/L)	32	87	125	207	494	391
Thallium (∓g/L)	*1*	*1*	*1*	*1*	*1*	*1*

Day of 7/24/100

SMO Sample Number	Average Influent	33.808	33.809	33810	33811	33807
Av Daily Flow Rate (mL/hr)	NA	109	116	111	115	121
Residence Time (hr)	0	1.87	3.34	6.95	13.45	1935
Antimony (∓g/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (∓g/L)	*30*	2110	630	160	50	190
Manganese (∓g/L)	32	128	146	202	247	352
Thallium (+g/L)	*1*	*1*	*1*	*1*	*1*	*1*

Note: Numbers in italics are detection limits and indicate that the concentration of that species for that sample is below the detection limit. The concentrations of antimony and thallium were determined, but these elements were never detected in any sample.

Table C-3. The Concentrations of Various Radioactive Species Present at Samplings of the Column Influents and Effluents.

Column Characteristics

Column Identification	Influent	FE3	FE6	FE12	FE24	FE36
Length of Column (inch)	0	3.00	6.00	12.00	24.00	36.00
Mass of Iron Filings (g)	0	905	1867	3687	7283	10951
Pore Volume (mL)	0	203	387	774	1545	2342

Day of 7/16/97 (initial plug of effluent)

SMO Sample Number	Average Influent					33757
Uranium (total)	5.9					*0.7*
Americium (24 1)	*0.13*					*0.10*
Plutonium (239/240)	*0.11*					*0.08*

Day of 7/18/97

SMO Sample Number	Average Influent	33759	33760	33761	33762	33758
Av Daily Flow Rate (mL/hr)	NA	122	122	121	124	128
Residence Time (hr)	0	1.66	3.16	6.39	12.46	18.24
Uranium (total)	5.9	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Americium (241)	0.13	0.09	0.08	0.07	0.07	0.14
Plutonium (239/240)	*0.11*	*0.05*	*0.05*	*0.06*	*0.08*	*0.04*

Day of 7/22/98

SMO Sample Number	Average Influent	33831	33832	3.3833	33.834	33830
Av Daily Flow Rate (mL/hr)	NA	114	120	116	119	134
Residence Time (hr)	0	1.78	3.22	6.68	12@94	17.50
Uranium (total)	5.9	0.7	2.2	0@7	0.7	*0.7*
Americium (241)	*0.13*	0.10	*0.15*	*0.13*	*0.13*	*0.08*
Plutonium (239/240)	*0.11*	*0.06*	0.09	0.09	0.05	0.04

Day of 7/24/100

SMO Sample Number	Average Influent	33814	3381.5	33.816	33817	33813
Av Daily Flow Rate (mL/hr)	NA	109	116	111	*115*	121
Residence Time (hr)	0	1.87	3.34	6.95	13.45	19.35
Uranium (total)	5.9	3.8	*0.7*	*0.7*	*0.7*	*0.7*
Americium (241)	*0.13*	*0.14*	*0.09*	*0.11*	*0.12*	0.09
Plutonium (239/240)	*0.11*	*0.07*	*0.05*	*0.05*	*0.06*	0.04

Note: Numbers in italics are detection limits and indicate that the concentration of that species for that sample is below the detection limit.

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