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Advanced Subsurface Containment Systems Design and Performance Evaluation of Reactive Media
Technical Task Plan No. AL-28-SS-40

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

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

LABORATORY AND PILOT SCALE 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 to identify the optimum treatment reagent for use in a Permeable Reactive Barrier Treatment System at Rocky Flats Environmental Technology Site (RFETS). 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 most cost effective 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. Design parameters including saturated hydraulic conductivity, treatment residence time, and head loss across the media were provided to the design team in support of the final design.

1. INTRODUCTION

The primary objective of this project was to identify the optimum treatment media (reagent) for the 903 Mound Site at Rocky Flats Environmental Technology Site (RFETS) proposed reactive barrier installation. The evaluation was divided into two parts: (1) a laboratory scale optimization of three potential reagents; and (2) a pilot-scale, field column study to verify laboratory results. 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).

2. 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 which 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.

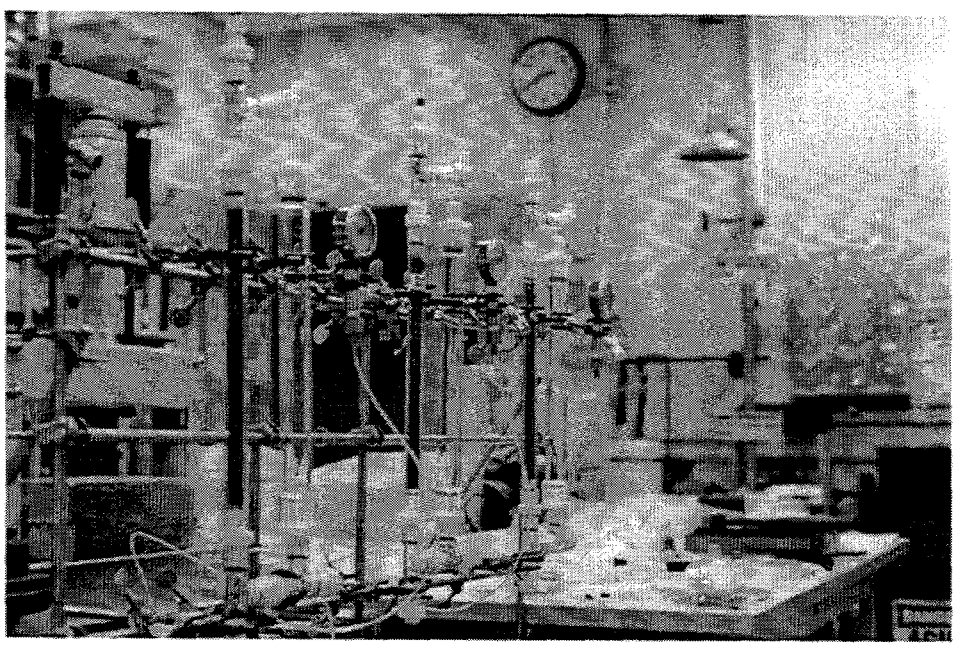

Figure 1. Laboratory Column Testing.

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 1 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 1. 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 2. Sampling the effluents of other columns was performed in a similar manner.

Table 2. 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 3 and 4. 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 4. 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 5 and 6 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 5 and 6).

Table 3. 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 4. 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 5. 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
$CaCI_2$-$2H_20$	147.02	1.00 x 10-3	2.940
KCI	74.56	0.05 x 10-3	0.0746
HCI (36-37%)	36.46	1.00 x 10-3	1.967

Table 6. 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	SO_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.

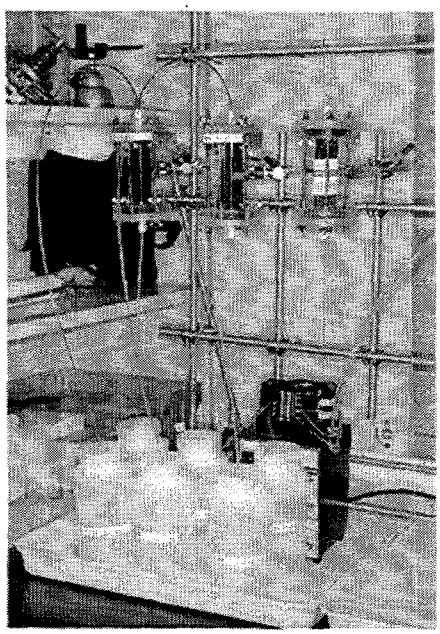

Figure 2. Laboratory column setup.

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 (Appendix A - Tables 7, 8, 9, 10, 11, 12, 13, and 14) 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.

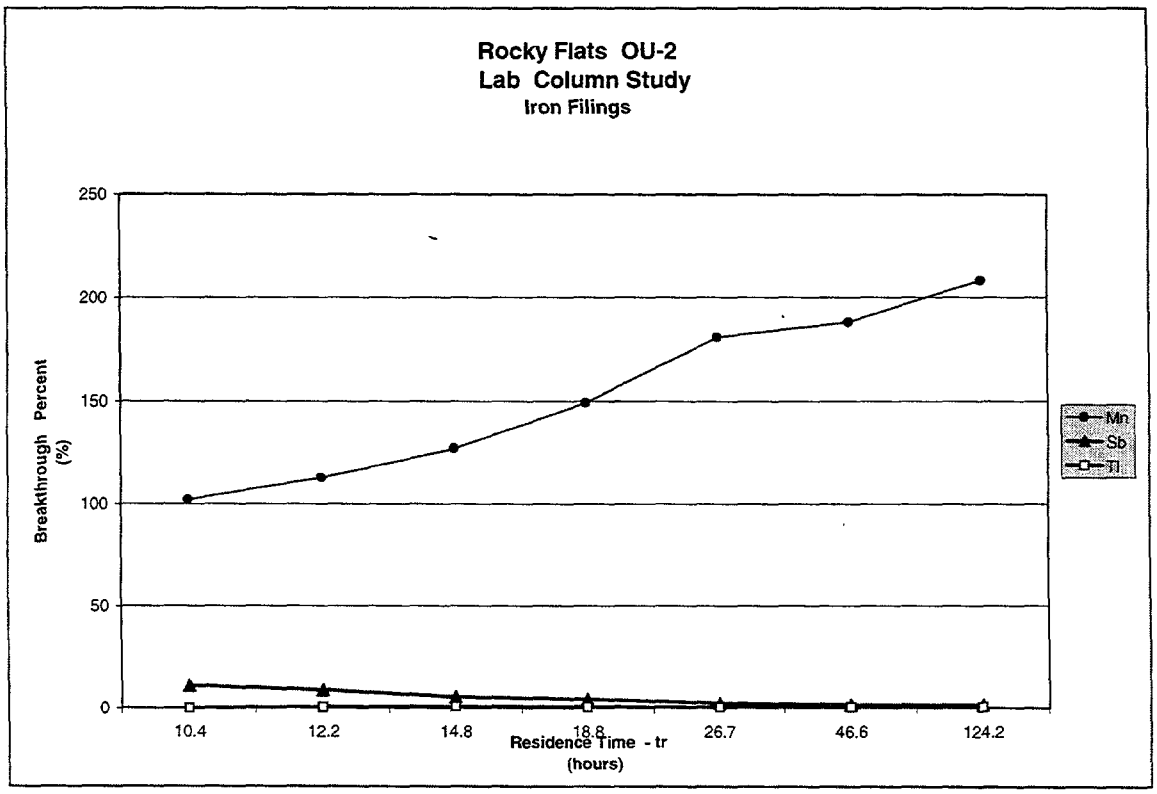

Figure 3. Iron Filings Lab Column Results.

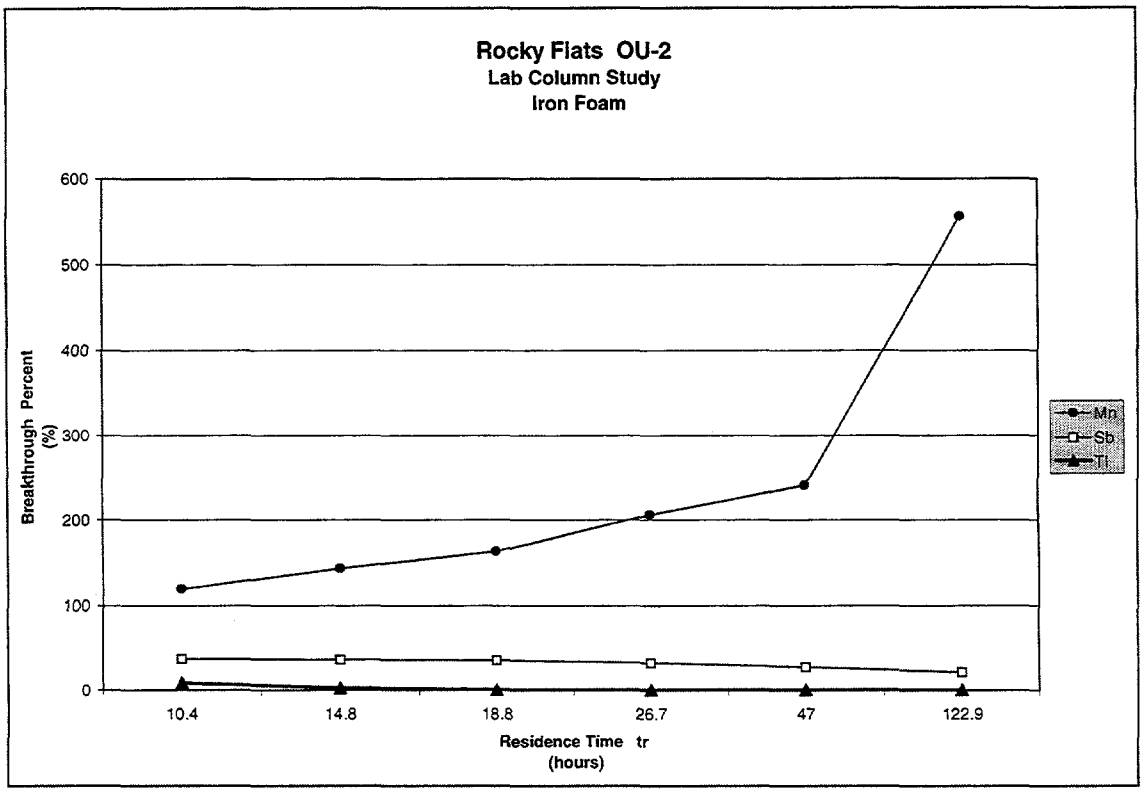

Figure 4. Iron Foam Lab Column Results.

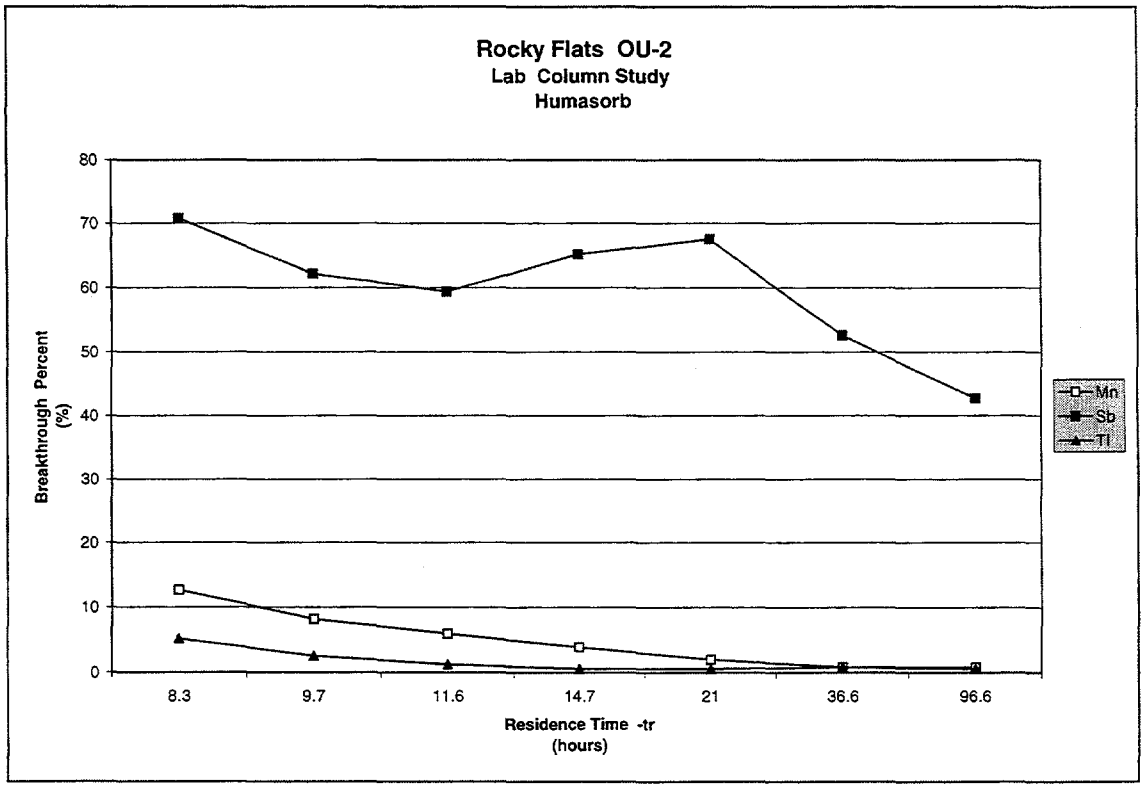

Figure 5. Humasorb Lab Column Results.

Conclusions

Columns containing various reagents 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 report. 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 CCℓ4. 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 15, 16, and 17 present the results for the three media samples at each of the bulk densities tested.

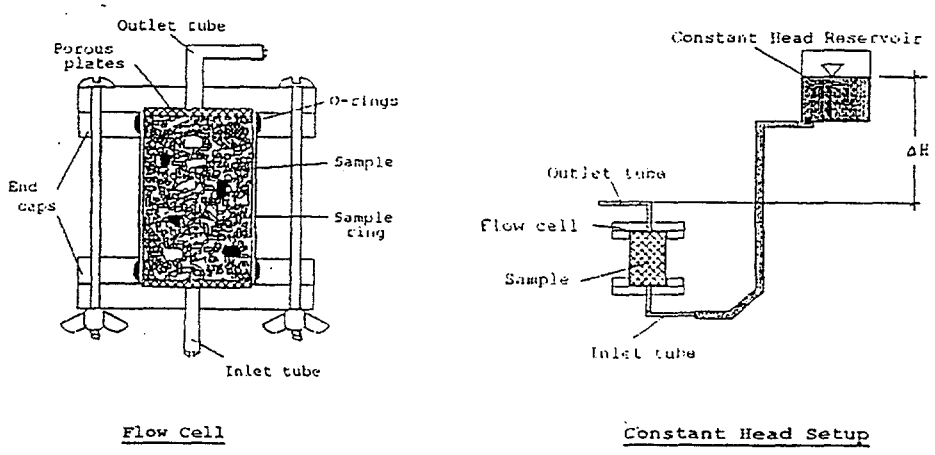

Figure 6. Constant head and flow cell apparatus.

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:

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

where: outflow mass = mass of flow through cell + container mass
tare = mass of container
p_{H_2O} = 0.9978g/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 X 10^{-2} cm/s
Iron filings	3 X 10^{-2} cm/s
Humasorb-CS	1.5 X 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.

3. PILOT FIELD COLUMN STUDY

Column Scale Field Validation

The 903 Mound Site Plume at RFETS contains low level radioactive contaminants including uranium 238 and small amounts of chlorinated and brominated organic compounds. Between 1954 and 1958, approximately 1400 drums of lathe solvents from turning uranium and beryllium parts were deposited in shallow pits and covered with soil. It is estimated that ten percent of the drums leaked before the drums and some of the surrounding soils were removed in 1970. Low levels of these contaminants migrated into soils downgradient from the original burial site and have turned up in slow moving ground water channels that run along the bedrock at a depth of 20 feet or less. The contaminants ultimately end up in South Walnut Creek at the bottom of the hill. There is little motivation to excavate and remove all the

remaining contaminated soil in this area since ground water contaminant levels are only slightly above drinking water standards and such a proposition would be very costly. A cost effective alternative to excavation known as reactive barrier technology was proposed for the site cleanup. It was decided that this was an ideal site for a demonstration of this novel technology.

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 a remediation method. 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.

The reactive barrier design has a water collection system made of an impermeable material (HDPE) and two large reactor tanks containing iron filings. The ground water collection system is composed of an impermeable wall placed in situ downgradient of the plume that captures contaminated groundwater directing it into a pipe and ultimately into the reactor tank. The entire collection process is passive, i.e., gravity feed. Presumably, clean effluents from the reactor 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 accomodate sampling. In addition, the iron may be replaced in the future. Laboratory column studies performed by Sandia National Laboratories and Environmental Technologies Inc. provided an optimization of potential treatment media. The optimum choice was Connelly Iron filings based on its performance in laboratory column studies. The influent samples used for these tests were fabricated in the laboratory to approximate an average matrix determined in ground waters in the mound area. This discussion focuses on the results of additional column studies with Connelly iron that were performed on site using influents pumped from the seep (SWO59) in the Rocky Flats Mound Site Plume area. It was thought that a study of this type was needed to accurately validate residence times, saturated hydraulic conductivity, and head loss across the media for the effective treatment of contaminated ground water for this specific site.

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.

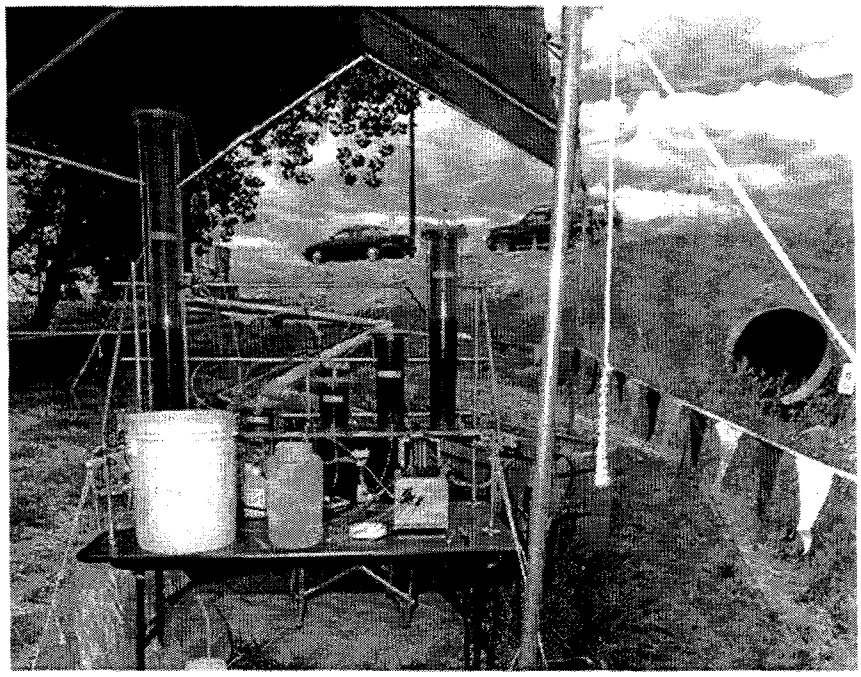

Figure 7. Pilot-scale field columns at RFETS 903 Mound Site.

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 which 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 which 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 $HC\ell$ 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 18, 19, and 20 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.)

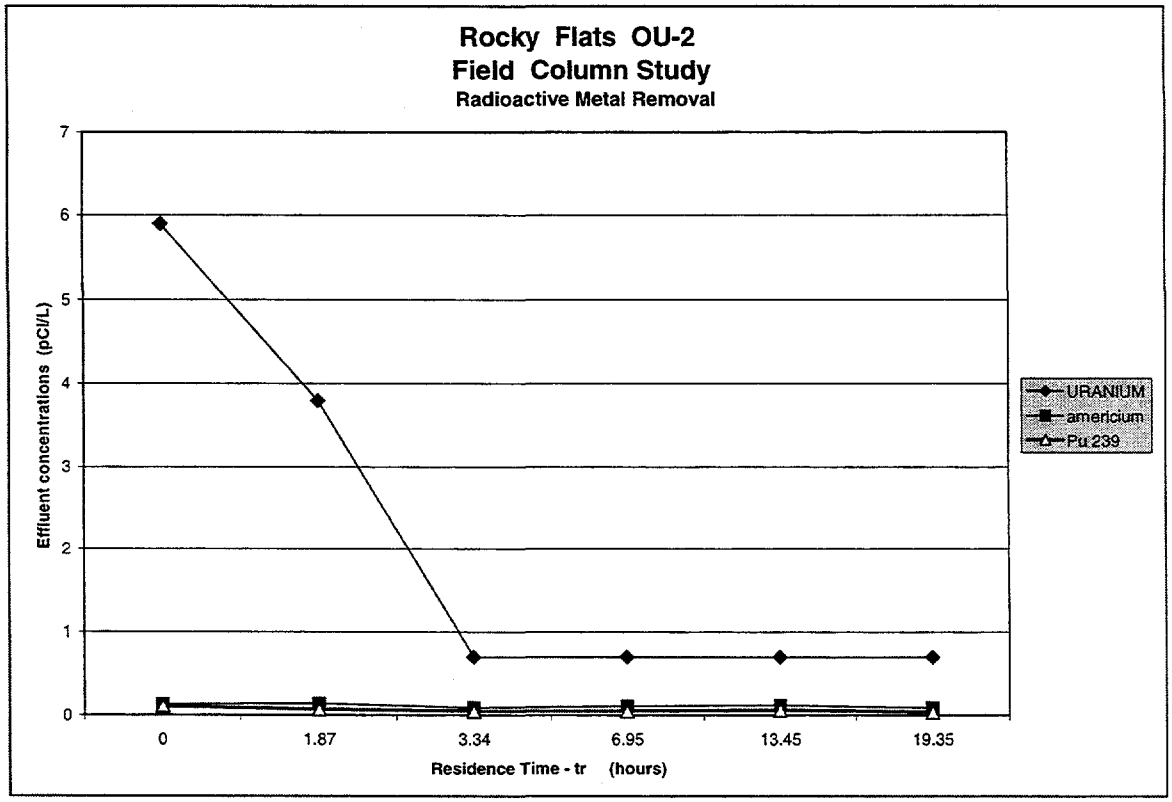

Figure 8. Radioactive Metals Removal.

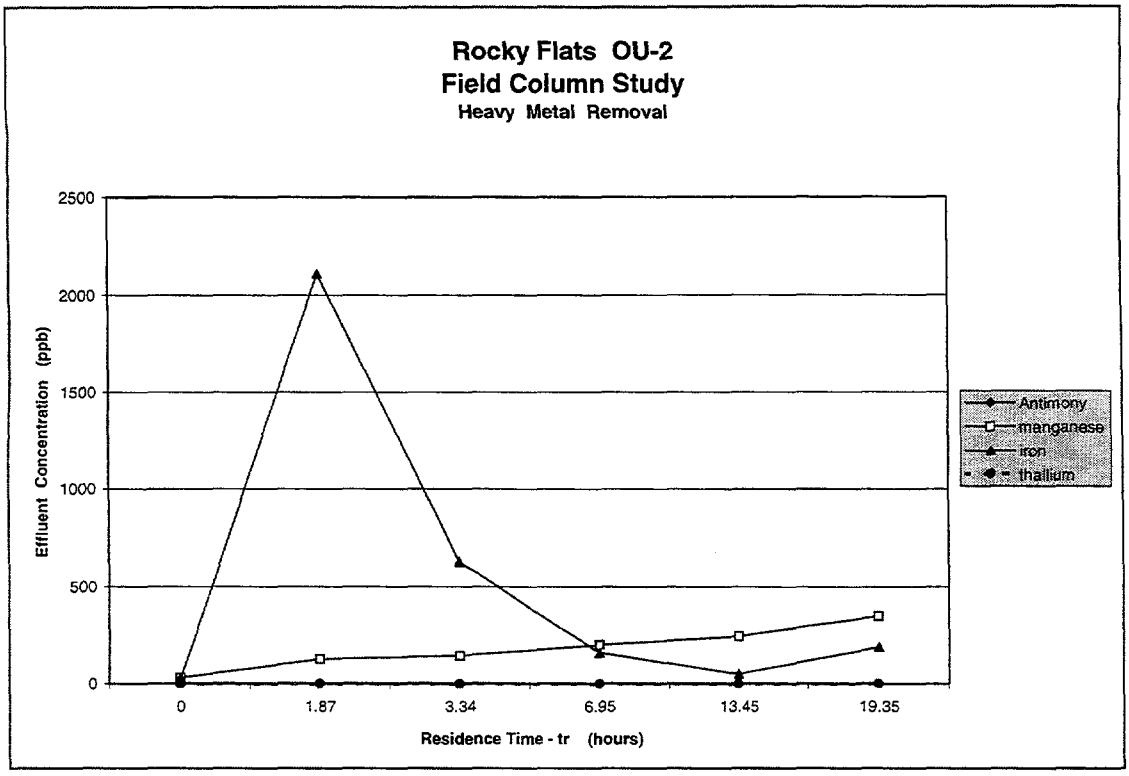

Figure 9. Heavy Metals Removal.

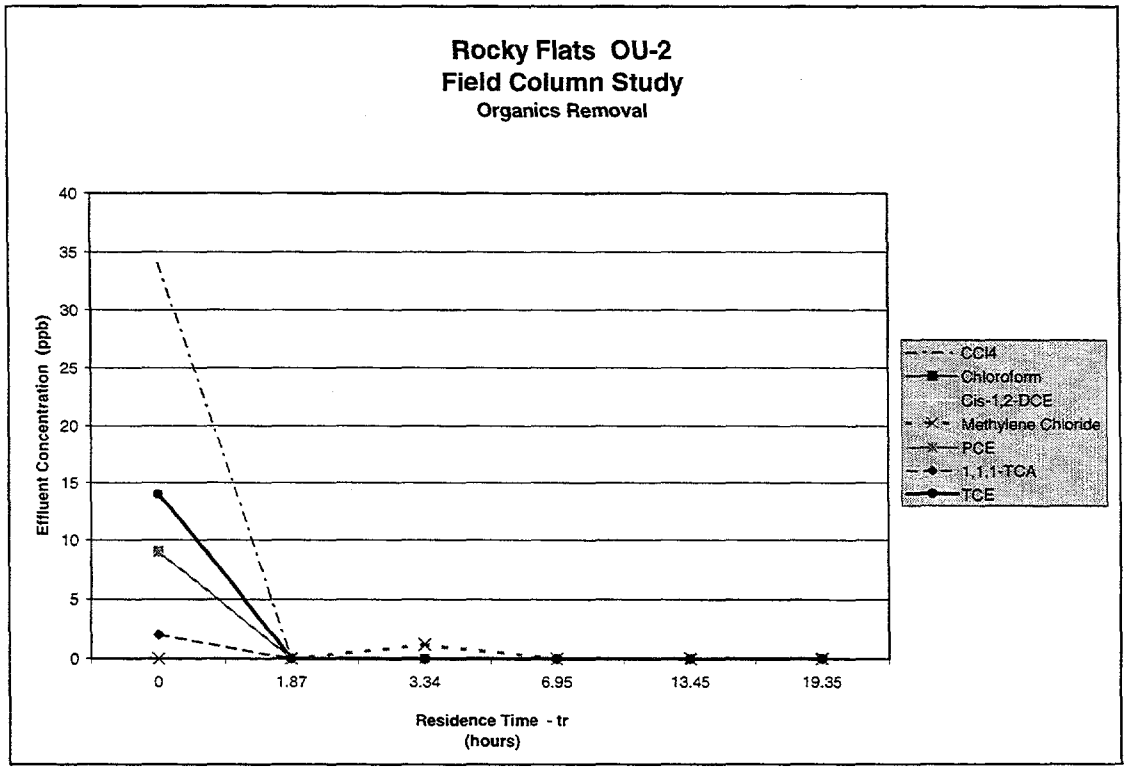

Figure 10. Organic Compounds Removal.

Conclusions

In the pilot-scale, field-column study the primary COCs - uranium, TCE, PCE, and $CC\ell 4$ 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 will allow for sampling along the flow path to better clarify the actual required residence time (tr). A more reliable tr value will allow 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.

APPENDIX A

Table 7. 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 8. 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 9. 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 10. 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 11. 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 12. 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 13. 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 14. 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 15. 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 16. 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 17. Results of saturated hydraulic conductivity tests using Humasorb-CS media.

APPENDIX C

Table 18. 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 which were present in at least one sample were reported.

Table 19. 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 (Ŧg/L)	*3*
Iron (Ŧg/L)	310000
Manganese (Ŧg/L)	34300
Thallium (Ŧg/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 (Ŧg/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (Ŧg/L)	*30*	1280	2060	4880	1210	280
Manganese (Ŧg/L)	32	194	255	481	786	162
Thallium (Ŧg/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 (Ŧg/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (Ŧg/L)	*30*	7680	*1510*	620	1280	790
Manganese (Ŧg/L)	32	210	195	198	1200	490
Thallium (Ŧg/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 (Ŧg/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (Ŧg/L)	*30*	1100	430	140	90	370
Manganese (Ŧg/L)	32	87	125	207	494	391
Thallium (Ŧg/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 (Ŧg/L)	*3*	*3*	*3*	*3*	*3*	*3*
Iron (Ŧg/L)	*30*	2110	630	160	50	190
Manganese (Ŧg/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 20. 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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