

WSRC-RP-92-1207

**ELECTROKINETIC MIGRATION STUDIES ON REMOVAL OF  
CHROMIUM AND URANYL IONS FROM 904-A TRENCH  
SOIL (U)**

by J. P. Bibler  
Westinghouse Savannah River Company  
Savannah River Site  
Aiken, South Carolina 29808

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**Other Authors:**

T. F. Meaker  
(WSRC)  
A. B. O'Steen  
(WSRC)

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KEY WORDS: soil  
decontamination,  
chromium removal  
in situ soil  
decontamination

September 30, 1992

TO: DISTRIBUTION

FROM: J.P. BIBLER, 773-A *JPB*  
T.F. MEAKER  
A.B. OSTEN, 773-A *AO*

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Mr. Meaker was a Teacher Research Associate (TRAC) in the U. S. Department of Energy Office of Energy Research Program.

Attachment

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TO: D.L. FISH, 773-A

FROM: J.P. BIBLER, <sup>SP/5</sup> 773-A, T.F. MEAKER, <sup>630</sup> A.B. OSTEEEN, 773-A

**ELECTROKINETIC MIGRATION STUDIES ON REMOVAL OF CHROMIUM  
AND URANYL IONS FROM 904-A TRENCH SOIL (U)**

**1.0 SUMMARY**

This report describes a laboratory-scale study, in which electrokinetic migration technology was used to remove chromium and uranium, as well as other ions, from soil taken from a bore hole adjacent to the 904-A trench at the Savannah River Technology Center. Imposition of an electric current on humid (not saturated) soil successfully caused cations to migrate through the pore water of the soil to the cathode, where they were captured in an ISOLOCK™ polymer matrix and in a cation exchange resin incorporated in the polymer. Chemicals circulated through the anode/polymer and cathode/polymer were able to control pH excursions in the electrokinetic cells by reacting with the H<sup>+</sup> and OH<sup>-</sup> generated at the anode and cathode, respectively. The study indicates that ions adsorbed on the surface of the soil as well as those in the pores of soil particles can be caused to migrate through the soil to an appropriate electrode. After 10 days of operation at 20-25 V and 2 mA, approximately 65% of the chromium was removed from two 3.5 kg soil samples. A 57 % removal of uranium was achieved. The study shows that electrokinetic migration, using the ISOLOCK™ polymer will be effective as an in situ treatment method for the removal of metal ion contaminants in soil adjacent to the 904-A trench.

**2.0 INTRODUCTION**

The 904-A trench, which includes the concrete secondary containment structure and the enclosed piping and piping supports, has been used since 1953 to transfer low level contaminated liquids from the Savannah River Technology Center (SRTC), buildings 773-A and 779-A, to the 776-2A storage tanks for disposal as radioactive wastes (Figure 1). The trench, and some of the soil around it, is known to contain residual radioactivity and chemical contamination from a spill that occurred in 1971. Analysis of core samples (Figure 2) taken around the trench in 1984 indicated elevated concentrations of some chemical species

(Table 1) relative to uncontaminated soil from the same region. Core samples were taken again this year along the 904-A trench for analysis to determine the location and amount of soil contamination that still exists.

Table 1. Low Level Contamination Along the 904-A Trench (1984)<sup>1</sup>

<u>Species</u>	<u>"Elevated Concentrations"</u>	<u>"Background Concentrations"</u>
Inorganics, $\mu\text{g/g}$		
arsenic	0.4 to 2.4	<0.2
barium	5 to 16	2 to 5
cadmium	2.5 to 6	<1
chromium	15 to 40	1 to 3
copper	3 to 5	1 to 2
iron	1000 to 25000	1000 to 3000
magnesium	100 to 200	20 to 50
manganese	30 to 40	5 to 10
nickel	3 to 8	<1
lead	8 to 20	<2
Zinc	50 to 200	20 to 40
Radionuclides, pCi/g		
tritium	0.5 to 0.8	0.07 to 0.5
Co-60	0.02 to 0.07	<0.02
Th-232	2 to 3	1.5 to 2
Cs-137	0.02 to 0.06	<0.02
Pu-239/240	0.05	<0.05
Sr-90	0.03 to 0.2	<0.03
U (total)	0.05	<0.05

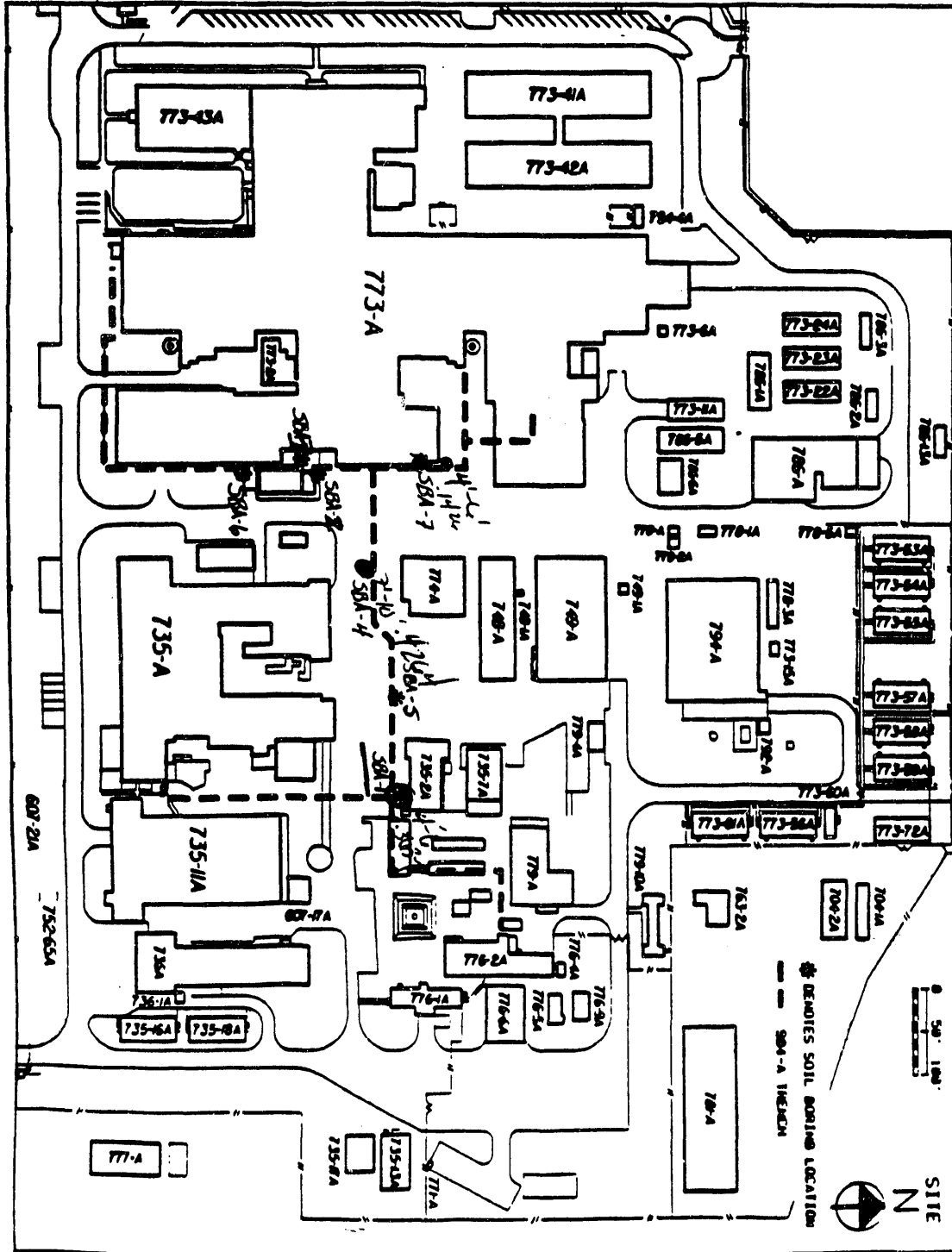


Figure 1. 700-A Area Map

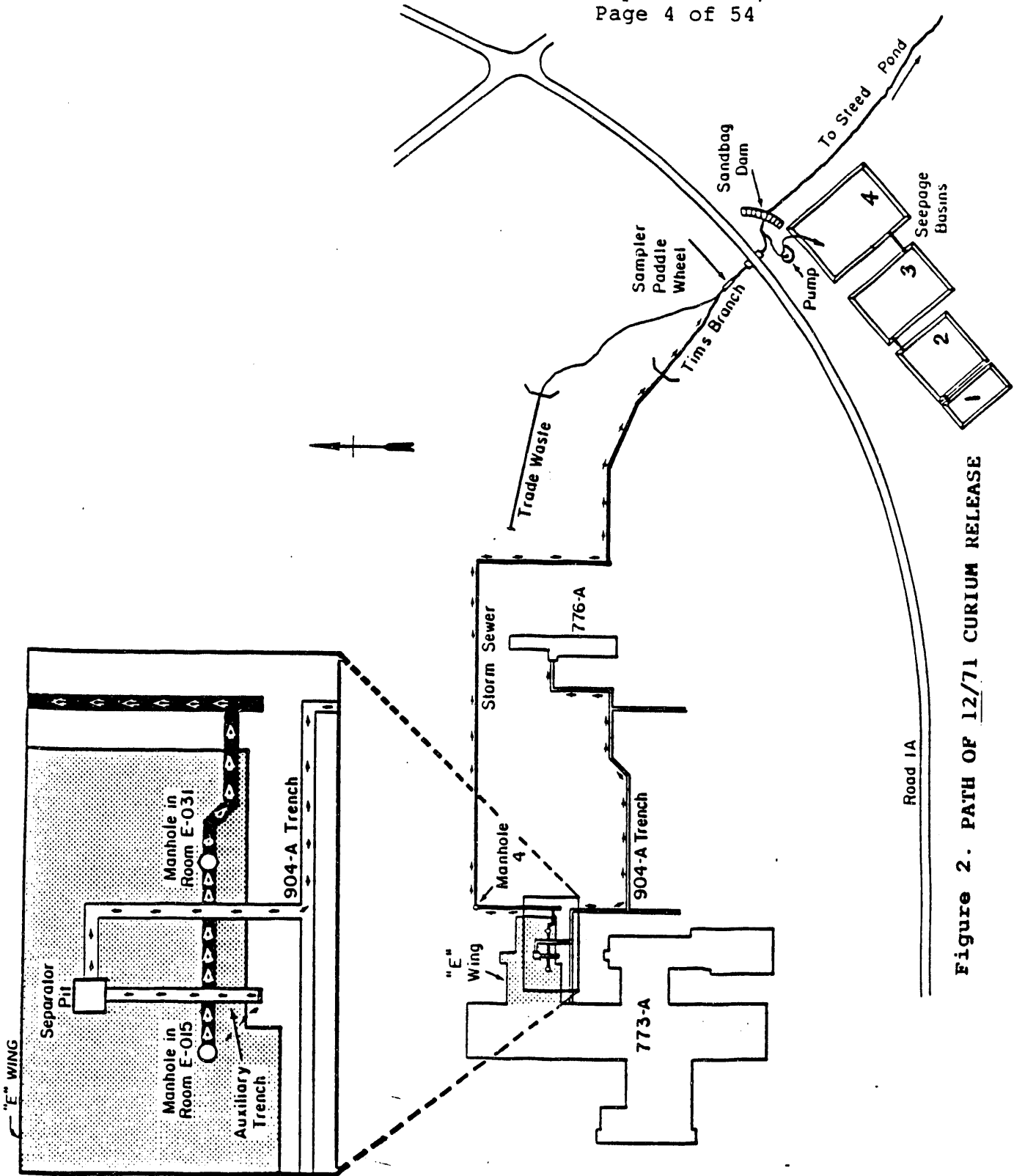


Figure 2. PATH OF 12/71 CURIUM RELEASE

It has been proposed to continue to use, or to replace all or parts of, the trench to transfer liquid wastes to the waste tank farm at 776-A. The 904-A trench resides in an area that has been designated as a Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) site. Also, the waste tanks into which the piping in the trench empties are permitted under the Resource Conservation and Recovery Act (RCRA). Because of the contamination from the spill and because the trench experiences a significant inleakage of groundwater, it does not meet RCRA standards for secondary containment. Remedial action may be required for both conditions. As part of that remedial action, excavation of all or part of the trench will be necessary. Excavated soils that are found to contain excessive amounts of hazardous or radioactive materials will have to be disposed of and replaced with uncontaminated soil.

This study was undertaken to evaluate a technology that has the potential to effect in situ decontamination of the soil. If it can be demonstrated that the soil can be decontaminated in place prior to repair of the trench, the cost of disposing and replacement of the soil around the trench may be avoided. One core sample, SBA-1 (See Figure 3), was obtained for testing of electrokinetic migration technology in lab-scale experiments for the removal of chromium and uranium from the soil. It was originally planned to study the removal of radioactive cesium during this test, but radiochemical analysis of soil leachates showed that Cs-137 was no longer present at detectable levels (6 E-5  $\mu\text{Ci}/\text{kg}$  soil leached; 3 E-5  $\mu\text{Ci}/\text{mL}$  in the leachate).

### 3.0 ELECTROKINETIC MIGRATION TECHNOLOGY

Electrokinetic remediation of soil has been demonstrated for saturated and unsaturated soils<sup>2-20</sup>. In electrokinetic remediation, electrodes are implanted in soil and a direct current is imposed between the electrodes. The application of direct current leads to three effects (Figure 4): ionic species in the soil-water solution will migrate to the oppositely charged electrode (electromigration), charged solids will migrate to the oppositely charged electrode (electrophoresis), and a bulk flow of water is induced toward the cathode (electroosmosis). The dominant process among these three in unsaturated soil has been demonstrated to be electromigration.<sup>2</sup> The combination of these phenomena leads to a movement of contaminant ions toward one or other of the electrodes electrodes



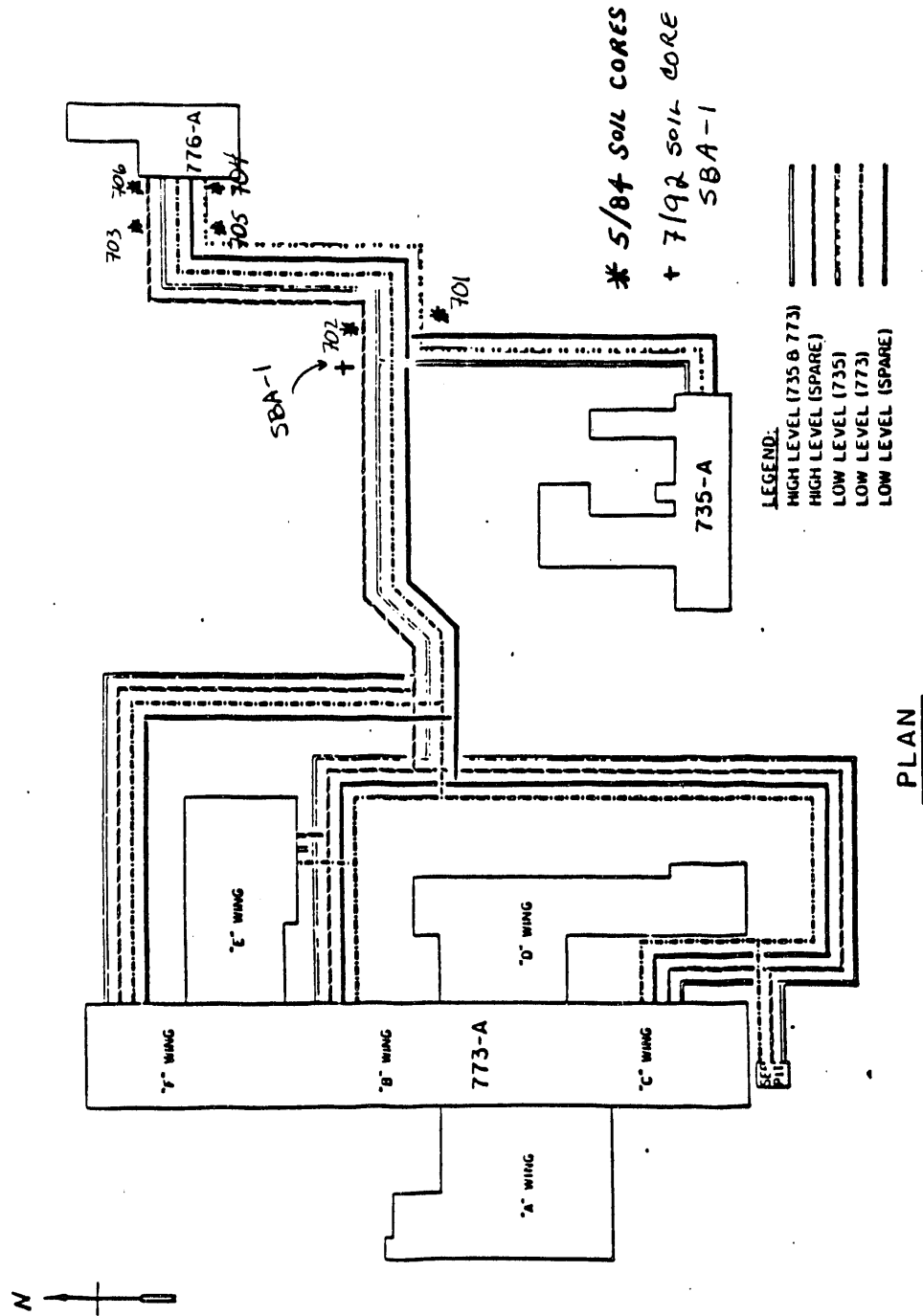


Figure 3. Sites of Soil Core Sampling Along the 904-A Trench

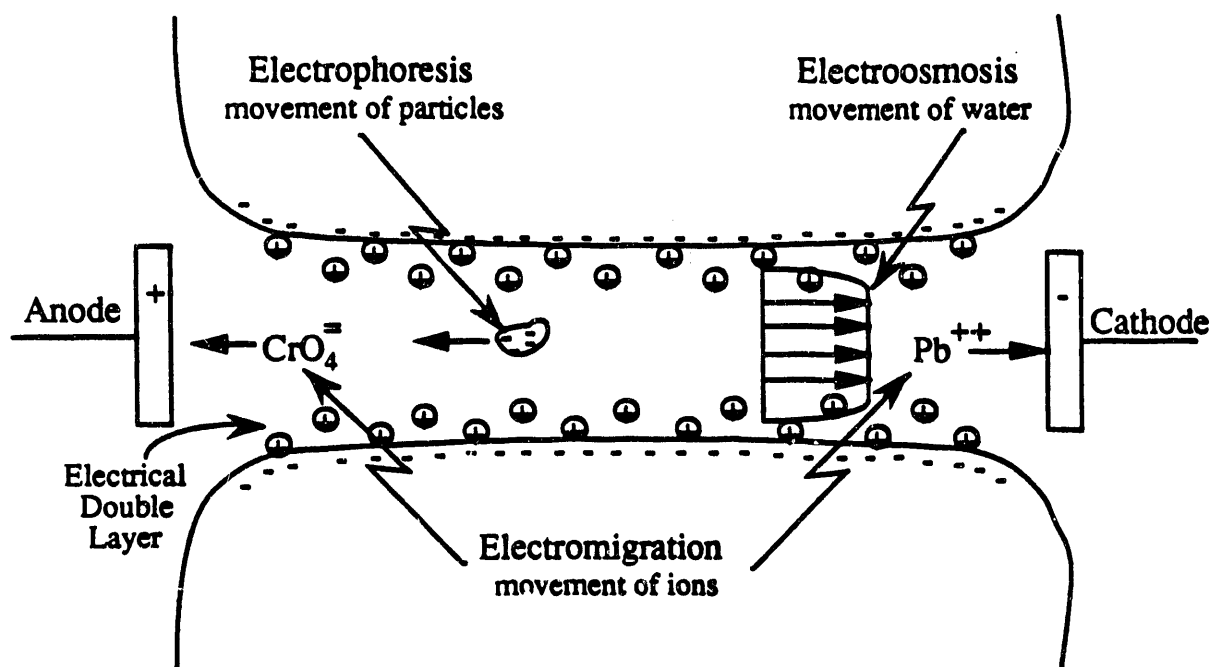


Figure 4. Electrokinetic Phenomena Pertinent to In Situ Remediation

where they may be removed from the ground water by a variety of methods. Among these are electroplating at the electrode, precipitation or co-precipitation near the electrode, pumping of water near the electrode to bring a solution of the ions to the surface, or stabilizing the ions in a solid matrix such as an ion exchange resin.

#### **4.0 EXPERIMENTAL**

In this experiment, humid soil with an unbound water content of approximately 10% by weight was subjected to treatment by direct current. The pH at the anode was controlled by the circulation of a saturated CaO solution through a polymer (the ISOLock™ polymer that is the property of Isotron™ Corp.) surrounding the electrode. Similarly, the pH at the cathode was controlled by circulation of a 1 M acetic acid solution.

#### **4.1 Soil Collection**

Soil cuttings from the 14'-16' depth of borehole SBA-1, along the 904-A Trench, were collected (See Appendix 1). These cuttings contained primarily soil from that depth but also some of the soil removed from all levels above 14 feet. A 2' x 3" split spoon, lined with a 2' x 2.5" plastic inner sleeve, was used to retrieve soil exclusively from the 14'-16' layer. Soil was packaged in plastic bags to prevent evaporation of the moisture and transported to SRTC for analyses and testing.

#### **4.2 Soil Characterization**

##### **4.2.1 Moisture Content**

Unsieved samples of the soil cuttings and of the soil in the split spoon were weighed and air-dried to constant weight at 23°C. The weight percent water associated with the soil was computed. Bound water content was determined by placing weighed samples of air-dried split spoon soil in an oven at 107°C until they had reached constant weight.

##### **4.2.2 Resistance of the Split Spoon Soil Sample**

The sample taken in the split spoon was contained in the plastic liner and protected from drying out by its packaging in a plastic bag. A special apparatus, designed by Isotron™ Corp. (Figure 5), was used to measure the conductivity of the soil. The soil at

each end of the liner was moistened slightly with deionized water to assure conductance. Voltage was increased from 2 to 20 volts in two volt increments. Ammeter readings were taken every 30 seconds at each voltage setting until current stabilized. After the current stabilized, the voltage was increased another 2 volts and the procedure was repeated. The observed current, in mA, from each of these steps was plotted versus the voltage applied to determine the resistance,  $R$ .

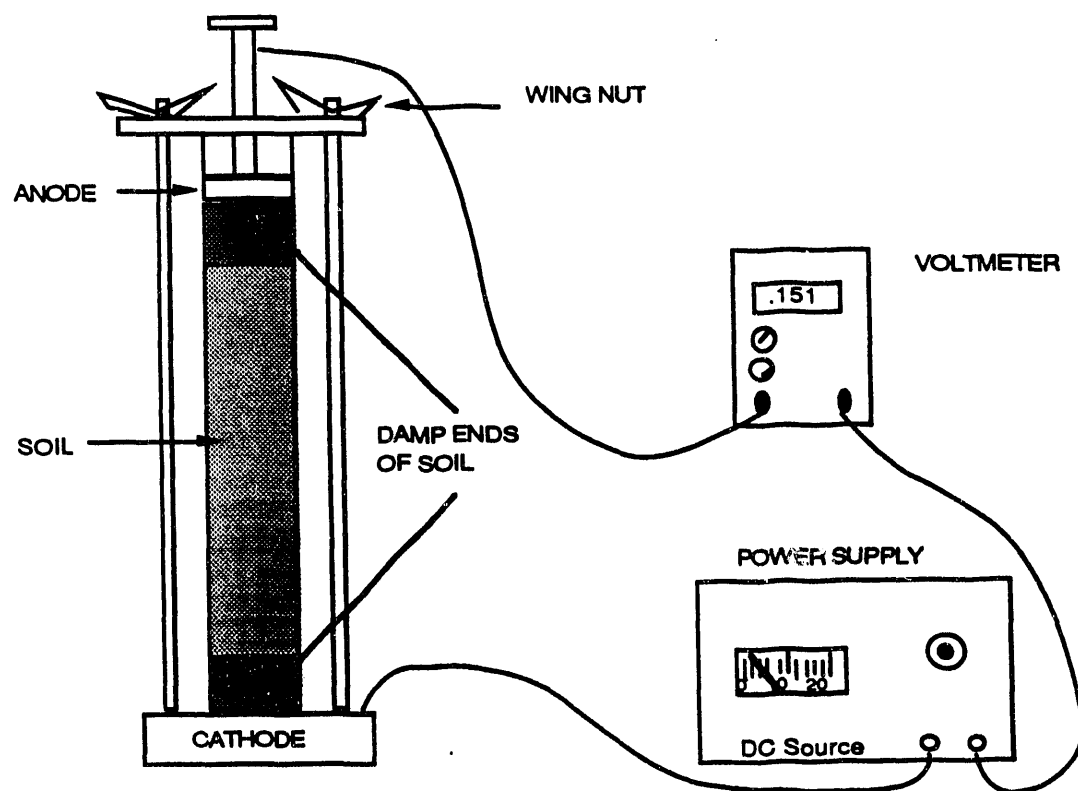


Figure 5. Conductance Apparatus

#### 4.2.3 Soil Homogenization

The soil cuttings, after air-drying, were processed through a series of standard sieves. The fractions collected were < 20 mesh (<850  $\mu\text{m}$ ), 20-40 mesh (850-425  $\mu\text{m}$ ), 40-60 mesh (425-250  $\mu\text{m}$ ), and 60-80 mesh (250-180  $\mu\text{m}$ ).<sup>23</sup> Particle size distribution in the 150-600  $\mu\text{m}$  region was determined for each fraction using a Brinkman particle size analyzer. Samples of each of these fractions was sent to the SRTC Analytical Development Section (ADS) for X-ray diffraction and fluorescence analyses, and inspection using a scanning electron microscope. The drying, sieving, and analytical procedures just described were also applied to the sample of soil obtained in the split spoon.

#### 4.2.4 Leaching of Soils

Five one-gram samples of air-dried soil from the 20-40 mesh fraction of both cuttings soil and split spoon soil were leached using 20 mL of 16 M  $\text{HNO}_3$  for 48 hours at 23°C. After that time, the leachate was separated from the soil by passing the mixture through a 0.45  $\mu\text{m}$  filter. The leachate was analyzed by ADS using the following "routine customer assisted" analytical techniques<sup>22</sup>: ICPEs (inductively coupled plasma atomic emission spectroscopy) for chromium and several other metals, UChemcheck<sup>TM</sup> fluorescence spectrophotometry for total uranium content, and  $\gamma$ -scan and gross  $\alpha$ -counting for radionuclides. Samples were also leached in similar fashion in 30 mL of aqua regia ( 2 volumes 16 M  $\text{HNO}_3$  and 3 volumes 12 M  $\text{HCl}$ ). After filtration, the aqua regia leachate was analyzed by ICPEs.

Concentrations in the leachate were back-calculated to yield a concentration for each species identified in the soil.

#### 4.2.5 Bulk Density of Soils

The bulk density, the volume occupied by 1 gram of air-dried soil when saturated, was determined. A weighed sample of 20-40 mesh air-dried soil was placed in a 10 mL graduate cylinder and covered with deionized water. The mixture was allowed to stand for 24 hours, after which the volume of the moist soil was recorded.

### **4.3 Operation of the 1-D Electrokinetic Cell**

#### **4.3.1 Cell Design**

Two one-dimensional electrokinetic cells were assembled as shown in Figure 6. The cell container was a plastic tub (Figure 7). A cathode electrode assembly, consisting of a mild steel wire mesh electrode in ISOLOCK™ polymer that was impregnated with Duolite™ GT-73 cation exchange resin was placed at one end of the tub. The anode assembly, a titanium-coated iridium oxide mesh electrode in ISOLOCK™ polymer, was placed at the other end. Both polymers contained inlet and outlet tubes associated with a small well in the polymer, through which 1 M acetic acid (at the cathode) and saturated CaO (at the anode) were circulated by means of a peristaltic pump in order to control pH at the electrodes. Soil was placed between the electrode assemblies and a current was passed through the soil. Current and voltage were continuously monitored. Voltage was maintained as close to 25 V as possible, though voltage fluctuated over a 10-day period of operation between 20 and 25 V. Current was steady at 2 mA throughout for both cells. During operation, the top of the soil was covered with plastic to prevent evaporation at the surface of the soil.

#### **4.3.2 Soil Preparation**

Two 3139 gram batches of air-dried 20-40 mesh cuttings soil were mixed carefully with 361 grams of deionized water to restore the weight percent water in the soil to 10.3%. The moistened soil was allowed to equilibrate in a plastic bag for several days. The moistened soil was placed in the cell tubs between the electrode assemblies just before operation of the cells. Plastic was placed over the soil during operation to prevent evaporation.

#### **4.3.3 Sampling of Soil in the Cell**

After the cells had operated for a desired amount of time, the current was discontinued and the soil was sampled to identify any changes that had taken place during the operation. Approximate 5-gram samples were retrieved 1 cm from the anode assembly, 1 cm from the cathode assembly, and in the middle of the cell, all from a depth of about 2 cm. Only 150 g (0.04%) of the original 3.5 kg of solid were lost to sampling. The pH of these samples was checked using pH indicator paper. The moisture content of the samples was

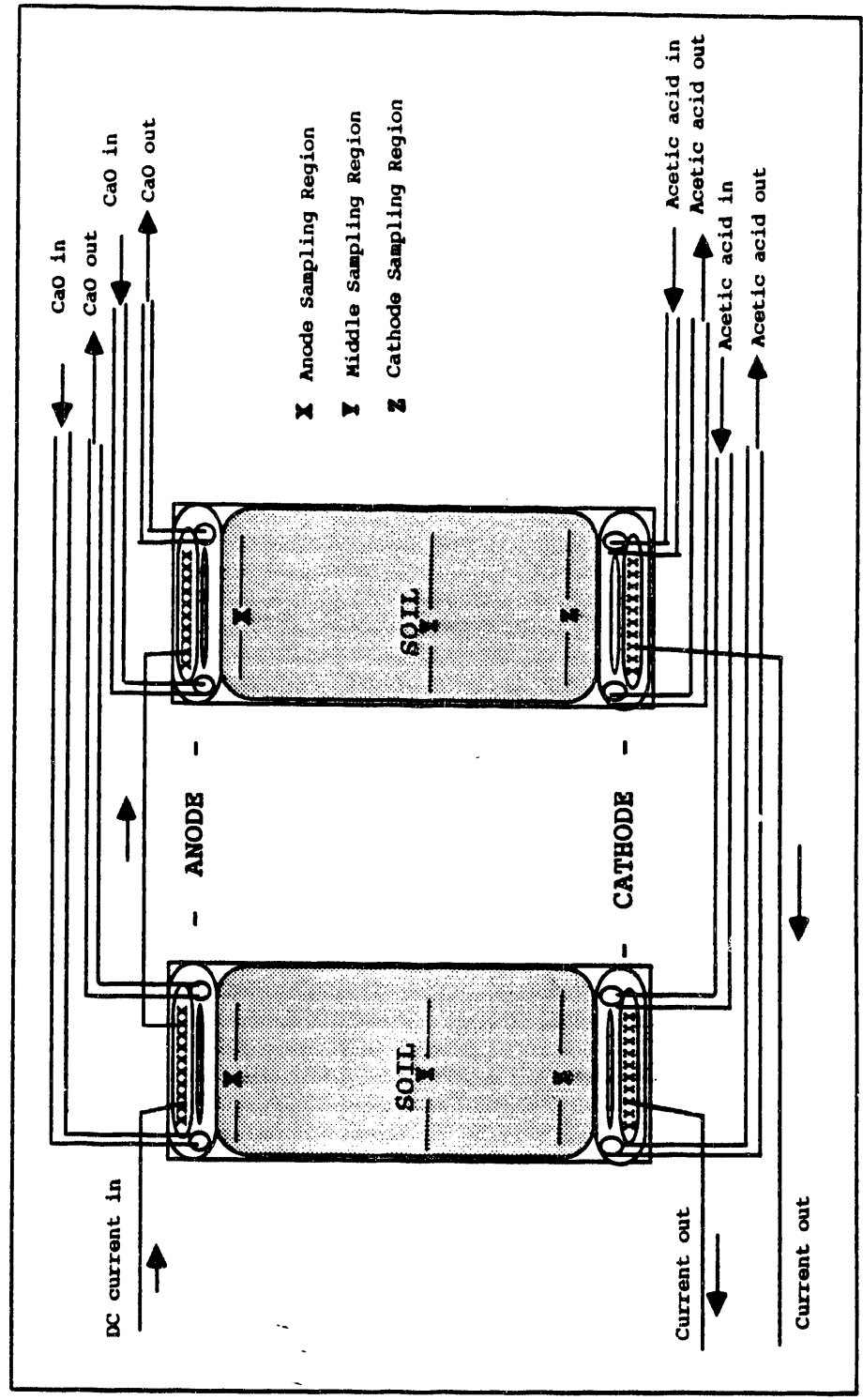


Figure 6. Two-Cell Set-Up

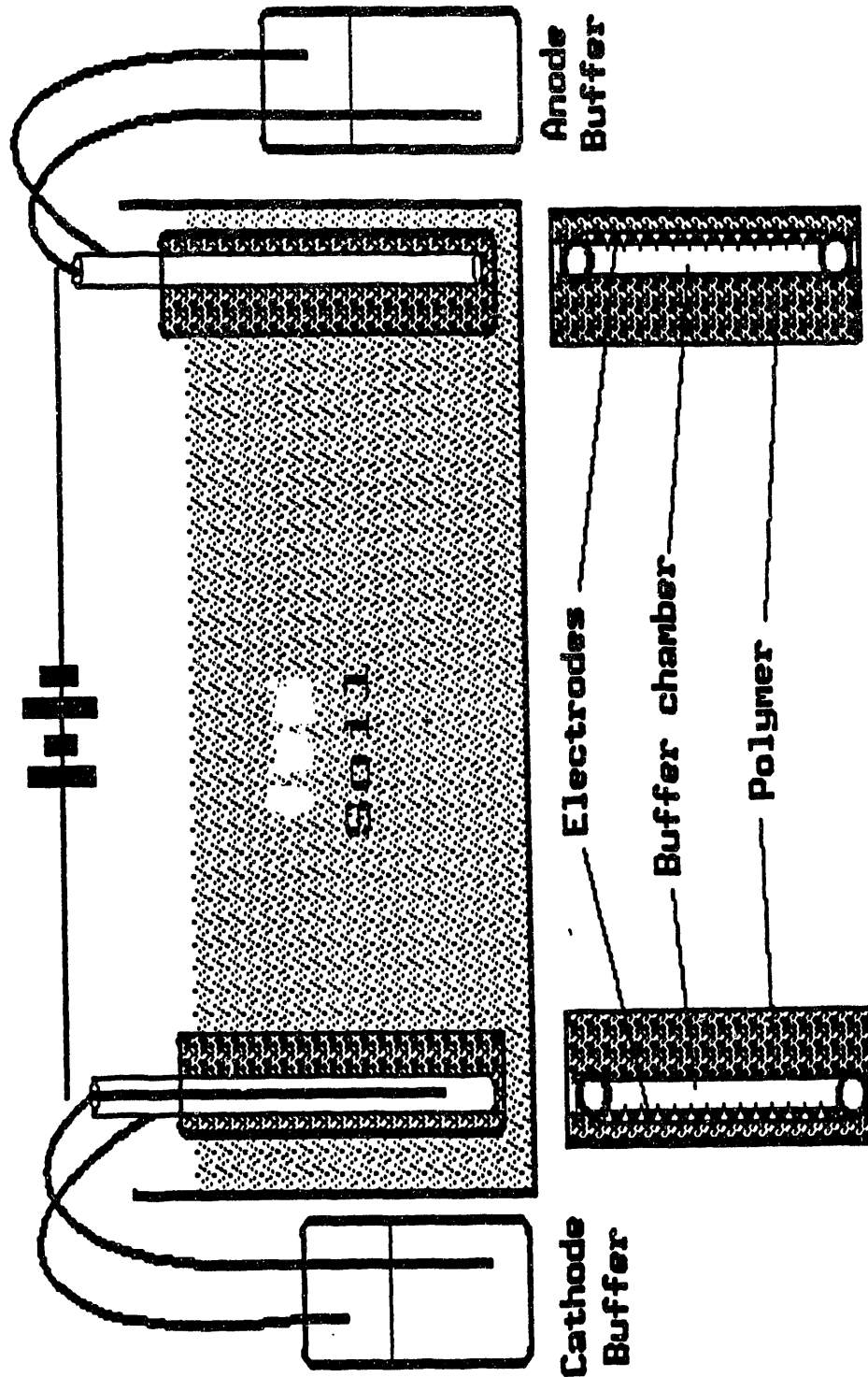


Figure 7. A Cross-section of the Electrokinetic Migration Cell



determined as noted in Section 4.2.1, above. Then, weighed fractions of the air-dried samples were leached with 16 M HNO<sub>3</sub> or aqua regia, as described in Section 4.2.4, and sent for metals analysis by ICPES and UChemcheck™. Aqueous leachates were analyzed for anion content by ion chromatography (IC).

After sampling, the soil bed in the cell was smoothed to fill the voids created by sampling and the cell was returned to service.

#### 4.3.4 Leaching Polymer and Electrodes

After the cells were shut down and dismantled, weighed pieces of the anode and cathode and their polymers, including polymer containing resin, were leached in aqua regia. Leachates were sent for analysis by ICPES. UChemcheck™ methods for total uranium were found to be invalid in the presence of the amount of chloride present in the aqua regia.

## 5.0 RESULTS

### 5.1 Soil Characterization

Table 2 gives some basic properties of unsieved soil from the split spoon and of 20-40 mesh cuttings soil.

Table 2. Some Physical Properties of Soils Used in This Study

<u>Soil</u>	<u>pH</u>	<u>wt. % water</u>	<u>wt. % bound water</u>	<u>Bulk density</u>
Split Spoon, unsieved	6	11.44	0.80	1.3 g/mL
Cuttings, 20-40 mesh	6	10.34	0.79	1.3 g/ml

The X-ray diffraction results, identifying crystalline components in four sized fractions of soil found in the split spoon, are given in Table 3. Iron oxide/hydroxide is also present in the soils but was either not concentrated enough or in sufficient quantity of a crystalline form to produce a signal in the X-ray

spectrum. Also found in Table 3 are metals in the soil, identified in X-ray fluorescence spectra.

Table 3. X-ray Data for Sieved Split Spoon Soil

<u>Mesh Size</u>	<u>grams (wt% of total)</u>	<u>Compounds Identified by X-Ray Diffraction</u>	<u>Metals Identified by X-Ray Fluorescence</u>
>20	75 (3.2%)	Silicon oxide/quartz, Kaolinite-1A, albite, (crystalline)	Fe, K, Ca, Ti, Cr Cu, Zn, Ni, Pb, Th Sr, Zr, Ba, Nb, Ce
20-40	2,000 (85.9%)	Silicon oxide/quartz, Kaolinite-1A	Fe, K, Ca, Ti, Cr Cu, Zn, Ni, Pb, Nb Sr, Zr, Ba, Th, Ce
40-60	250 (10.7%)	Silicon oxide/quartz, Kaolinite-1A, Illite-1M	Fe, K, Ca, Ti, Cr Cu, Zn, Ni, Pb, Th Sr, Zr, Ba, Nb, Ce
60-80	30 (0.13%)	Silicon oxide/quartz, Kaolinite-1A, Illite-1M	Fe, K, Ca, Ti, Cr Cu, Zn, Ni, Pb, Th Sr, Zr, Ba, Nb, Ce

Note: Kaolinite-1A is aluminum silicate hydrate  
Illite-1M is potassium aluminum silicate hydroxide  
Albite is a feldspar, Na/Ca aluminum silicate

Chemical analyses for major chemical species in untreated soil are tabulated in Table 4. Also included in Table 4 are results from radiochemical analyses, which indicate the absence of Cs-137, and other radionuclides identified in the 1984 report.<sup>1</sup> It was originally planned to study the electrokinetic migration of Cs<sup>+</sup>, but that ion was no longer found in this soil.

Table 4. Analytical Results Based on Leach Solutions from  
Cuttings Soil

Analysis	Method	mg/kg of Soil		
		HNO <sub>3</sub> Leach <sup>a</sup>	Aqua Regia Leach <sup>b</sup>	Water Leach <sup>a</sup>
<u>Inorganic Species</u>				
Ca	ICPES	390±30	469±49	
Cu	ICPES	1.70±0.08 <sup>c</sup>	4.99±1.64	
Pb	ICPES	BDL	15.7±1.04	
Ba	ICPES	0.67±0.32	8.23±0.55	
Sr	ICPES	0.44±0.03	1.84±0.23	
Cr	ICPES	2.81±0.24	14.2±0.71	
Zn	ICPES	27.8±3.7	34.8±2.9	
U	UChemcheck™	0.61±0.14	not determined	

Radionuclide Analyses

Cs-137	γ-scan	BDL	BDL
other γ	γ-scan	BDL	BDL
gross α	α-count	>50 d/m/mL	>50 d/m/mL
gross β	scintillation	BDL	BDL

Anion Analyses

chloride	19±3
nitrate	84±5
phosphate	69±6
sulfate	140±3

<sup>a</sup> Average of 5 samples unless noted otherwise

<sup>b</sup> Triplicate samples

<sup>c</sup> Only 2 of 5 samples were above detection limit

BDL = below detection limits of the instrument

The soil resistivity is calculated from Equation 1.

$$\rho = R A \Theta / l \quad \text{Eq. 1}$$

where:  $\rho$  is resistivity [ $\Omega$ -cm]

R is initial resistance from Ohm's Law  $R = V/I$  [ $\Omega$ ]

where V is the initial voltage [V]

I is the initial current [A]

A is the cell cross sectional area [ $136 \text{ cm}^2$ ]

$\Theta$  is the volumetric water content [ $.134 \text{ cm}^3/\text{cm}^3$ ]

where  $\Theta$  is the bulk density of the soil \* wt % water

l is the length between electrodes. [ $21.5 \text{ cm}$ ]

This definition of resistivity has been modified<sup>27</sup> to account for the cross sectional area available for current flow through the pore water, since it is reasonable to assume all of the current travels through the pore water in unsaturated soils. This will compensate for small differences in moisture content when comparing several soils.

The value for R was determined for the split spoon soil using the apparatus and method described in Section 4.2.2. It is assumed here that the cuttings soil has a resistance that is not significantly different from that found for the split spoon sample. Table 5 lists the initial voltage and current readings taken during the test. A plot of A vs V should describe a straight line of slope equal to R. That plot is shown in Figure 8.

The average resistance of this soil is effectively  $3.15\text{E}+4$  Ohms. That value is comparable to resistance values obtained by Isotron<sup>TM</sup> Corp. for soil from four boreholes taken from the Old TNX basin at the Savannah River Site.<sup>21</sup> When TNX soil resistance values are corrected for the volumetric water constant, they range from  $7\text{E}+3$  Ohms to  $1\text{E}+4$  Ohms. The modified resistivity of the 904-A trench soil used in this test, from Equation 1, is  $2.67 \text{ } \Omega$ -cm.

Table 5. Initial Current and Voltage Readings for Split Spoon Soil

<u>Interval #</u>	<u>Initial Volts</u>	<u>Initial Amps</u>	<u>R. calculated</u>
1	0.0	4.0E-6	0.0E+0
2	2.0	1.0E-6	2.0E+4
3	4.0	1.5E-4	2.7E+4
4	6.0	2.1E-4	2.9E+4
5	8.0	2.7E-4	3.0E+4
6	10.0	3.2E-4	3.2E+4
7	12.0	3.7E-4	3.2E+4
8	14.0	4.4E-4	3.2E+4
9	16.0	5.2E-4	3.1E+4
10	18.0	5.9E-4	3.0E+4
11	20.0	6.6E-4	3.0E+4

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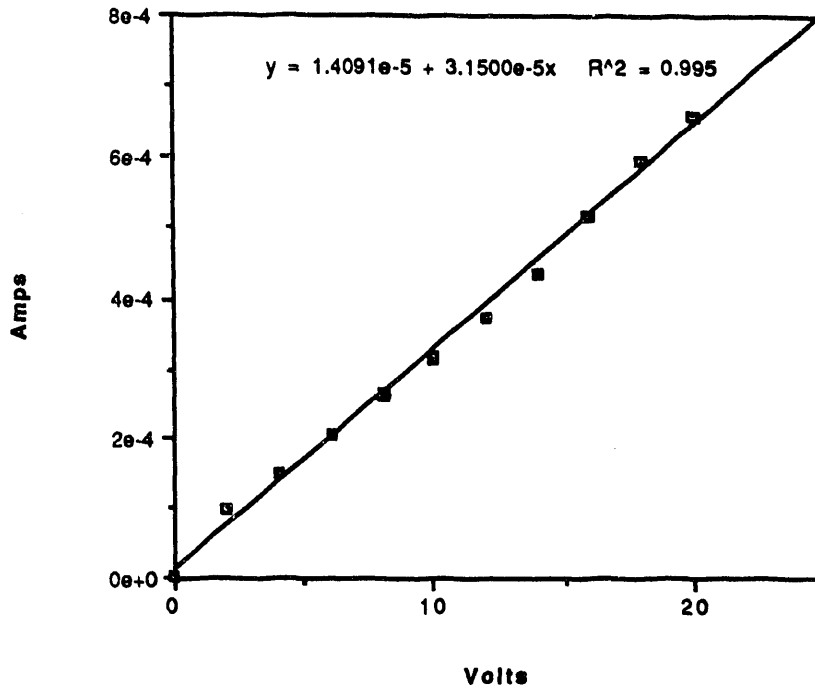


Figure 8. Resistance of Split Spoon Soil Sample

### 5.1.2 Cell Operation

Two 1-dimensional cells containing cuttings soil were operated for a total of almost 9 days ( $7.78E+5$  sec). The split spoon cell flooded with acetic acid during the first hour of operation, invalidating any data from that cell. The down-time for sampling and data taking took approximately one hour each day. Both cells ran between 20 and 25 volts and steadily produced a current of 2 mA during that time. Table 6 compiles the daily average voltage and current during operation.

Table 6. Cell Voltage and Current Record During Operation

DAY	Voltage		mA	
	Cell 1	Cell 2	Cell 1	Cell 2
0	20	20	7	7
1	20	20	2	2
3	20	20	2	2
4	22.5	22.5	2	2
5	24.9	24.9	2	2
6	25.2	25.2	2	2*
7	25.2	25.2	2	2
10	25.2	25.2	2	2

\* Current fluctuated between 1 and 4 mA over 24 hrs. but held mostly at 2 mA. Problem was traced to a poor connection.

Typically, the current density is determined by dividing the current by the cross sectional area of the cell. For this experiment, this results in a cell current density of  $1.5E-2$  mA/cm<sup>2</sup>. As noted earlier, however, it is more reasonable to assume that all of the current travels through the pore water, suggesting a more appropriate way of defining current density, especially in unsaturated soils. The pore water current density is the cell current density divided by  $\theta$ , the volumetric water content of the soil. For this system, the pore water current density was  $0.11$  mA/cm<sup>2</sup>.

### 5.1.3 Soil Analyses After Treatment

The ISOLOCK™ polymer was able to effectively minimize the expected pH excursions at the electrodes. By providing a medium to hold chemicals, the polymer allowed the CaO circulating at the anode to react with hydrogen ion produced there from the electrolysis of water. Similarly, acetic acid circulating through the polymer at the cathode was able to neutralize the hydroxide ion formed there. The pH of the moist soil, as measured with pH indicator paper, remained near 6 for soil in all sections of the cells. It is

evident from Table 7 that transport of water from the anode to the cathode is very small, indicating that electroosmosis effects are small compared to those of electromigration for the movement of ions.

Table 7. pH and Water Content of Cuttings Soil After Treatment

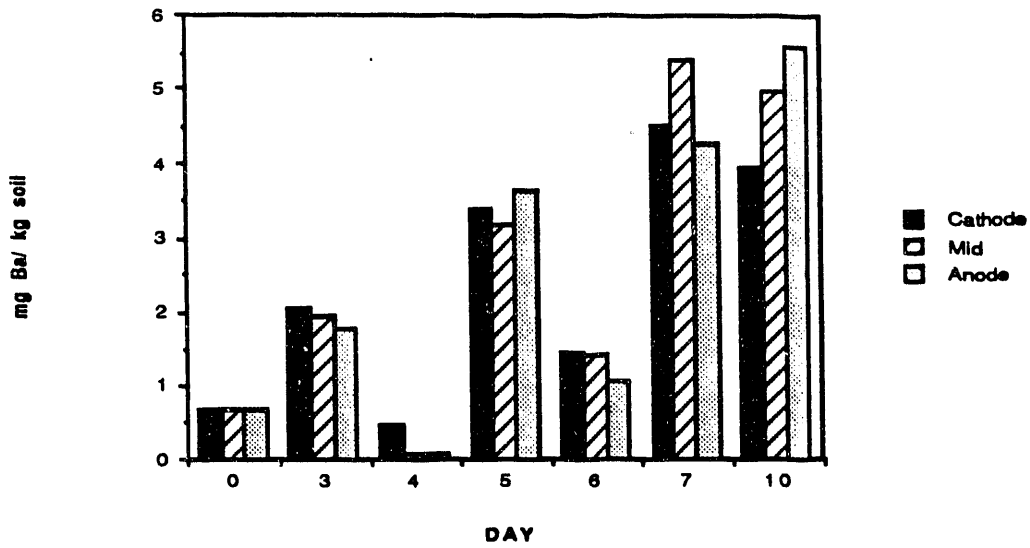
Operation Time, days	wt % H <sub>2</sub> O by Section					
	Cell 1			Cell 2		
	Cathode	Middle	Anode	Cathode	Middle	Anode
0	10.3	10.3	10.3	10.3	10.3	10.3
3	14.4	11.8	12.0	13.0	10.3	10.1
4	14.0	12.7	12.5	13.1	11.0	11.5
5	13.9	13.0	12.9	13.6	12.4	12.2
6	14.4	13.3	13.4	13.6	12.6	13.7
7	13.7	12.0	12.7	14.6	11.8	11.8
10	13.8	12.8	12.1	13.7	9.8	10.8

Results from leaching anode, cathode, and soil sections in 16 M HNO<sub>3</sub> after treatment with the current showed some migration of the ions. The concentrations in the soil of ions of interest, noted in Table 4, are shown in Figures 9-15 below. Tables 8-23, found in Appendix 2, contain the data from which the graphs were made. Calcium ion is not graphed because the concentration of Ca<sup>2+</sup> remained essentially constant throughout the experiment, as it should have. Calcium ion was continually being introduced from the pH regulating solution at the anode to retain charge balance for the system. Thus, although calcium ion does migrate to the cathode, it exhibited an essentially constant concentration in the soil because it was being added at the anode.

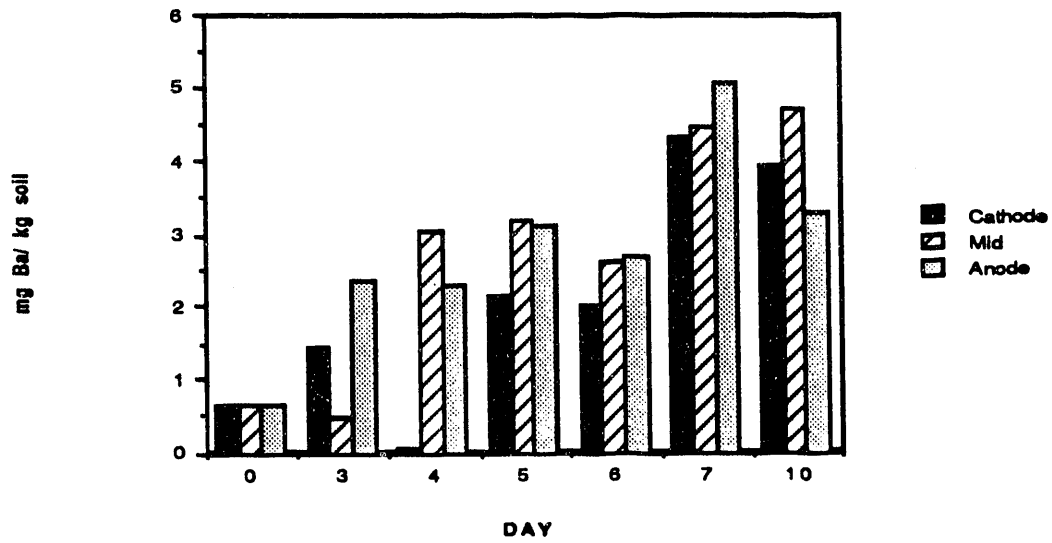
A barium ion cell profile is shown in Figure 9. Ba<sup>2+</sup> represents a typical alkaline earth ion and its behavior, in the absence of pH excursions in the cell, should not be significantly different from that of other alkaline earth metals. All data in the graphs represent HNO<sub>3</sub> leaches. Aqua regia leaches always found higher ion concentrations in the untreated soil (see Table 4).



**CELL 1 Ba PROFILE**



**CELL 2 Ba PROFILE**



**Figure 9. Barium Ion Soil Profiles**

Other  $M^{2+}$  ions were observed. Of these,  $Sr^{2+}$  should, and does, exhibit behavior similar to that of  $Ba^{2+}$ . The  $Sr^{2+}$  soil profile is found in Figure 10. Three transition metal ions,  $Cu^{2+}$ ,  $Pb^{2+}$ , and  $Zn^{2+}$  were also checked. Their concentrations in the soil after treatment in an electric field are shown in Figures 11-13, respectively.

Chromium was probably introduced from the spill to the soil as  $CrO_4^{-2}$ . During this test, the chromium was found to be migrating toward the cathode, indicating that it was  $Cr^{3+}$  that was responding to electrokinetic migration. (Figure 14) Aqua regia leach results from soil taken after 10 days of operation closely agree with nitric acid leach results for the same soil for most metals, indicating that those metal ions had become more accessible to the leaching solution.

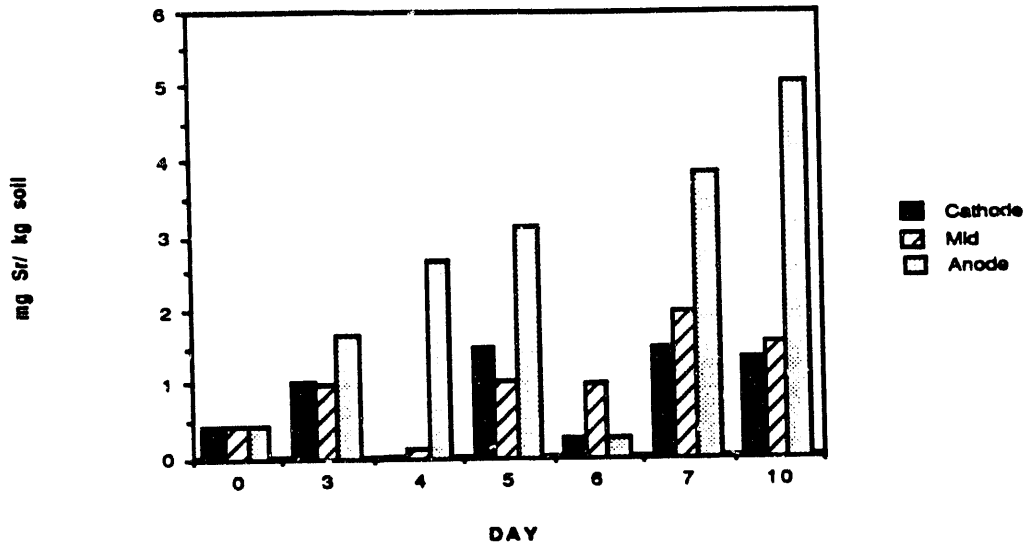
Data indicate that uranium showed little evidence of migration until the sixth day of treatment (Figure 15).

Analysis of dissolved, weighed fractions of the polymers from each electrode and of the resin found in the cathode polymer located the metals of interest (except U, which could not be analyzed in aqua regia) at the cathode. Aqua regia leaching was conducted on weighed pieces of each metal electrode, to dissolve any metals that might have plated out on the electrode. The leached solutions also indicated that the migration of metal ions from the soil to the cathode occurred. Unfortunately, the mild steel cathode contained 8% Cr, making it difficult to quantify the amount of Cr from the soil in that leachate. These data are contained in Table 22.

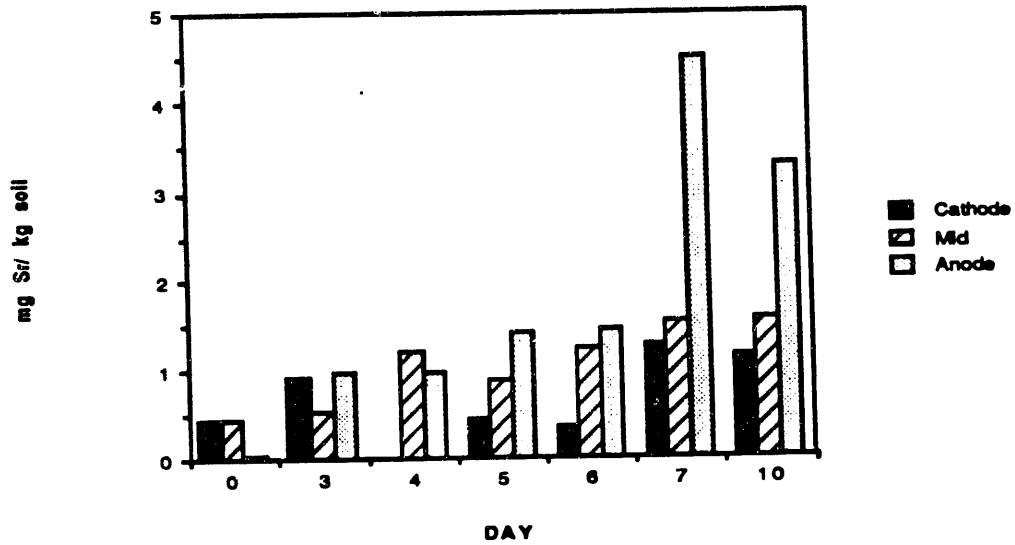
Table 22. Composition of Electrode Assembly Aqua Regia Leachates

Metal	mg Metal/g Polymer		mg Metal/g Cathode Resin	mg Metal/g Electrode	
	Cathode	Anode		Cathode	Anode
Ba	0.007	0.00	0.016	0.009	0.00
Sr	0.006	0.00	0.020	0.003	0.00
Cu	0.017	0.00	0.024	0.56	0.00
Zn	0.54	0.16	1.8	0.51	0.026
Cr	0.02	0.00	0.031	0.213	0.00
U	analyses not possible-Chloride ion interferes				

**CELL 1 Sr PROFILE**



**CELL 2 Sr PROFILE**



**Figure 10. Strontium Ion Soil Profiles**

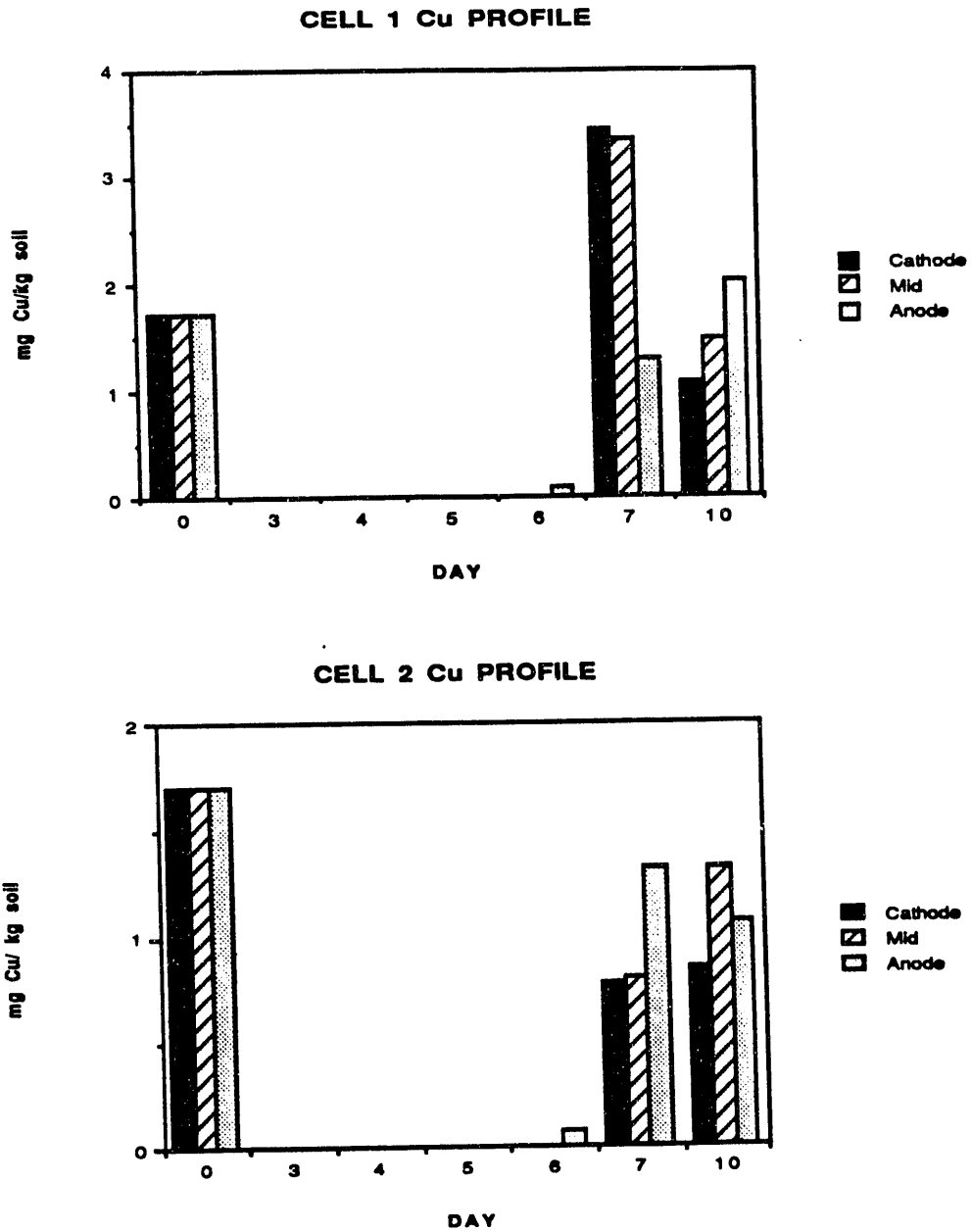
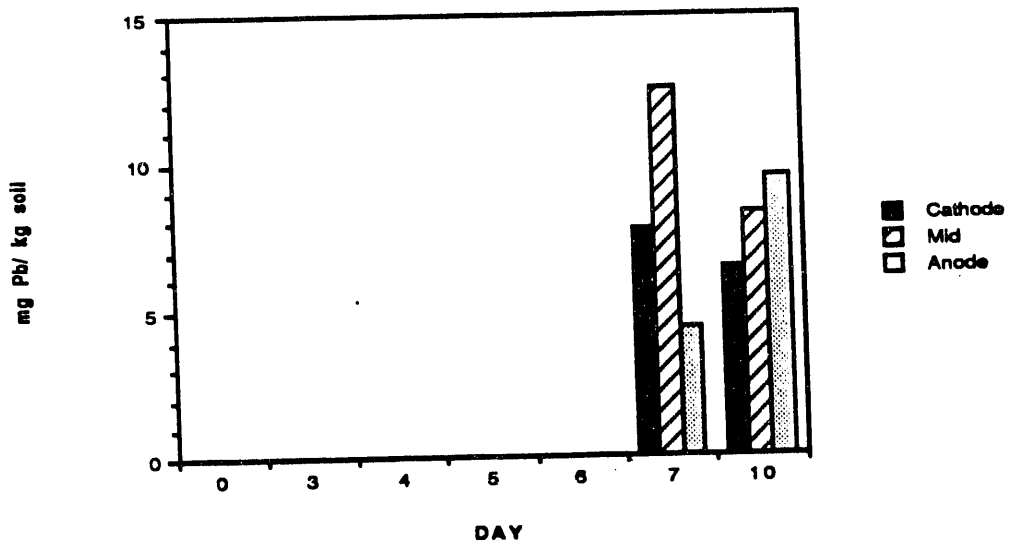
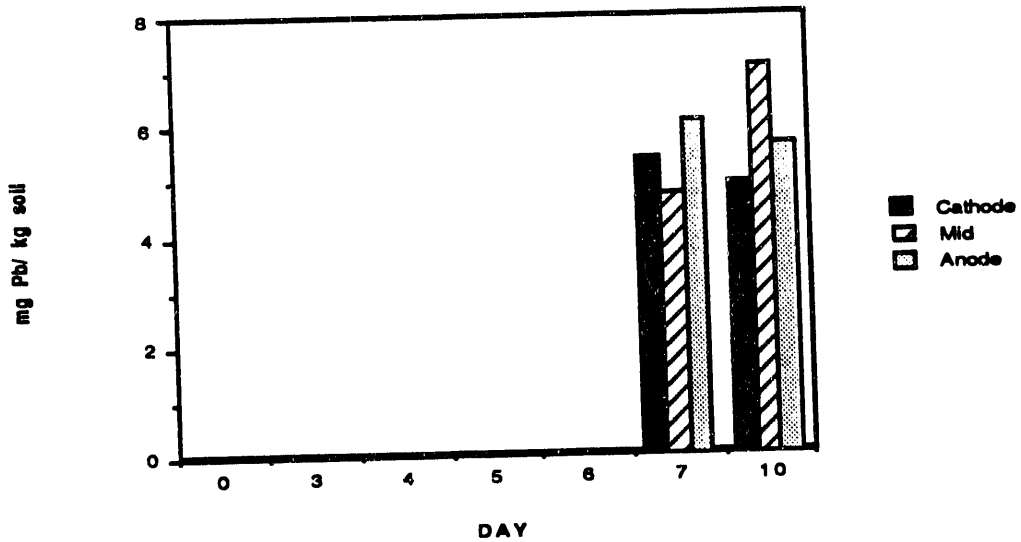


Figure 11. Copper (II) Ion Soil Profiles

**CELL 1 Pb PROFILE**

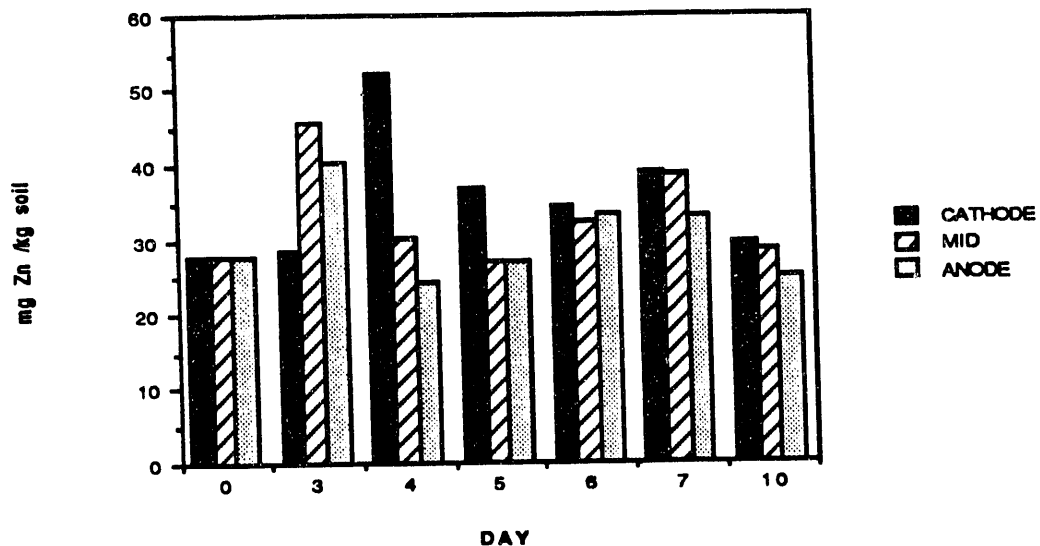


**CELL 2 Pb PROFILE**

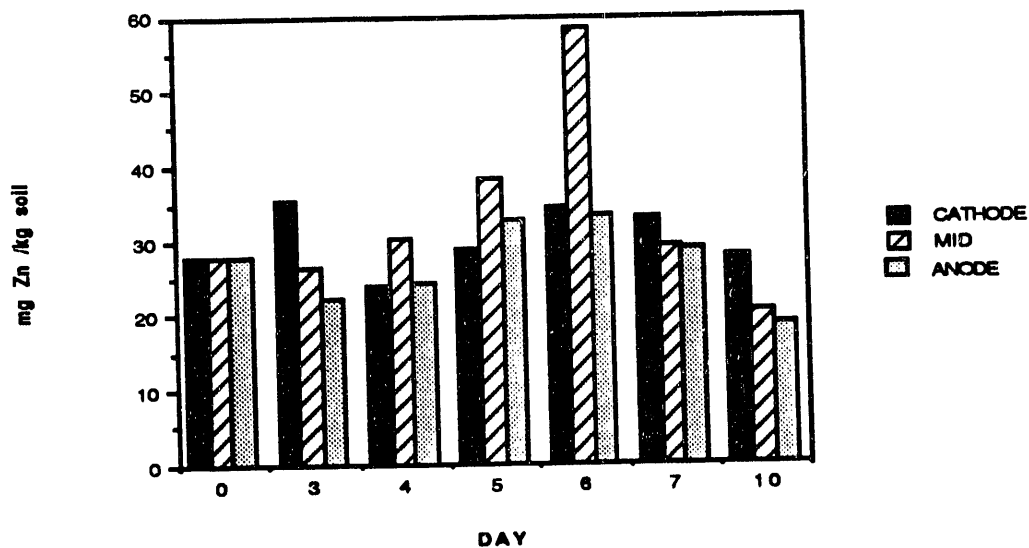


**Figure 12. Lead Ion Soil Profiles**

**CELL 1 Zn PROFILE**

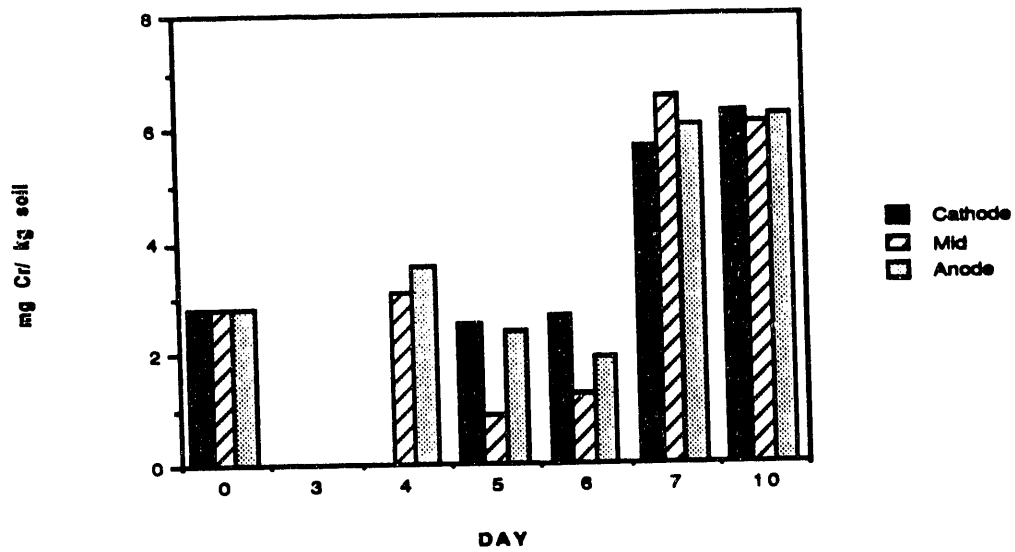


**CELL 2 Zn PROFILE**

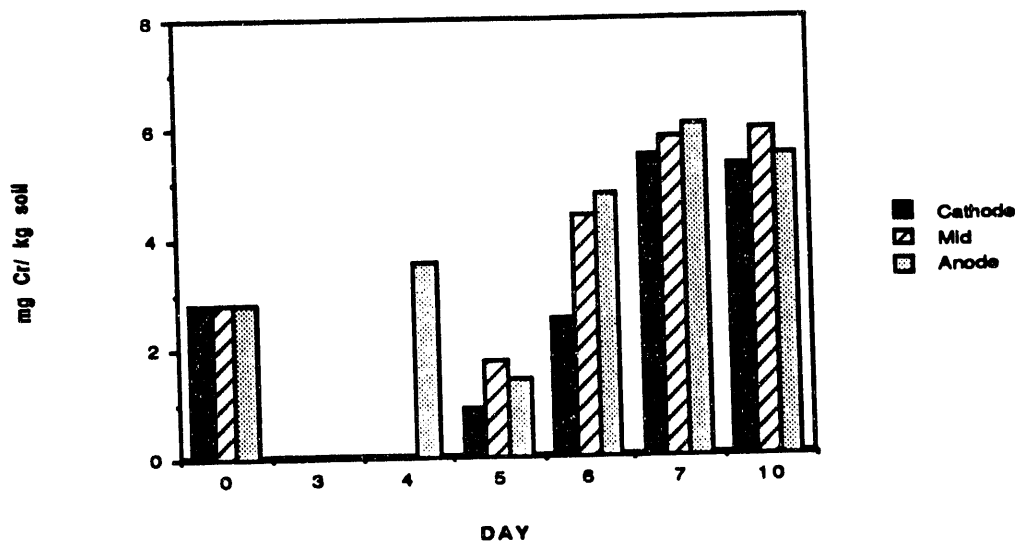


**Figure 13. Zinc Ion Soil Profile**

**CELL 1 Cr PROFILE**

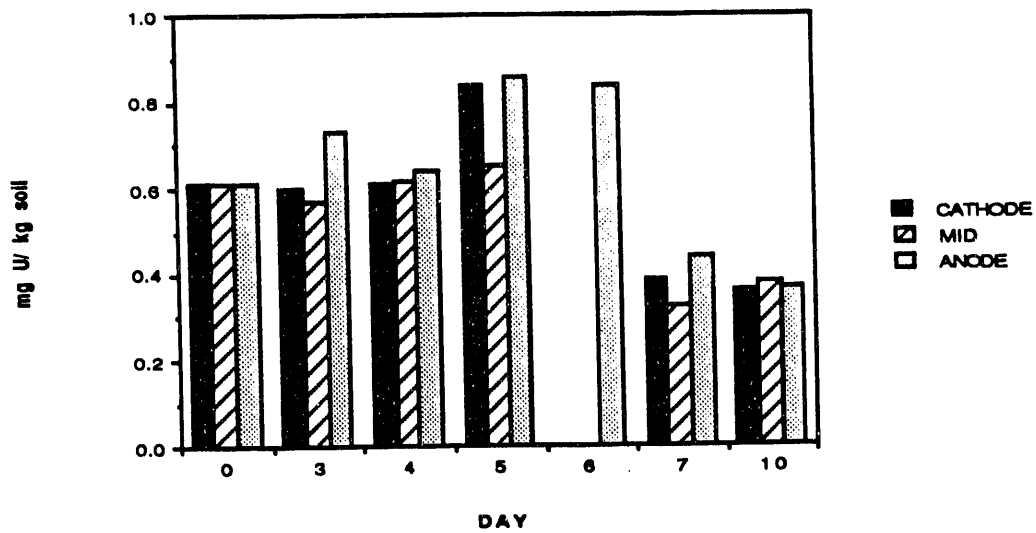


**CELL 2 Cr PROFILE**

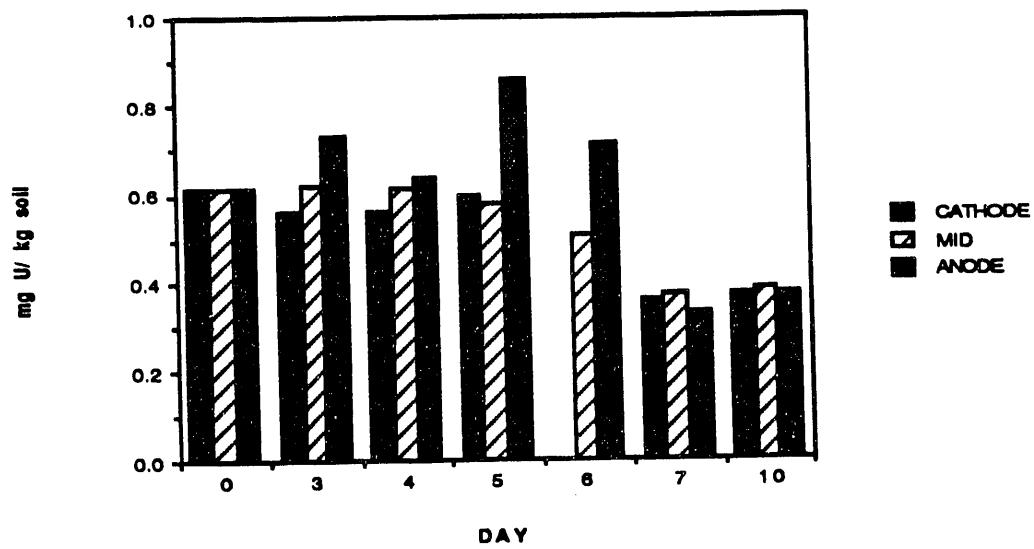


**Figure 14. Chromium Ion Soil Profile**

**CELL 1 U PROFILE**



**CELL 2 U PROFILE**



**Figure 15. Uranium Ion Soil Profile**



## 6.0 DISCUSSION

Data for the 1-dimensional cell electrokinetic migration studies done in this work are for the cuttings soil. The original intent of the study was to perform the cell test using soil from the split spoon. Flooding of the cell containing the split spoon sample precluded the use of that soil for experimentation. Results of the soil characterization studies that were done on split spoon soil are presumed to be valid for the cuttings soils that were ultimately used for the cell tests. In discussing leach tests, however, it is important to differentiate between split spoon and cuttings soils. The concentrations of ions leached from the soils are greater in the split spoon sample because auger cuttings were not present to dilute the soil. Therefore, comparisons are made throughout this report between concentrations for cuttings soils and not between cuttings soils and split spoon soil.

This study shows that leaching of soils is an area that needs further research. Five samples were submitted for each analysis because of the imprecision in analytical results. This imprecision is attributed to sample variability and not to the analyses themselves. The leaching solution was also important. Concentrations of ions in 16 M  $\text{HNO}_3$  leachates were significantly less than those in aqua regia leachates and significantly greater than in acetic acid leachates. It is apparent that a specific fraction of all the ions sorbed on the soil is more difficult to leach than the bulk of those ions. This may be because the more-difficult-to-leach fraction is trapped in the pores of the soil, rather than on the surface of soil particles, and must first diffuse to the leachate. A study is underway in our laboratory to devise a leaching procedure that gives consistent and accurate results with SRS soils.

Electrokinetic migration technology has been demonstrated in this work to be capable of causing cations to migrate to the cathode. Using the ISOLOCK™ polymer, which serves for pH regulation as well as trapping of the mobilized ions, the ions can be removed from the soil system in a solid matrix with the expenditure of a very small amount of electricity. Regulation of the pH at the electrodes eliminates pH excursions in the soil that can cause precipitation in the soil or formation of soluble complexes that cannot be removed from the system. Mass balance has not been established quantitatively in this study because the polymer did

not appear to sorb and trap the ions uniformly in its matrix. That very matrix also interfered with calculations for mass balance because fillers used in the polymer were found to contain small amounts of zinc and lead ions, two of the ions being studied.

Although current density during the 10-day test was constant, the graphs in Figures 9-14 show that migration of the ions through the soil was not constant. Surges of ion movement are evident. A rationale for this behavior is that ions sorbed on the surface are displaced easily under the influence of the current. These migrate immediately to the electrode. Ions trapped inside the pores of the soil must first diffuse out of the soil before they can migrate. Increased concentration in the treated soil due to diffusion from the pores appears at day 6 in the graphic profiles of all ions studied. The diffusion step is the slow step of the process. Once liberated, however, the ions then migrate in a second "wave" through the soil toward the appropriate electrode, where they are captured. This behavior agrees with behavior of the soil in leaching tests. Weak or dilute acid solutions leach a small fraction of the ions from the soil compared to more concentrated acids. Often, the ion concentrations in portions of treated soil are found to be much higher than in untreated soil. It is believed that this is due to the fact that ions that were originally in the soil pores have been released by the action of the current and are more easily leached. Since electrokinetic migration technology appears to be able to remove ions trapped in the pores of the soil, development of a rigorous leaching procedure is important if mass balance is ever to be achieved for the process. An aqua regia leach of treated soils on days 3-6 of operation would probably have identified measurable concentrations of all ions of interest, whereas the concentrations of lead and copper ions, for example, in the same soils were below detection limit (30  $\mu\text{g/mL}$ ) in a nitric acid leachate.

It might be argued that the introduction of acetate ions to the soil from the cathode chamber could solubilize metals sorbed on the soil through the formation of complex ions. This process could also explain the ion distributions observed in the soil during treatment. However, studies with this soil showed that acetic acid could not effectively leach anything from the soil except lead and zinc ions, and then only in very small concentrations. Other complexants might assist the solubilization of metals during the operation of a cell, but acetate complexation is not considered an important factor here.

In this test, it is apparent that chromium was ultimately present

as  $\text{Cr}^{3+}$ . If it was introduced to the soil as  $\text{CrO}_4^{-2}$ , as expected, it may have been reduced in situ by microorganisms before this test began. Reduction to  $\text{Cr}^{3+}$  could explain low concentrations in dilute acid leachates; the kinetics of dissolution are very slow for  $\text{Cr}^{3+}$ . Lindgren, et. al. have observed<sup>2</sup> the electrokinetic migration of chromate ion in sand (10 wt % water) to the anode after 22 hours of treatment. They noted that the total chromium content in the sand near the anode at the end of the experiment was significantly less than the amount of chromium added initially, and postulate that most of the Cr(VI) might somehow have been reduced and precipitated as Cr(III). For longer operating times, such as were employed in this test, any  $\text{Cr}^{3+}$  would migrate to the cathode.

If the Cr in the aqua regia leach (Table 4) is considered the total chromium in the soil, each 3.5 kg cell contained 49.7 mg Cr. After 10 days of operation, leach results for the three portions of each cell's soil bed, when totaled, indicate that 63-65% of the Cr had been removed from the soil.

## 7.0 CONCLUSIONS

- This study shows that electrokinetic migration technology, using the Isotron™/ISOLOCK™ approach, will be effective for an in situ treatment of soil adjacent to the 904-A trench for the removal of any metal ion contaminants.
- Electromigration of metal ion contaminants found in duplicate 3.5 kg samples of soil taken from the 904-A trench area at SRTC has been demonstrated in a 1-dimensional experiment. The migration of chromium, lead, zinc, copper, and uranium ions was monitored daily during a 10-day test at 20-25 V and 2mA. At the end of the test, 65% of the Cr had been removed from the soil; 57% of the uranium was removed.
- Metal cations migrated to the cathode where they were removed from the soil and trapped in a solid matrix of ISOLOCK™ polymer and the GT-73 cation exchange resin beads that were incorporated in the polymer. The electrodes were imbedded in the polymer.

- Electromigration techniques appear to effect the release of ions that are so tightly bound to the soil that they are difficult to leach from the soil. This behavior indicates the need for development of special leaching techniques, possibly soil digestion techniques, that will accurately reflect the total concentration of ions in the soil.
- Although the low current density induced migration of ions through the soil bed, it did not appear to destroy or degrade the soil. Sodium, aluminum, and silicon concentrations were monitored throughout the progress of the test. Concentrations of these species in the leachates did not change, indicating that clay in the soil had maintained its integrity. Iron, from amorphous iron oxy/hydroxides found in the soil, was captured by the polymer surrounding the cathode, however.
- Regulation of the pH at each electrode with chemicals was effective and was important in the prevention of precipitation or complex formation by the ions in the soil bed.
- Uranyl ion will require more time to effect removal from this soil, compared to time required for simple  $M^{2+}$  ions, due to its lower mobility.

## 8.0 QUALITY ASSURANCE

Data generated in this study is recorded in WSRC-NB-92-231 and WSRC-NB-92-259. Reagent grade chemicals were used in leaching. Analyses were performed by the SRTC Analytical Development Section following methods developed for "routine customer assisted" analysis.<sup>22</sup> Standard addition methods were used to check uranium analyses. IC, ICPEs, and radioactive counting analyses were monitored using blanks and standards traceable to the National Bureau of Standards.

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APPENDIX 1

Field Geologic Log for Borehole SBA-1

JSA 30-3

## FIELD GEOLOGIC LOG

PROJECT	DATE	SHEET			
SRL 904-A Process Trench	5/20/92	1 of 1			
WELL NO. SBA-1	REFERENCE DATUM (msl) ~ 362.5'	DRELLING CONTRACTOR Graves			
LOGGED BY Bill Joyce	SAP COORDINATES N 106,288 E 51,961	DRILLER Kent Buchner			
	COMPANY SEC Donohue	DRELLING METHOD Hollow Stem Augering and Split Spooning (2")			
RUN NUMBER	DEPTH, FEET	LITHOLOGY	PERCENT RECOVERY	SAMPLE DESCRIPTION	DRILLING COMMENTS
	0				Descriptions based on observations from outside the established RCA area and interpretation of drilling response. Oversight not allowed to handle samples.
	1		Auger Cuttings	SAND (silt 10%) med gra, grayish brown - med brown - med reddish brown, shag - strand, wall setd, dry	
	2			Easily drilled, auger cuttings	
	3			Backfill material	
	4			Split-spoon with no inner sleeve	Hydraulically pushed - easily done
	5		9	SAND As above	
	6			Split-spoon with no inner sleeve	Hydraulically pushed - easily done
	7		9	SAND (silt 5-10%) med gra, med reddish brown - med red - dk yellowish orange, shag - strand, wall setd, dry	
	8		Auger Cuttings		
	9				
	10			Split-spoon with no inner sleeve	Hydraulically pushed - easily done
	11		4		
	12		Auger Cuttings	SAND (silt 15%) med gra, med reddish brown - med red - dk yellowish orange, shag - strand, wall setd, med dry (slightly moist)	
	13			2" split-spoon with 1/2" plastic inner sleeve	Homemade split-spoon
	14		100	SAND (silt 20-25%, clay 5-10%) med - fin gra, pale purple - dk reddish brown - dk yellowish orange - pale red - white (kaolin) mottled, shag - strand, wall setd, med moist	110 blows for 6" Very hard
	15				
	16				
	17				
	18				
	19				
	20			Total depth: 16.0'	



## APPENDIX 2

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Table 8. Cell 1 Ca Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	513	416	456			462	49
3	461	540	574	568	569	542	47
4	443	474	394		484	449	40
5	560	396		424	418	450	75
6	362	413	316	422	305	364	54
7	367	515	397	422	545	449	77
10	483	348		356	341	382	68
Mid section							
0	513	416	456			462	49
3	503	507	504		566	520	31
4		517	440	409	594	490	83
5	404	433	433	400	425	419	16
6	490	347	411	368	397	403	55
7	543	458	504	464	467	487	36
10	425	491	412	397	396	424	39
Anode section							
0	513	416	456			462	49
3	515	609	501	631	658	583	71
4	574	587	583	523	498	553	40
5	532	507	452	570	483	509	45
6	424	406	425	420	493	434	34
7	710	733	689	755	644	706	43
10	285	341	340	429	505	380	87

Blank spaces indicate outlier values that were rejected.

Table 9. Cell 2 Ca Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
	Cathode section						
0	513	416	456			462	49
3	523	555	577	512	536	541	26
4	568	653		626	632	620	36
5	325	365	323	349	453	363	53
6	362	400	331	325	369	357	30
7	374	397	380	341	365	371	21
10	385	310	411	381	435	384	47
	Mid section						
0	513	416	456			462	49
3	571	410	585	513	387	520	80
4	525	541	423	392	408	454	74
5	347	406	343	366	506	374	31
6	468	635	461	453	442	505	76
7	418	411	384	414	456	414	21
10	432	453	456	390		437	28
	Anode section						
0	513	416	456			462	49
3	402	382	415	456	397	410	28
4	535	426	551	427	472	482	59
5	400	402	426	462	400	418	27
6	495	444	574	594	512	524	61
7		477	537	518	545	519	30
10	373	201	265	238	282	272	64

Blank spaces indicate outlier values that were rejected.

Table 10. Cell 1 Cu Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	1.76	BDL	1.64	BDL	BDL	1.70	0.08
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	3.75	2.81	4.06	3.44	0.57
7	3.15	BDL	1.19	1.12	1.09	1.08	0.12
10		0.90					
Mid section							
0	1.76	BDL	1.64	BDL	BDL	1.70	0.08
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	3.21	3.81	3.52	3.34	0.43
7	2.81	BDL	1.49	1.71	1.63	1.48	0.20
10		1.30					
Anode section							
0	1.76	BDL	1.64	BDL	BDL	1.70	0.08
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	1.43	1.11	1.31	1.28	0.23
7	1	1.55	2.03	2.33	2.24	2.02	0.29
10		1.59					

Blank spaces indicate outlier values that were rejected.  
 BDL = Below Detection Limit

Table 11. Cell 2 Cu Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	1.76	BDL	1.64	BDL	BDL	1.70	0.08
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	-
5	1.12	BDL	BDL	BDL	BDL	1.12	BDL
6	BDL	BDL	BDL	BDL	BDL	BDL	0.24
7	0.662	1.05	0.905	0.789	0.424	0.77	0.13
10	0.874	0.93	1.02	0.744	0.705	0.85	
Mid section							
0	1.76	BDL	1.64	BDL	BDL	1.70	0.08
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	-
5	BDL	0.82	BDL	BDL	BDL	0.817	BDL
6	BDL	BDL	BDL	BDL	BDL	BDL	0.31
7	0.483	0.50	0.797	1.03	1.18	0.80	0.20
10	1.04	1.35	1.59	1.27	1.37	1.32	
Anode section							
0	1.76	BDL	1.64	BDL	BDL	1.70	0.08
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	0.40
6	BDL	BDL	0.551	0.651	1.28	0.83	0.13
7	1.09	1.33	1.43	1.35	1.4	1.32	0.21
10	1.12	0.85	1.33	1.21	0.857	1.07	

BDL = Below Detection Limit

Table 12. Cell 1 Pb Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	4.57	BDL	BDL	BDL	BDL	4.57	-
6	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7	8.12	5.73	6.49	10.3	8.29	7.79	1.77
10	6.42	5.85	6.31	6.93	6.38	6.38	0.44
Mid section							
0	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7	12.8	11.8	10.9	12.8	14.3	12.52	1.27
10	7.82	8.46	8.46	8.46	8.6	8.29	0.42
Anode section							
0	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7	5.76	5.76	3.33	4.42	4.06	4.39	1.02
10	8.57	8.94	9.49	10.9	9.61	9.50	0.89

Blank spaces indicate outlier values that were rejected.  
 low Detection Limit

Table 13. Cell 2 Pb Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	-
6	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7	4.66	5.47	5.78	5.56	5.37	5.37	0.49
10	5.87	4.72	4.18	5.78	4.91	4.91	0.88
Mid section							
0	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7	3.53	BDL	3.6	6.33	4.73	4.73	1.39
10	7.11	7.07	7.17	6.90	7.06	7.06	0.12
Anode section							
0	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3	BDL	BDL	BDL	BDL	BDL	BDL	BDL
4	BDL	BDL	BDL	BDL	BDL	BDL	BDL
5	BDL	BDL	BDL	BDL	BDL	BDL	BDL
6	BDL	BDL	BDL	BDL	BDL	BDL	BDL
7	4.72	5.3	7.24	7.20	6.05	6.05	1.13
10	5.74	6.97	4.59	5.02	5.61	5.61	0.90

Blank spaces indicate outlier values that were rejected.

BDL = Below Detection Limit

Table 14. Cell 1 Ba Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	0.90	0.45	BDL	BDL	BDL	0.67	0.32
3	2.30	2.19	1.90	1.79	2.13	2.06	0.21
4	0.35		0.29		0.71	0.45	0.23
5	2.41		3.84	3.69	3.63	3.39	0.66
6	1.70	1.42	1.13		1.62	1.47	0.25
7	4.21	4.40		4.76	4.75	4.53	0.27
10	4.98	3.84	3.46	3.54		3.96	0.70
Mid section							
0	0.90	0.45	BDL	BDL	BDL	0.67	0.32
3	1.88	1.94	1.92		2.07	1.95	0.08
4	0.11	0.06	0.07	0.07	0.06	0.07	0.02
5	2.97	3.50	3.52	3.13	2.79	3.18	0.32
6	1.32	1.16	1.30	1.78	1.54	1.42	0.24
7	5.39	5.02	5.60	5.63	5.34	5.40	0.25
10	4.85	4.73	5.00	5.56	4.79	4.99	0.34
Anode section							
0	0.90	0.45	BDL	BDL	BDL	0.67	0.32
3	2.16	1.74	1.41	2.04	1.61	1.79	0.31
4	0.07	0.07	0.07	0.07	0.07	0.07	0.00
5	3.82	3.74	3.63	3.37	3.64	3.64	0.17
6	1.39	1.27	0.70	0.89	0.99	1.05	0.28
7	4.25	4.15	4.18	4.59	4.27	4.29	0.18
10	5.97	4.55	6.48	5.65	5.29	5.59	0.73

Blank spaces indicate outlier values that were rejected.  
 BDL = Below Detection Limit



Table 15. Cell 2 Ba Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	0.90	0.45	BDL	BDL	BDL	0.67	0.32
3	1.29	1.44	1.32	1.42	1.72	1.44	0.17
4	0.07	0.07	0.06	0.06	0.07	0.07	0.002
5	1.54	2.02	2.27	2.23	2.70	2.15	0.42
6	1.83	2.42	1.44	1.72	2.58	2.00	0.48
7	4.52	4.33	4.13	4.30	4.29	4.31	0.14
10	3.86	3.79	3.93	4.08	4.01	3.93	0.12
Mid section							
0	0.90	0.45	BDL	BDL	BDL	0.67	0.32
3	3.67	2.67	0.57	0.50	0.33	0.47	0.12
4	3.71	3.20	2.82	3.32	2.87	3.07	0.41
5	2.53	1.86	3.19	2.77	3.05	3.18	0.34
6	4.41	4.15	3.12	2.98	2.65	2.63	0.49
7	4.61	4.54	4.28	4.54	4.85	4.45	0.27
10	4.61	4.54	4.84	4.74	4.79	4.70	0.13
Anode section							
0	0.90	0.45	BDL	BDL	BDL	0.67	0.32
3	2.46	2.36	2.84	2.27	1.83	2.35	0.36
4	2.97	2.05	1.74	1.96	2.74	2.29	0.53
5	2.84	3.10	3.48	3.35	2.71	3.10	0.33
6	2.94	2.24	2.58	3.10	2.68	2.71	0.33
7	4.58	4.40	5.59	5.11	5.71	5.08	0.59
10	3.07	3.10	3.10	3.33	3.66	3.29	0.27

Blank spaces indicate outlier values that were rejected.  
 BDL = Below Detection Limit

Table 16. Cell 1 Sr Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0		0.43	0.47		0.41	0.44	0.03
3	0.92	1.04	1.13	1.02	1.07	1.04	0.08
4	0.04	0.04	0.04	0.002	0.04	0.03	0.016
5	2.60	1.10	1.10	1.17	1.03	1.48	0.75
6	0.18	BDL	BDL		0.40	0.27	0.12
7	1.27	1.49	1.24	1.64	1.86	1.50	0.26
10	1.46	1.10	1.09	1.10	1.89	1.33	0.35
Mid section							
0		0.43	0.47		0.41	0.44	0.03
3	0.98	1.01	0.97		0.99	0.99	0.02
4	0.37	0.08	0.04	0.03	0.03	0.11	0.15
5	0.97	1.19	1.06	0.94	0.94	1.02	0.11
6	2.63			0.21	0.12	0.99	1.42
7	1.90	1.85	2.03	1.99	1.99	1.95	0.07
10	1.57	1.65	1.53	1.55	1.57	1.57	0.05
Anode section							
0		0.43	0.47		0.41	0.44	0.03
3	1.33	1.54	1.48	2.22	1.70	1.65	0.34
4	3.68	2.19	1.32	3.45	2.61	2.65	0.96
5	2.84	3.10	3.48	3.35	2.71	3.10	0.33
6	0.37	0.23	0.22	0.22	0.33	0.27	0.07
7	3.11		2.94	4.88	4.43	3.84	0.96
10	4.15	4.55	4.43	6.42	5.78	5.07	0.98

Blank spaces indicate outlier values that were rejected.  
 BDL = Below Detection Limit

Table 17. Cell 2 Sr Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0		0.43	0.47		0.41	0.44	0.03
3	0.91	0.96	0.85	0.92	1.00	0.92	0.06
4	BDL	BDL	BDL	BDL	BDL	BDL	-
5	0.26	0.42	0.43	0.53	0.70	0.47	0.16
6	0.35	0.32	0.33		0.43	0.36	0.05
7	1.14	1.40	1.27	1.24	1.25	1.26	0.09
10	1.12	1.02	1.31	1.21	1.19	1.17	0.11
Mid section							
0		0.43	0.47		0.41	0.44	0.03
3	0.54	0.38	0.53	0.60	0.65	0.54	0.10
4	1.39	1.34	1.10	1.18	1.01	1.20	0.16
5	1.04	0.83	0.92	0.81	0.91	0.90	0.09
6		1.19	1.35	1.30	1.14	1.25	0.10
7	1.48	1.52	1.46	1.61	1.60	1.53	0.07
10	1.67	1.56	1.59	1.53	1.47	1.56	0.07
Anode section							
0		0.43	0.47		0.41	0.44	0.03
3	1.13	1.01	1.06	0.90	0.78	0.98	0.14
4	1.26	0.86	0.92	0.78	1.11	0.99	0.20
5	1.27	1.81	1.44	1.35	1.27	1.43	0.22
6	1.85	1.12	1.42	1.37	1.44	1.44	0.26
7	5.58	3.92	5.36	3.15	4.53	4.51	1.01
10	4.89	2.63	3.46	2.19	3.45	3.32	1.03

Blank spaces indicate outlier values that were rejected.  
 BDL = Below Detection Limit

Table 18. Cell 1 Cr Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	2.98	2.98	2.45	2.67	2.99	2.81	0.24
3	BDL	BDL	BDL	BDL	BDL	BDL	-
4	BDL	BDL	BDL	BDL	BDL	BDL	-
5	2.91	2.51	1.90	1.87	3.67	2.49	0.84
6	5.18	2.50	2.82	2.55	2.56	2.67	0.18
7	7.50	5.72	5.11	6.45	6.04	5.70	0.57
10		6.00	5.77	6.40	5.83	6.30	0.71
Mid section							
0	2.98	2.98	2.45	2.67	2.99	2.81	0.24
3	BDL	BDL	BDL	BDL	BDL	BDL	-
4	2.62	3.65	2.98	3.10	3.11	3.09	0.37
5	1.04	0.83	0.92	0.81	0.91	0.90	0.09
6	6.52	1.19	1.35	1.30	1.14	1.25	0.10
7	5.96	6.93	6.64	6.38	6.35	6.56	0.24
10		6.09	6.15	6.16	6.20	6.11	0.09
Anode section							
0	2.98	2.98	2.45	2.67	2.99	2.81	0.24
3	BDL	BDL	BDL	BDL	BDL	BDL	-
4	3.98	3.36	3.43	3.27	3.72	3.55	0.29
5	1.95	2.71	2.10	2.77	2.39	2.38	0.36
6	2.42	2.15	1.99	1.61	1.37	1.91	0.42
7	5.88	5.76	5.78	6.33	6.58	6.07	0.37
10	5.94	6.07	6.33	6.21	6.57	6.22	0.24

Blank spaces indicate outlier values that were rejected.

BDL = Below Detection Limit

Table 19. Cell 2 Cr Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	2.98	2.98	2.45	2.67	2.99	2.81	0.24
3	BDL	BDL	BDL	BDL	BDL	BDL	-
4	BDL	BDL	BDL	BDL	BDL	BDL	-
5	BDL	0.77	0.67	1.14	2.72	0.86	0.25
6	2.19	2.99	2.42	2.21	5.49	2.51	0.34
7	5.26	5.82	5.27	5.45	5.60	5.46	0.23
10	5.10	5.17	5.31	5.39		5.31	0.20
Mid section							
0	2.98	2.98	2.45	2.67	2.99	2.81	0.24
3	BDL	BDL	BDL	BDL	BDL	BDL	-
4	BDL	BDL	BDL	BDL	BDL	BDL	-
5	1.84	2.03	2.13	1.41	1.34	1.75	0.36
6	3.52	3.13	5.41	5.50	4.51	4.41	1.08
7	5.62	5.80	5.56	6.05	6.12	5.83	0.25
10	6.09	5.81	6.11	5.80	5.85	5.93	0.15
Anode section							
0	2.98	2.98	2.45	2.67	2.99	2.81	0.24
3	BDL	BDL	BDL	BDL	BDL	BDL	-
4	3.98	3.36	3.43	3.27	3.72	3.55	0.29
5	1.22	0.98	1.72	5.44	1.76	1.42	0.38
6	4.85	4.49	4.46	5.94	4.59	4.77	0.41
7	5.76	6.05	6.47	5.66	6.10	6.06	0.26
10	5.87	5.39	4.92	5.66	5.39	5.45	0.36

Blank spaces indicate outlier values that were rejected.  
BDL = Below Detection Limit

Table 20. Cell 1 Zn Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	34.10	27.30	24.70	25.30	27.50	27.78	3.74
3	30.60	36.80	21.80	61.70	24.10	28.33	6.77
4	36.50		59.40	35.90	39.30	52.53	13.93
5			35.40	35.80	28.40	36.87	2.12
6	37.10	39.90	30.50	31.60	34.00	34.34	4.76
7	45.30	42.80	41.20	24.00	26.30	38.98	1.89
10	32.20	33.60	31.70			29.56	4.17
Mid section							
0	34.10	27.30	24.70	25.30	27.50	27.78	3.74
3	37.80	43.90	41.50	54.50	50.30	45.60	6.74
4	25.70	29.70	36.70	39.40	20.70	30.44	7.70
5	22.00	23.10	33.10	22.50	34.00	26.94	6.05
6	36.00	33.40	31.30	33.80	27.90	32.48	3.06
7	38.30	39.30	48.90	27.80	28.80	38.83	8.22
10	26.10	29.30	24.40		34.00	28.32	3.67
Anode section							
0	34.10	27.30	24.70	25.30	27.50	27.78	3.74
3	32.10	49.40	37.60	32.40	51.30	40.56	9.23
4	19.90	33.90	20.20	20.20	22.90	24.23	6.59
5		21.50	31.00	34.70	34.00	27.10	4.97
6	23.00	34.60	41.60	32.70	26.60	33.58	6.68
7	32.40	38.90	35.00	26.10	25.50	33.12	4.48
10	24.80	30.00	18.60			25.00	4.11

Blank spaces indicate outlier values that were rejected.

Table 21. Cell 2 Zn Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	34.10	27.30	24.70	25.30	27.50	27.78	3.74
3	30.70	37.50		30.30	43.30	35.45	6.19
4		24.40	25.30	21.70		23.80	1.87
5		28.30	31.60	30.10	26.00	29.00	2.41
6	37.10	39.90	30.50	35.80	28.40	34.34	4.76
7	30.10	29.90	32.80	35.80	36.00	32.92	2.95
10	25.50	25.40	23.50	29.10	36.10	27.92	5.00
Mid section							
0	34.10	27.30	24.70	25.30	27.50	27.78	3.74
3	22.70	21.10	39.20	22.90		26.48	8.52
4	25.70	29.70	36.70	39.40	20.70	30.44	7.70
5	47.40	34.20	2.80	37.50	40.10	38.40	5.78
6	52.20	75.80	47.20	47.20		58.40	15.27
7	27.00	28.60	29.30	31.70	29.50	29.22	1.70
10	17.70	28.30	18.10	22.40	16.30	20.56	4.89
Anode section							
0	34.10	27.30	24.70	25.30	27.50	27.78	3.74
3	22.70	21.10		22.90		22.23	0.99
4	19.90	33.90		20.20	22.90	24.23	6.59
5	31.50	28.30	37.50	41.40	25.10	32.76	6.66
6	23.00	34.60	41.60	34.70	34.00	33.58	6.68
7	30.20	27.30	20.70	32.40	33.80	28.88	5.19
10	18.30	22.80	15.60			18.90	3.64

Blank spaces indicate outlier values that were rejected.

Table 22. Cell 1 U Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	0.61	0.61	0.61	0.61	0.61	0.61	0.14
3	0.55	0.61	0.50	0.74	BDL	0.60	0.11
4	0.75	0.60	0.59	0.59	0.54	0.61	0.08
5	0.99	0.67	0.86	BDL	0.83	0.84	0.13
6	BDL	BDL	BDL	BDL	BDL	-	-
7	0.32	0.47	0.34	0.48	0.34	0.39	0.08
10	0.38	0.36	0.34	0.39	0.36	0.36	0.02
Mid section							
0	0.61	0.61	0.61	0.61	0.61	0.61	0.14
3	0.66	0.66	0.64	0.54	0.36	0.57	0.13
4	0.49	0.80	0.58	0.658	0.59	0.62	0.11
5	0.67	0.84	0.49	0.65	0.59	0.65	0.13
6	BDL	BDL	BDL	BDL	BDL	-	-
7	0.34	0.32	0.34	0.37	0.32	0.33	0.01
10	0.39	0.39	0.39	0.37	0.36	0.38	0.02
Anode section							
0	0.61	0.61	0.61	0.61	0.61	0.61	0.14
3	0.63	0.74	BDL	0.83	1.07	0.73	0.14
4	0.49	0.53	0.58	0.68	0.93	0.64	0.18
5	0.82	0.76	0.83	1.15	0.75	0.86	0.17
6	0.83	0.67	0.92	0.93	0.44	0.84	0.12
7	0.49	0.50	0.45	0.34	0.44	0.44	0.06
10	0.35	0.37	0.39	0.39	0.35	0.37	0.02

BDL = Below Detection Limit  
 Blank spaces indicate outlier values that were rejected.



Table 23. Cell 2 U Concentrations (mg/kg) in Soil Sections After Treatment

Day	Sample #1	Sample #2	Sample #3	Sample #4	Sample #5	Average	Std. Dev.
Cathode section							
0	0.61	0.61	0.61	0.61	0.61	0.61	0.14
3	0.55	0.56	0.57	BDL	0.68	0.56	0.06
4	0.33	0.68	0.48	0.64	0.66	0.56	0.15
5	0.55	0.59	0.77	0.64	0.48	0.60	0.11
6	BDL	BDL	BDL	BDL	-	BDL	-
7	0.37	0.36	0.36	0.38	0.35	0.36	0.01
10	0.35	0.37	0.37	0.39	0.39	0.37	0.02
Mid section							
0	0.61	0.61	0.61	0.61	0.61	0.61	0.14
3	0.66	0.64	0.65	0.58	0.57	0.62	0.04
4	0.51	0.85	0.55	0.54	0.62	0.61	0.14
5	0.63	0.56	0.53	0.52	0.65	0.58	0.06
6	0.45	0.45	0.50	0.63	0.50	0.51	0.07
7	0.45	0.34	0.33	0.34	0.35	0.37	0.05
10	0.40	0.38	0.33	0.40	0.35	0.38	0.02
Anode section							
0	0.61	0.61	0.61	0.61	0.61	0.61	0.14
3	0.63	0.74	BDL	0.83	1.07	0.73	0.14
4	0.49	0.53	0.58	0.68	0.93	0.64	0.18
5	0.82	0.76	0.83	1.15	0.75	0.86	0.17
6	0.54	0.79	0.73	0.79	0.72	0.71	0.10
7	0.33	0.31	0.33	0.35	0.33	0.33	0.02
10	0.39	0.39	0.36	0.37	0.34	0.37	0.02

BDL = Below Detection Limit

Blank spaces indicate outlier values that were rejected.

**END**

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**DATE  
FILMED**

**4/1/1993**

