

APPENDIX A
Lynntech Inc., Final Technical Report and Workplan

O-1 Treatability Study at Camp Stanley Storage Activity, Boerne, TX

FINAL TECHNICAL REPORT

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Preface

This final report was prepared by Lynntech, Inc. 7610 Eastmark drive, Suite 105, College Station, Texas 77840, for Parsons Engineering Science, Inc (Parsons ES) under Subcontract No.: 728487-3000-00. Mr. Ken Rice, was the Technical Monitor of the Project for Parsons ES.

The report describes remedial treatability study services performed at Camp Stanley Storage Activity (CSSA) under the contract to Parsons ES. The services included demonstration and evaluation of an electrokinetic soil remediation process for removal of heavy metals from contaminated soil. The design, fabrication, and performance testing of this new contaminated soil treatment system are described. The study included both bench scale tests of the electrokinetic treatability of soil contaminated by heavy metals and a demonstration of the process operation in a field test. The field test was carried out at Camp Stanley Storage Facility oxidation pond (SWMU O-1) at Boerne, TX.

The experimental laboratory work and the design and fabrication of the field test unit was carried out at Lynntech's facility. Chemical analysis of soil and pore water were performed at Lynntech's Analytical Laboratory and by EnviroTech Mid-Atlantic Laboratories, a certified analytical services company at Blacksburg, VA.

The work was performed in the period between April 1997 and January 1998. This report version of July 24, 1998, is a revised version of the report submitted March 25, 1998.

Summary

Electrokinetic remediation of contaminated soils is an emerging, innovative technology for soil clean-up which comprises the application of an electric field between the electrode wells positioned in the soil and utilization of the electrokinetic phenomena induced in the soil for removal of contaminants from the soil. This final report describes the demonstration and evaluation of the electrokinetic soil remediation process for removal of heavy metals from contaminated soil containing high limestone content. The design, fabrication, and performance testing of this new soil treatment system are described. The study included both bench scale tests of the electrokinetic treatability of soil contaminated by a mixture of heavy metals and a demonstration of the process operation in a field test. The field test was carried out at Camp Stanley Storage Facility O-1 site at Boerne, TX.

The treated area at the CSSA O-1 site is polluted by heavy metal contaminants, predominantly chromium and cadmium. Bench scale treatability study demonstrated highly efficient electrokinetic removal of chromium from CSSA O-1 soil. Up to 99.8% removal of chromium was achieved in large portion of soil (one third of soil), where remaining chromium concentration was only 1 ppm of 630 ppm initial concentration. This concentration is significantly lower than the cleanup goals of the project. The field test results clearly demonstrated an almost linear dependence of chromium removal on soil pH. Highest chromium removal, 34 %, was obtained near the anodes where soil was acidified down to pH = 2 - 4. Only 13 % chromium was removed near the cathode where less efficient acidification occurred. Removal of chromium near the cathode indicated that transport of negatively charged chromium in that region was exclusively by dielectrophoresis and electroosmosis.

Estimated cost of the process operation in the field showed that the energy expenditure cost was very low ca \$6/t of soil. This cost was only 1-2% of the total cost, which was entirely dominated by the cost of chemicals used in the process. This cost is too high for implementation of the process on a large scale, considering that the process needed to be further prolonged to achieve removal goals of the project. Recommendations were made in terms of the process design and how to apply the process for a potential remediation of soil at CSSA O-1 site.

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I. Introduction

A. Electrokinetic Soil Remediation - Background

Electrokinetic remediation of contaminated soils is an emerging, innovative technology for soil cleanup which comprises the application of an electric field between the electrode wells positioned in the soil and utilization of the electrokinetic phenomena induced in the soil for removal of contaminants from the soil. This technology has been tested at the bench scale for decontamination of soils polluted by heavy metals^{1,2,3}, organic contaminants^{4,5,6,7,8} and radionuclides^{9,10}. However, very few field tests^{11,12,13} have been initiated, and a demonstration of this technology in the field was needed. Electrokinetic soil processing technology is particularly attractive because it is an *in situ* method for soil decontamination and can be applied in soils of low permeability where hydraulic pumping of contaminants or reagents is inefficient. The method involves no excavation or off-site transportation of contaminated material, and should be very acceptable to the public in adjacent communities as a remediation method. The electrokinetic soil processing can be viewed as an entirely new technology for:

- Controlling the horizontal and/or vertical transport of contaminants in fine grain soils or layered soils of variable hydraulic permeability and moisture content,
- Introduction and distribution of reagents in the soil which can be utilized to enhance the contaminants solubility, to immobilize them or to achieve an optimum pH in soil for the treatment process.

The electrokinetic soil processing can operate both in saturated and in soil of very low moisture content (down to ca 7%)¹⁴. The process has a number of attractive features including the ability to control the movement of charged, anionic and cationic, as well as noncharged species. It possesses sufficient flexibility that it could be successfully operated in different soil textures. Compared to pump and treat or irrigation systems which utilize hydraulic flow for reagents, contaminants or water transport through the soil, the electrokinetic transport has the advantage that the pore fluid flow induced by an electric field (*electroosmotic flow*) utilizes a higher percentage of cross section of the porous medium than the hydraulic flow, which is prone to channeling.

The electroosmotic fluid flow control is exhibited particularly in small, capillary type pores, i.e., in clayey, fine grained, soils, where majority of the contaminants are concentrated. The accumulation of the contaminants in the layers of fine grained soil occurs due to the adsorption at soil particles of high surface area. In contrast to the electroosmotic flow, the hydraulic flow can

not be established in these tight soil layers because the hydraulic flow drastically decreases with the pore size.

The electrokinetic transport can be applied in sandy as well as in clayey soil layers. Ions, including either contaminants or treatment agents present in the pore fluid, can be transported by *electromigration* only, i.e., with minimum liquid transport through the soil. This feature is especially important because it allows the electrokinetic contaminant transport to be efficiently implemented in vadose zone soils.

The additives are usually added to the anode, cathode or both electrode wells and consist of environmentally benign chemicals which are added to the soil in a diluted form. The process requires the control of pH in the cathode well, where a base is formed due to the electrochemical hydrogen evolution reaction at the cathode. An organic acid is added as a neutralizer to the cathode well which also provides soluble anions or serves as a complexant for metal contaminants in the soil. In the anode well, an acid is produced electrochemically due to the oxygen evolution reaction. This acid propagates through the soil, acidifies the soil and helps in solubilizing metal compounds bound to the soil.

B. Objective and Scope of the Study

The overall objective of this Project was to perform remedial treatability study of an electrokinetic soil remediation process for treatment of soil at CSSA O-1 site, contaminated with heavy metals. The area O-1 has been identified with contamination exceeding cleanup levels in surface soils. A predominant contaminant at the site was chromium. The goal of the study was to provide data for the feasibility of electrokinetic remediation at the O-1 site. The scope of work encompassed:

- Performance of bench scale treatability tests using soil from the site and,
- Performance of field pilot scale treatability test.

Objectives were to determine the effectiveness of the process for heavy metal contaminants removal from soil under conditions encountered at an actual contaminated field site.

The objectives of the laboratory bench scale electrokinetic remediation procedure were:

- To obtain information on contaminant removal using soil samples taken from the CSSA O-1 site; and,
- To use this information to optimize the design of the field pilot system.

The objectives of the field pilot scale test were:

- To configure, integrate and install the pilot scale hardware at the 0-1 site;
- To operate and monitor the process for 60 days at CSSA O-1 site;
- To compile and evaluate the test results; and,
- To draw conclusions and make recommendations.

II. Technical Approach

A. Technical Aspects of Lynntech's Electrokinetic Soil Remediation Technology

1. Application of Non-uniform Electric Field

In Lynntech's electrokinetic process, an electric field is applied between the electrodes positioned in the soil: anodes are positive electrodes and cathodes are negative electrodes. Lynntech, Inc., uses pulsed electric field up to 300 V/m, and at a pulsing rate with on/off pulse duration in the range: on = 1-5 s and off 10 - 30 s. Application of pulsed electric fields reduces the time of the soil treatment and reduces the energy cost. In the process both dc (electromigration, electroosmosis, electrophoresis) and ac (dielectrophoresis) effects are induced which control the transport of contaminants and reagents in soil. Application of non-uniform electric field, which is enhanced by a specific geometrical arrangement of the electrodes in the field, brings up to 30 % faster removal of heavy metals from soil compared to the application of dc processes. Specific features of the process are described below:

- In non-uniform electric field a dielectrophoretic force is induced in soil, acting on both charged and non-charged particles and molecules dispersed in a pore fluid.
- Application of pulsed electric field causes: (i) a "disturbance" (polarization) of the electrochemical double layer present on soil particles, which enhances a contaminant desorption from the soil; (ii) polarization of non-charged contaminants in soil which enhances their movement in the soil; (iii) an "electrochemical stirring" of the soil pore fluid by frequent changes in voltage applied through the soil, and (iv) an increased electroosmotic flow compared to the DC process.

DC and AC electrokinetic phenomena induce a horizontal transport of pore fluid and contaminants between the electrodes (cf., Figure 1). Heavy metal ion contaminants are transported toward the anodes (e.g., chromates) or toward the cathodes (e.g., cadmium cations), depending on their charge in soil. Electrodes are mounted in the electrode wells. Heavy metals extracted from the soil in the cathode wells can be electrodeposited at the cathodes. The effluent accumulated in the cathode wells containing heavy metals not electrodeposited is stored and the volume of remaining metals can be reduced by applying one of the volume reduction methods, e.g., precipitation using hydroxides, sulfates or other metal salts in a separate tank or using electrolysis reversal, ion exchange or reverse osmosis.

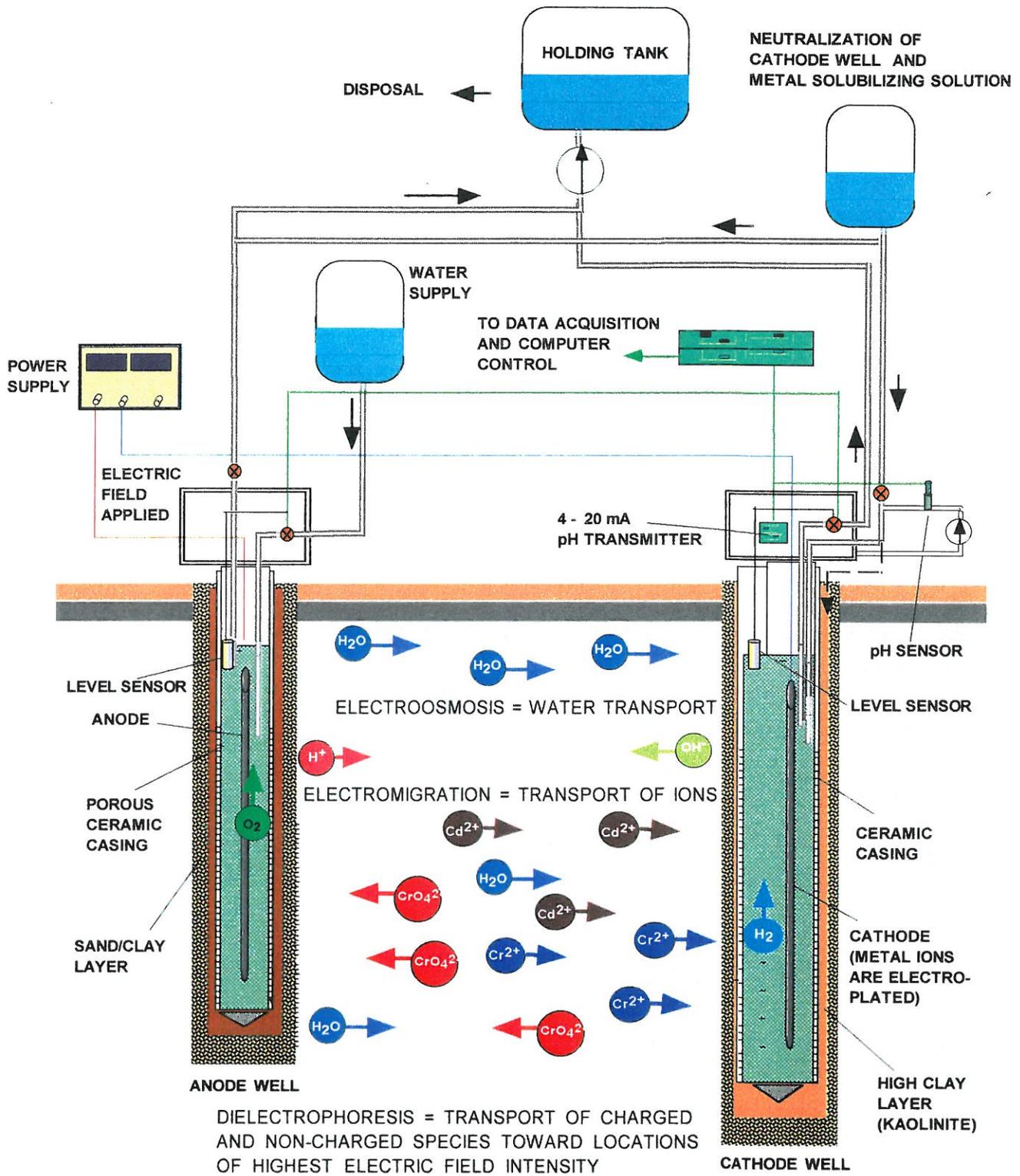


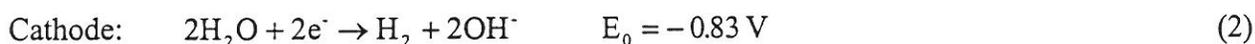
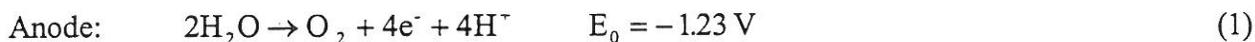
Figure 1. Principle of chromium and cadmium removal and process logistics used at CCSA site O-1. Both anode and cathode electrode well assemblies are shown including sensors and electronics for automated data acquisition and control.

2. Electrode Well Construction

Lynntech's process uses a proprietary design of the electrode wells which are constructed from low porosity ceramic tubing surrounded by a layer of packing material (cf., Fig.1). The packing material, a clay/sand mixture with adjusted hydraulic and electrokinetic permeability serves to further concentrate the contaminants at both electrode wells and to minimize the effluent volume. For the electrode processes to occur, the electrodes must be surrounded by water. Since the site is unsaturated, the electrodes must be placed in wells, which are maintained at all times with water. The ceramic material as well as packing material surrounding the wells forms the well casing that both retains water and promotes the electrokinetic processes through the casing.

Major contaminants at the CSSA 0-1 site are chromium,⁹ cadmium and perchloroethene. Chromium and cadmium are charged contaminants which are transported in soil under the applied pulsed electric field by electromigration, electroosmosis and dielectrophoresis. Chromates are expected to concentrate in the anode wells and cadmium in the cathode wells. The direction of the electroosmotic flow induced in the soil is from the anodes toward the cathodes and can help in removal of cationic contaminants as well as perchloroethene.

It is well understood that the electrochemical reactions at the electrodes used in the electrokinetic soil processing involve splitting of water to hydrogen at the cathode and oxygen at the anode.



where E_0 is the standard electrochemical reduction potential. During the electrokinetic soil processing, water in the immediate vicinity of the electrodes is electrolyzed (cf., Eq. 1 and 2) causing the pH of the soil to change. Protons formed at the anode migrate through the soil and form an acid front towards the cathode. This can aid in heavy metal removal by increasing the metal extraction at the soil pore surface. In contrast, OH^- ions formed at the cathode create a considerable difficulty. The soil pH in the cathode well and in the soil in the vicinity of the cathode wells can rise to above pH=12 causing the deposition of insoluble metal hydroxides and giving rise to regions of high electrical resistivity. The transport of metal contaminants thus drops and the voltage (i.e., the energy required to drive the process) increases. To prevent the base front movement in the soil from the cathode, addition of a buffer solution to the cathode wells was adopted as a best solution. From bench scale tests (see Results and Discussion) citric acid in combination with hydrochloric acid was determined to be best additive for the soil at CSSA O-1 site.

The requirements for the soil conditioning solution or additives to the soil were: (i) to be environmentally benign; (ii) to provide neutralization of the base produced electrochemically in the cathode well, and (iii) to provide anions which will form soluble salts or complex with metal contaminants in the soil. These anions are transported electrokinetically from the negative electrode (cathode) well toward the positive electrode (anode) well. The addition of the buffering/neutralizing solution was performed both in the cathode and anode wells (cf., Figure 1). An electrochemically produced acid in the anode well was used to acidify the soil and further enhance metal extraction from the soil. In the later stages of the field test, conditioning solution was additionally added through a gallery of injection wells.

The solution from both the anode wells and cathode wells was withdrawn occasionally to the collection tank. Addition of buffering/solubilization solution was added based on the requirements for pH control in the cathode wells as well as based on the water level measured by level sensors located in the anode and cathode wells.

B. Problems Encountered at CSSA O-1 Site

The soil at the oxidation pond O-1 site at the CSSA site is fill soil, approximately 3 - 4 feet in depth, consisting of gravelly silt and clay with marly limestone and caliche fragments. The hydrogeological characteristics of silty/clayey soil provide a good medium for the application of electrokinetic soil remediation process. The fill soil is underlined by a liner and 2" thick liner bedding sand. It was previously determined that the liner, consisting of a nylon reinforced polyethylene and a second rubber liner material, was destroyed in 1985 during site closure activities. Sampling on several occasions determined that the major contaminants at the site are chromium, cadmium and perchloroethene (PCE, or tetrachloroethene). Table 1 below summarizes the contamination levels at the site as well as the contaminant concentration criteria for closure under 30 TAC 335 Subchapter S Risk Reduction Standard 1.

The soil at the site consisted of two types of soil: (i) contaminated undisturbed fill soil, and (ii) contaminated disturbed soil which was moved and disturbed previously. The electrode wells were positioned to encompass both the undisturbed and disturbed portion of the soil equally (see Section III).

The major problem encountered at the site was high limestone content in the soil, which caused a high buffering capacity of the soil. In the bench scale tests it was determined that citric acid should be used as a best complexing or solubilizing agent for chromium and cadmium contamination in soil. However, the solubility as well as the electrokinetic mobility of the metal contaminants was strongly dependent on soil pH and the efficiency of soil acidification.

Table 1. Concentrations of major contaminants at SWMU 0-1 site: fill soil, 3 - 4 feet in depth.

Contaminant	Maximum Concentration mg/kg	Average Concentration mg/kg	Criteria for Closure mg/kg
PCE, perchloroethene	1,390	267.3	<0.005
Cadmium	4.8	1.62	0.45
Chromium	1,300	391.4	39.9

Therefore in the field test a combination of citric acid as a complexing agent and hydrochloric acid as an agent for cathode well neutralization and soil acidification was used.

The contamination at the site was found to be quite heterogeneous. We have utilized a method of sampling the "control zones", the zones where core samples were taken between the anode and cathode wells at equal distance. By taking the samples in close proximity to the locations in the control zone, both temporal and spatial transport of contaminant could be determined even in soil with nonhomogeneous distribution of contaminant. However, because of large number of rocks spread throughout the soil, core sampling was limited to a certain depth at several locations within the site and it was not always possible to accomplish a full sampling schedule.

A relatively shallow depth of the contamination at the site (3-4 feet) was favorable for the application of the electrokinetic methods because the soil temperature during the process could be kept low using voltage regulation, thus avoiding volatilization of the organic contaminants. Higher soil temperatures due to the electrical heating are usually a problem in deeper soil strata.

III. Experimental Techniques and Methodology

A. Bench Scale Treatability Tests

1. Soil Samples

Bulk soil sample was taken from CSSA O-1 site (three 5 gal buckets at 3 ft, 5ft and 6 ft depth). The soil was dried, sieved (-1/4"), grinded and homogenized in a crusher to obtain uniform distribution of contaminant in soil for the experiments. Chromium concentration found in the buckets was in the range 100 - 650 ppm. The soil from the bucket #3, containing 630 ± 15 ppm Cr (after homogenization), was used in the bench scale experiments.

2. Batch Tests for Determination of Optimum Extractant

The batch leachability tests were performed in ca. 100 ml beakers using 5 g of soil and adding predetermined volume of acid/leachant. Two types of batch tests were performed. The first involved a titration of soil with the acid additive (starting volume 30 ml) and continuous measurements of pH in the stirred soil/leachant slurry. This extraction procedure provided results on extraction of chromium and cadmium at different pH using a series of leaching agents. This test was considered a short term extraction test (ca 2 h). The second test was longer, solution was in contact with the soil for 16 h, and provided long term extraction results. The soil was mixed with 50 ml of leachant solution. Several organic acids and their combinations were tested as potential additives to the soil for the electrokinetic process.

3. Electrokinetic Tests for Removal of Chromium from CSSA O-1 Soil

The efficiency of chromium removal from CSSA O-1 soil by electrokinetic treatment was studied in PVC soil bed, 18" x 6" x 6.5". A schematic of the experimental setup is shown in Figure 2. Homogenized soil, containing 630 ± 15 ppm Cr was used in the experiments. The electrode wells consisted of ceramic tubing, made of the same material used for the construction of the electrode wells in the field. In this the conditions in the field are closely mimicked at the bench scale.

The experimental setup allowed automated addition of fluids and additives to the soil. Voltage distribution in the soil was measured using voltage probes positioned between the electrode wells. The changes in the voltage between the voltage probes indicates changes in

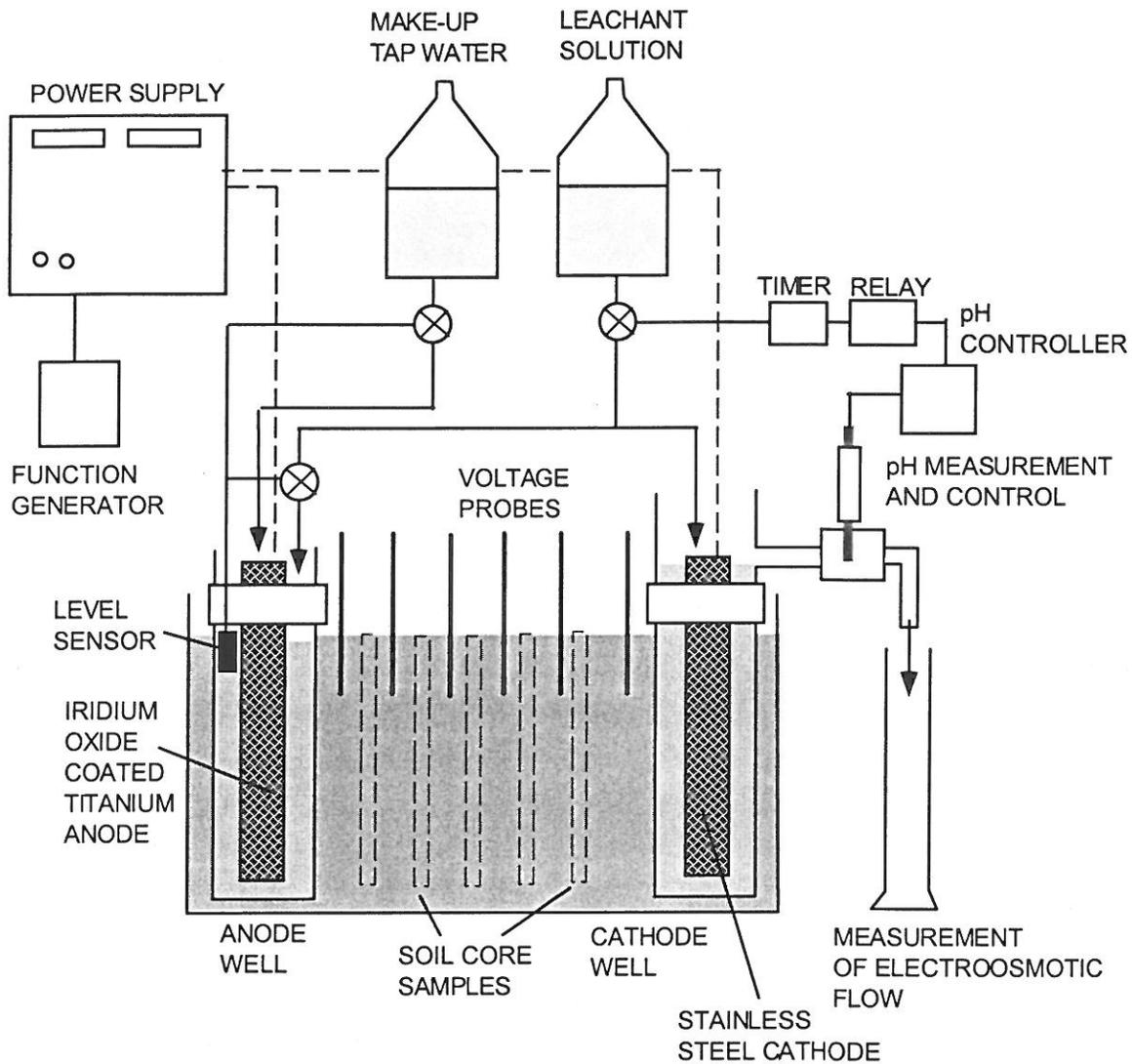


Figure 2. Schematic of the experimental setup for testing the electrokinetic removal of heavy metals from soil.

resistance of soil which can be caused by changes in moisture content of soil and chemical changes in soil. Thus, measurements of voltage distribution in soil provided an indication of chemical processes occurring in soil during the electrokinetic treatment.

4. Methods and QA/QC Procedures

At Lynntech's Analytical Laboratory, chromium and cadmium metals were determined on soil and in liquid samples using atomic absorption according to EPA standard analytical procedures (EPA SW 846, Method 3050). Analysis for bench scale tests of determining optimum leaching agents were performed at Lynntech's Analytical Laboratory. All other metal analyses

on soil and in solutions were performed by EnviroTech Mid-Atlantic Laboratories, a certified analytical laboratory from Blacksburg, VA (1861 Pratt Dr. Blacksbur, VA 24060, Phone (540) 231-3983). All analyses performed in this laboratory were in accordance with the EPA methods referenced in Code of Federal Regulation, Section 40 Part 136, "Methods for Chemical Analysis of Water and Wastes", EPA 600/4-79 revised march 1983 and/or "Test Methods for Evaluating solid Waste, Physical/Chemical Methods:, SW-486, 3rd Edition. A sample copy of the Analysis report from EnviroTech Mid-Atlantic Laboratories is attached in Appendix I. EnviroTech Mid-Atlantic Laboratories has certification numbers for Virginia, New Jersey, North Carolina, South Carolina and Tennessee. The analysis of metals performed by EnviroTech Mid-Atlantic Laboratories was accomplished by inductively coupled plasma method according to the EPA Standard Methods 200.7 or SW 846 6010 Series.

Cr(VI) ions were determined according to standard spectrophotometric method (Method 3500-CR-D, Standard Methods for the Examination of Water and Wastewater) using diphenyl carbazine as a colorimetric reagent. Chromium (III) (and other valence states lower than Cr(VI)) was determined as a difference between total Cr found by atomic absorption and Cr(VI) determined colorimetrically.

To obtain accurate chemical analysis of soil contaminants a special attention was paid to: (i) closely following proper analytical procedures, namely EPA SW 486 and acid digestion method EPA #3050, for analysis of heavy metals in soil, and (ii) sampling and handling of the core samples taken at CSSA O-1 site. In order to establish QA/QC criteria for the analytical procedures for heavy metal analysis in soil, several steps were adopted as a part of the routine procedure in the analysis of each core sample:

- a) The accuracy of the digestion procedures (corresponding to the EPA SW 486 and 3050 method) was verified by parallel digestion of Standard Reference Materials (SRM) obtained from National Institute of Standards and Technology, (NIST) or from Environmental Resource Associates. Table below shows a comparison of results (digestions and analysis) for chromium and cadmium obtained at Lynntech and certified values for a standard soil sample obtained from Environmental Resource Associates (sample #PPS 46/Lot 236). All the results obtained were within the acceptance range when compared to certified values for standard reference materials. Similar results obtained and available from EnviroTech Mid-Atlantic Laboratories are attached in the Appendix where numerous digestions and analysis of standard soil samples from NIST Standard Reference Material 2704 and 2710 were performed.

QA/QC Results for chromium and cadmium for standard soil sample #PPS 46/Lot 236, obtained from Environmental Resource Associates:

Metal	Chromium	Cadmium
Certified Value	183 ± 49	78 ± 22
Acceptance Range	134 – 222	56 – 100
Lynntech's Results		
Digestion 1	200	76.0
Digestion 2	178	71.8
Digestion 3	189.7	75.2
Digestion 4	187	77.5
Digestion 5	184	73.9
Digestion 6	174	74.1
Digestion 7	178	71.1
Digestion 8	170	79.2
Digestion 9	200	78.5
Average (9)	184 ± 15.0	75.2 ± 4.0

- b) Heavy metal analysis was performed on each core sample which was sliced into 6" benches, some cores were taken in duplicate (see Appendix I), including independent digestions and analysis by atomic absorption spectrometer.
- c) Reagent blank was run in parallel to each digestion, i.e. eventual presence of the trace metal impurities in reagents, used at the same concentrations and volumes as for soil digestion, was tested and measured by atomic absorption spectroscopy.
- d) A set of heavy metal standard solutions used for calibrating the atomic absorption signals were regularly run to check the stability of the standard absorption signal for each metal. Measurements of the standard solutions were normally repeated after eight unknown samples or more frequently when found to be necessary.
- e) If anomaly in results was found, e.g. from eventual spot contamination, the sample was double-checked and rerun.
- f) The analytical results reported by EnviroTech Mid-Atlantic Laboratories are accompanied with several quality control data which include: (i) quantitation limit = the lowest concentration of analyte that can be positively quantified; (ii) %STD – percent standard deviation error between measured samples and a standard sample which contains known amount of metal; (iii) % spike recovery = $100 * (\text{actual reading} - \text{unspiked sample}) / \text{amount}$

of spike added); and (iv) %RD = relative percent difference = $100 * (1^{st} \text{ sample result} - 2^{nd} \text{ sample result}) / \text{sample result mean}$, which is obtained by repeated measurements of the same sample. The EPA requirements for the standard methods used are that %STD and %RD must be below 10 – 20 %. This requirement was satisfied in all the measurements performed.

- g) At several occasions the analytical results obtained at Lynntech, Inc. were compared with the results obtained by EnviroTech MidAtlantic, Inc, Blacksburg, VA and were found to be in good agreement. Table below shows few examples of the data used as interlaboratory calibration checks.

Comparison of analytical results obtained by two independent laboratories:

Sample ID	Chromium (ppm)	
	Lynntech, Inc.	EnviroTech Mid-Atlantic
IR21 (11/06/97)	441	367
2R2S (11/06/97)	440	387

The above QA/QC procedures were applied in analysis of samples from the bench tests and field test.

B. Field Test

1. Field Equipment

The field equipment for performance of electrokinetic soil remediation at CSSA O-1 site consisted of: (i) power supply Sorensen (600 V, 16 A) for generation of a pulsed electric field in the soil; (ii) stable electrodes; (iii) electrode wells; (iv) well fluid management; (v) management of the soil pH and liquid level in the wells, and (vi) contaminant collection. Lynntech’s pilot system integrates and automates each of these functions.

Electrode wells. A proprietary electrode well construction (cf., Fig. 1) that is fundamentally different from standard monitoring or injection wells was used at the site. The walls of the wells were formed from a ceramic casing (4" dia) surrounded by a layer of clay (tightly packed mixture of 20 % kaolinite and 80% sand). The low hydraulic permeability prevented water loss ensuring fluid is maintained in the well, which is essential when carrying out electrokinetics in unsaturated soil. Another function of the well casing is to adsorb the contaminants. Metals and solvents, extracted from the soil are concentrated on a high surface area clayey layer, which decreases the concentration of contaminants in the effluent. Contaminants can be recovered from the clay, e.g., by acid washing.

Ceramic casing was capped with a PVC box, which closed the well. Each well box contained necessary electronics for monitoring and controlling the pH and solenoid valves for fluid addition or extraction. The cathode well boxes contained: a stainless steel cathode, a pH controller, a pH probe, high and low well solution level sensors, and solenoid valves for controlling the addition of neutralizer/leachant (citric acid and hydrochloric acid) and withdrawal of the effluent. The anode well boxes contained: a dimensionally stable electrode (iridium oxide coated titanium), a low well solution level sensor, and one solenoid valve for the addition of water or leachant.

Six anodes and two cathode wells were positioned in rows as shown in Figure 3. Cathode wells were surrounded by the anode wells so that each cathode was centrally positioned to four anode wells. This arrangement of the electrode wells enhanced the non-uniformity of the electric field. In addition to the electrode wells, both horizontal and vertical injection wells were mounted between the electrode wells (cf., Fig. 3) to enhance the delivery of conditioning solution to the soil.

Process Control - Trailer. The process was operated and monitored from a trailer which contained: (a) NEMA 4 box which housed electronics for process control and automated data acquisition; (b) 10 kW power supply (Sorensen 600V, 16 A); (c) computer system for data acquisition and process control; (d) necessary field portable analytical equipment, e.g., pH meter, apparatus for deionized water, balance, etc. All the analog and digital signals are electronically isolated from the computer system using in-house developed opto-isolation amplifier boards. The process control and monitoring was performed remotely from Lynntech's headquarters in College Station, TX. A technician visited the site 1-2 times per week for preparation of chemicals and routine maintenance.

Storage tanks provided for (a) addition of citric/hydrochloric acid in both the cathode and anode wells; (b) effluent collection. Each anode and cathode well was connected to the trailer using one multipin electrical cable for energizing the electrodes, valves and pumps, for connection of analog signal probes and transferring digital signals to and from the computer. Solutions were transported using 1/2" PVC tubing, fittings and manual override valves.

2. Methods and QA/QC procedures

The analytical techniques and QA/QC procedures established in bench scale study were used for analysis of soil and well water samples taken from the field. The site characterization was performed by taking core samples in the vicinity of each electrode well (cf., Fig. 3) as well as along two profiles: (i) anode 1 – middle point – cathode 1, and (ii) anode 6 – middle point – cathode 2. The core samples were taken at the control profiles regularly (ca every 20-22 days).

The samples were taken as close as possible to the control zone sampling points. In this way, both temporal and spatial changes in contaminant concentration could be obtained. At the end of the treatment several trenches were excavated and soil sampled again at three depth and at locations corresponding closely to the locations of core samples taken during the process operation.

The size of the treatment area was 6 ft x 7 ft and 4 ft in depth. The treatment area encompassed two zones: (i) disturbed zone one in which the soil was disturbed by previous excavations, and (ii) undisturbed zone.

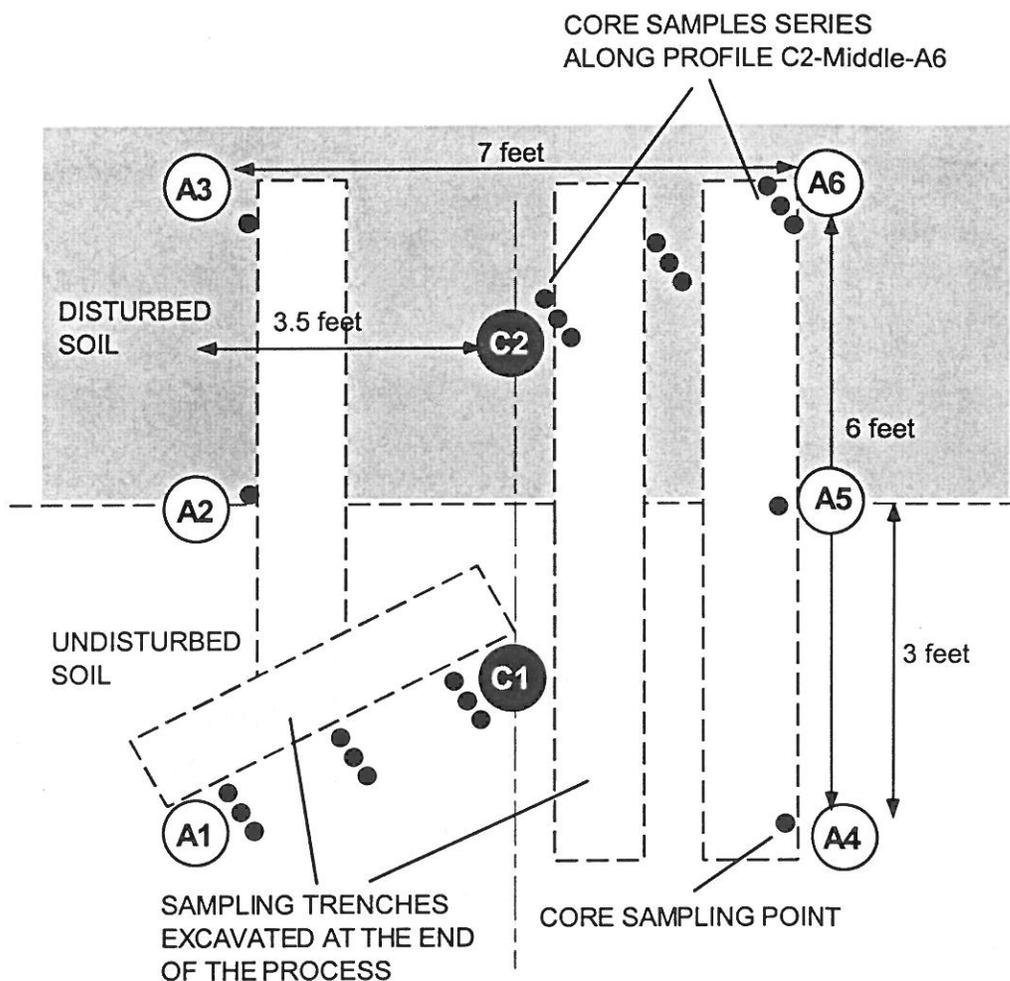


Figure 3. Position of the electrode wells and locations where soil core samples were taken every three weeks. This method of sampling allowed monitoring the process by both spatial and temporal changes in contaminant concentration in soil. At the end of the process four trenches were excavated within the treated area and samples taken down to ca 4 feet.

IV. Results and Discussion

Results obtained in the study are divided in two sections describing the bench scale electrokinetic treatability study of soil taken from the CSSA O-1 site and field scale demonstration of the process operation.

A. Bench Scale Treatability Study

1. Soil Mechanical Analysis

Data in Table 2 summarize mechanical analysis of soil samples taken from the site. A letter from Buchanan/Soil Mechanics, Inc. is included in the Appendix I, which certifies that only ASTM and U.S. Army Corps of Engineers standard techniques and methods were used to analyze the soil.

Table 2. Summary of Soil Mechanical Analysis

Parameter	DATA	Method
Specific Gravity	2.73	ASTM D 854
Atterberg Limits	LL (liquid limit) = 30	ASTM D 4318
	PL (plastic limit) = 20	ASTM D 4318
	PI (plasticity index) = 10	ASTM D 4318
Dry Density	104 pcf	ASTM D 698
Optimum Moisture Content	19.0 %	ASTM D 698
Hydraulic Permeability	2.35×10^{-8} cm/s	U.S. ACE, 1110-2-1906, 1970
Sieve Analysis	Percent passing	ASTM C 136 and ASTM D 422
passing 3/8" sieve	100 %	
passing No. 4 sieve	92.3 %	
passing No. 10 sieve	84.8 %	
passing No. 20 sieve	78.7 %	
passing No. 30 sieve	75.3 %	
passing No. 40 sieve	73.3 %	
passing No. 60 sieve	71.9 %	
passing No. 100 sieve	71.7 %	
passing No. 200 sieve	71.7 %	
Soil Classification	Brown sandy clay with fine gravel.	

Based on the soil mechanical analysis, the soil at the CSSA 0-1 site can be classified as brown sandy clay with fine gravel. The parameters which are relevant for the performance of the electrokinetic feasibility study in the soil are the soil type and its hydraulic permeability. The soil is sandy clay with very low hydraulic conductivity (2.35×10^{-8} cm/s), which indicated that the soil is suitable for the application of electrokinetic process at the site.

2. Determination of Optimum Extractant for Chromium from CSSA O-1 Soil

The batch tests were performed using 5 g of soil from the site (sieved at -1/4") and adding a total volume of 50 ml of leachant solution. Samples were homogenized and starting chromium contamination in soil was 630 ppm. Single and mixed extractants were tested. pH of the leaching solution as well as the soil pH after 16h in contact with the extractants were measured. Highest chromium removal from the soil was obtained when oxalic acid and citric acid were the components of the extraction solutions. The data are shown in Figure 4 as a function of pH of soil (filtrate) after the extraction. The graph clearly demonstrates that by lowering the soil pH, higher efficiency of chromium removal can be achieved. Several leachants (pointed in the graph) extracted chromium more efficiently than others at approximately comparable soil pH. In almost all of these cases citric acid was a component of the chromium extraction solution. This was interpreted by a possible formation of stable chromium complexes with citrates, which can significantly enhance the solubilization of chromium in soil.

Oxalic acid exhibited highest chromium removal, ca 72 %. This acid is the strongest acid among those tested and the high removal was attributed to relatively low pH achieved using this acid. When used in combination with other leachants, chromium removal was not higher than that expected from the pH effects. It was contemplated that little complexation occurred between oxalic acid and chromium contaminant in the soil. However, oxalic acid is less soluble than the citric acid and citric acid was used as a principal component of the leachant solution in further tests.

The pH of CSSA O-1 soil was ca 10, and soil exhibited a high buffering capacity. Tests were performed to determine the most efficient acid both for acidifying the soil and extracting chromium from soil. (It was found that there will be no problems in solubilizing cadmium contaminant in CSSA O-1 soil. However, extraction experiments concentrated on chromium extraction because cadmium concentration found in soil was below 2-3 ppm). These experiments involved titration of the soil using above-mentioned acids (up to 10 minutes at each point for pH equilibration). Acids were used at higher concentrations depending on their solubility in water. This provided insight into practical use of these acids in the field.

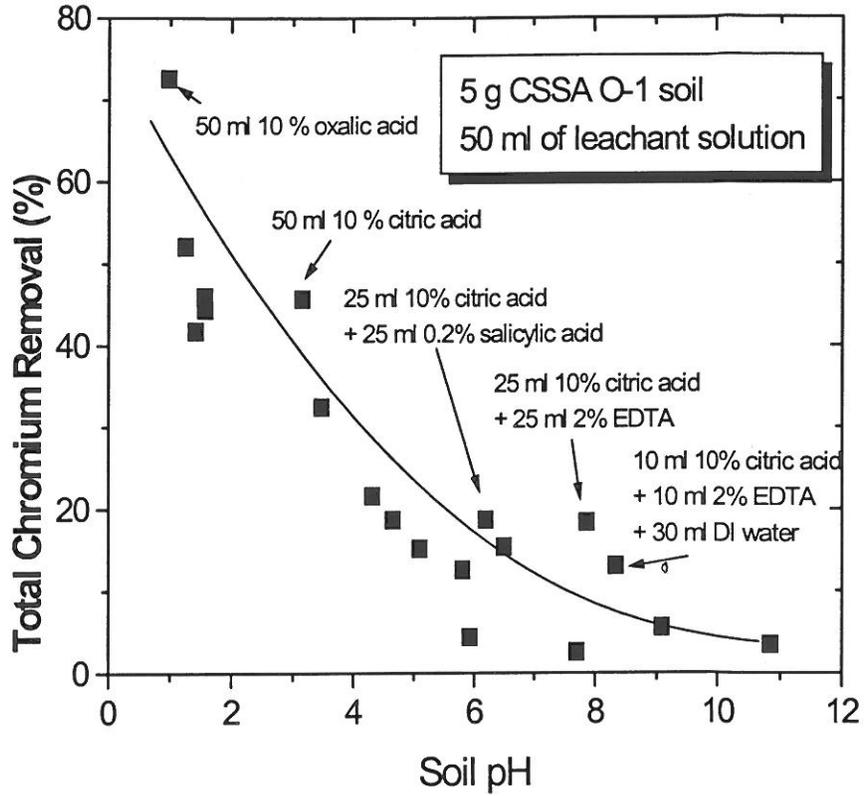


Figure 4. Dependence of chromium extraction on soil pH achieved after addition of the extractants.

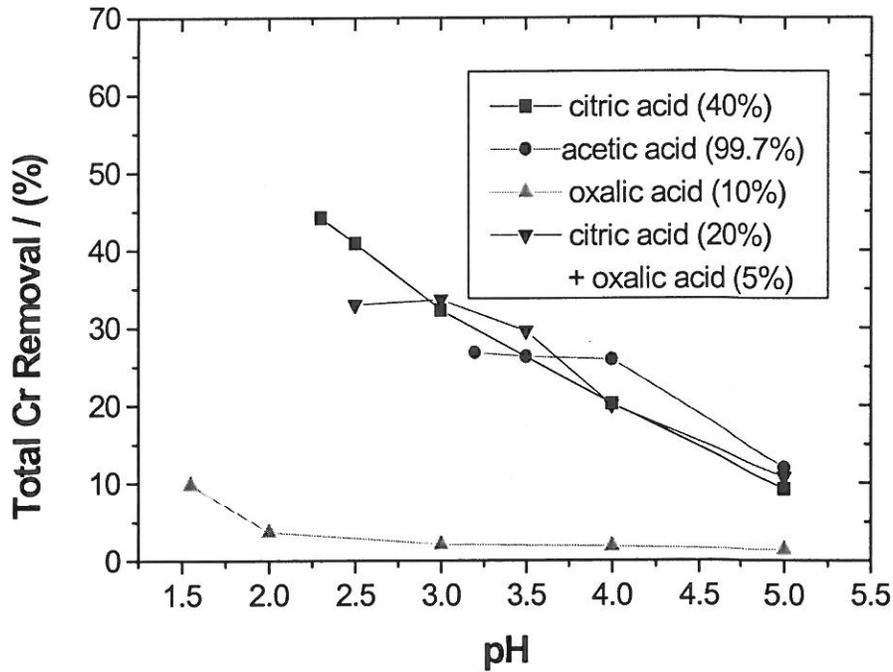


Figure 5. Titration of CSSA O-1 soil using environmentally benign acids and efficiency of chromium extraction from soil. Starting chromium concentration in soil was 630 ppm.

Figure 5 confirms that highest chromium removal in the short term (ca 2 h) titration experiments was achieved using citric acid. Oxalic acid (maximum solubility ca 15 %) showed most efficient acidification of soil, but lowest extraction of chromium. It is noteworthy that amount of acetic acid used to acidify the soil to pH 3.2 was ca twenty times larger than the amounts of citric and oxalic acid needed to acidify the soil to the same pH. Oxalic acid appeared as most efficient acidifier for CSSA O-1 soil. However, the results point out that citric acid can be efficiently used as a complexing agent and solubilizer for chromium removal.

3. Determination of the Valence State of Chromium Contaminant After Extraction

One of the concerns in the electrokinetic soil processing is that the metal ion contaminants could become mobile once they are solubilized in the soil pore fluid. Thus, the control of their containment within the treatment zone is of highest importance. In the electrokinetic process, high electric fields can contain the contaminants within the treatment zone by controlled electromigration and electroosmotic flow in soil. In the case of chromium contaminant it is important to determine the valence state of chromium in soil pore fluid because Cr in its Cr(VI) form is a highly toxic contaminant.

It was found that citric acid when added to contaminated CSSA O-1 soil: (i) prevents conversion of Cr from its lower valence state(s), e.g., Cr(III) to Cr(VI) ions; (ii) converts Cr(VI) ions to lower Cr valence states, and (iii) helps in keeping Cr contaminant in the lower valence state ionic forms. These findings are demonstrated by the following experiments performed using soil from CSSA O-1 site.

CSSA O-1 soil was titrated using citric acid (cf., Fig. 6) and chromium ion species analyzed in the filtrate after extraction. Figure 6 demonstrates that majority of Cr contaminant in the solution after the extraction was in the valence state lower than Cr(VI). It is noteworthy that extraction with other acids used in the investigation did not show significant levels of Cr(VI) ions in the solution. We have spiked CSSA O-1 soil samples with Cr(VI) ions and performed extractions in acetic and citric acid solutions of varying concentrations. Surprisingly, recovery of Cr(VI) in citric acid solutions was very low, which indicated that initially spiked Cr(VI) was converted to lower valence states during the extraction. Results are shown in Figure 7 as the percentage of Cr(VI) ions converted to lower valence states of chromium. When the acetic acid was used, even at high concentrations (95 %, cf., Fig. 7), no Cr(VI) reduction occurred in the pore fluid. Cr(VI) reduction exhibited a clear dependence on the concentration of citric acid demonstrating that citric acid (possibly in contact with the soil components) is capable of efficiently reducing spiked Cr(VI).

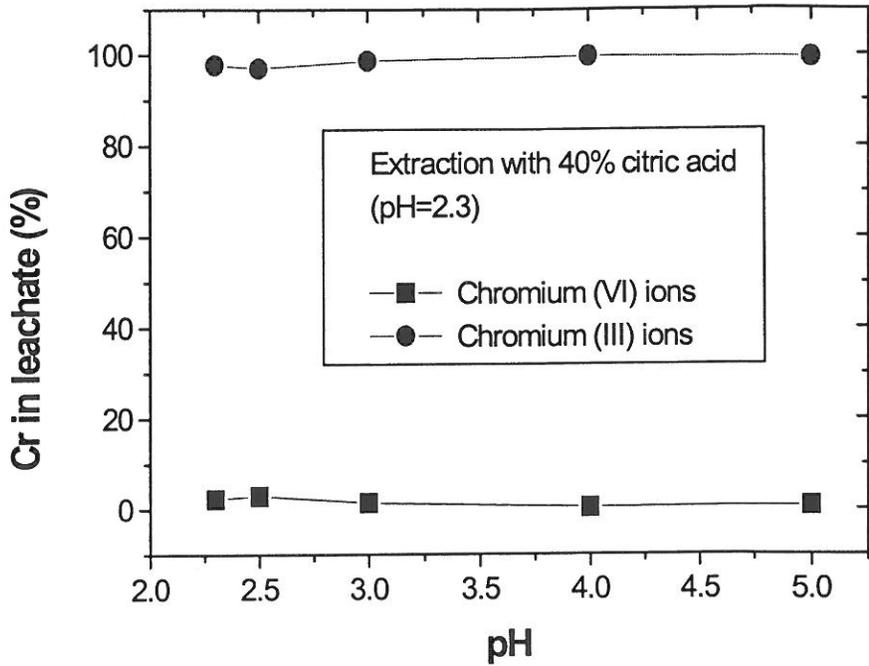


Figure 6. Titration of 5 g CSSA O-1 soil using citric acid and distribution of lower valence state chromium species, e.g., Cr(III), and Cr(VI) species in the solution after extraction. Starting chromium concentration in soil was 630 ppm.

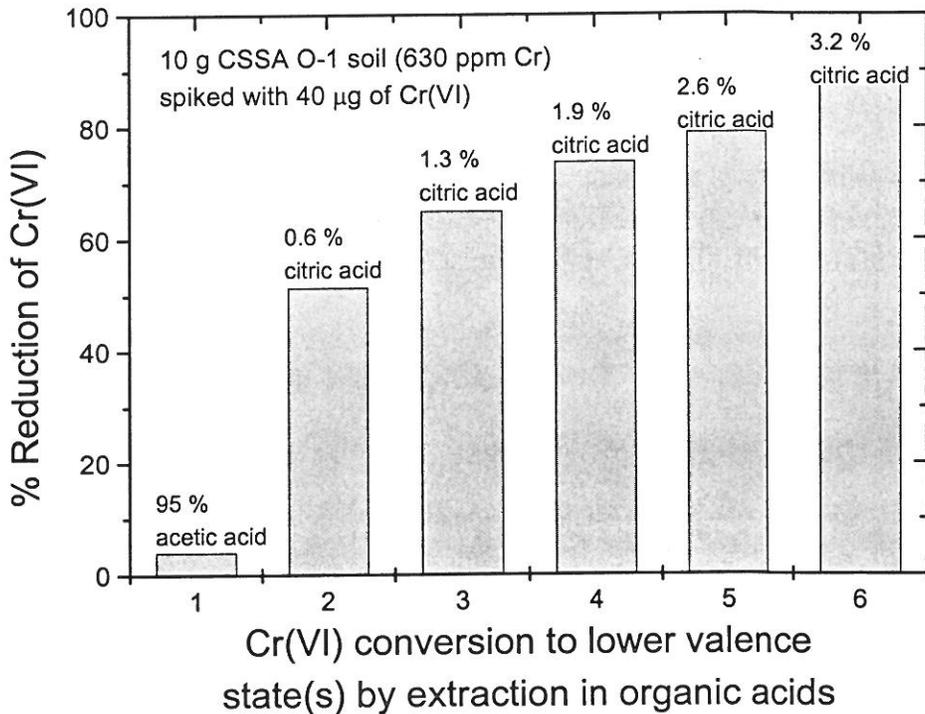


Figure 7. Reduction of Cr(VI) in Cr(VI) spiked CSSA O-1 soil samples by extraction in environmentally benign organic acids.

Titration performed in the presence of CSSA O-1 soil and with no soil present indicated that possibly some soil components in the presence of citric acid beneficially catalyzed the reduction of chromium (VI) species.

4. Determination of Optimum Extractant for Cadmium from CSSA O-1 Soil

Table 3 summarizes the results of extraction of cadmium from CSSA O-1 soil using twenty different extracting agents.

Table 3. Summary of cadmium extraction from CSSA 0-1 soil using a number of leachants.

Extractant	Cadmium (ppm)
Starting Concentration in Soil	3.9 ± 0.4
50 ml deionized water	0.28
50 ml 10 % oxalic acid	< 0.1
50 ml 10 % citric acid	< 0.1
50 ml 0.2 % salicylic acid	< 0.1
25 ml 10% oxalic+25 ml 10% citric	< 0.1
25 ml 10% oxalic+25 ml 0.2% salicylic	< 0.1
25 ml 10 % citric+25 ml 0.2 salicylic	< 0.1
20 ml 10 % oxalic+30 ml DI water	< 0.1
20 ml 10 % citric + 30 ml DI water	< 0.1
20 ml 0.2% salicylic + 30 ml DI water	0.18
50 ml 10 % acetic	1.15
50 ml 2% EDTA	0.58
25 ml 10 % acetic + 25 ml 2% EDTA	1.24
25 ml 10 % acetic + 25 ml % citric	0.39
25 ml 10 % citric + 25 ml 10 % oxalic	< 0.1
25 ml 10 % citric + 25 ml 2 % EDTA	1.15
25 ml 10% oxalic + 25 ml 2% EDTA	< 0.1
10 ml 10 % oxalic+10 ml 2%EDTA+30 ml DI water	0.19
10 ml 10 % citric+10 ml 2%EDTA+30 ml DI water	0.96
10 ml 10 % acetic+10 ml 2%EDTA+30 ml DI water	0.96

Table 3 demonstrates that the starting concentration of cadmium in CSSA 0-1 soil was very low. An average value of 3.9 ppm, was obtained from 11 measurements from homogenized samples taken from the site. This value is close to maximum concentration of cadmium of 4.5 ppm, reported at the site (cf., Table 1). Variation in results of 0.4 ppm (equal to one standard

deviation) obtained by analyzing a homogenized samples is close to the criteria for closure of 0.45 ppm (cf., Table 1). If the confidence interval is taken to be 95%, i.e., two standard deviations, the variation in the analysis of a homogenized sample is 0.8 ppm, approximately twice the level of the criteria for closure. The standard error is than 21 % ($100 \times 0.8/3.9$), which makes it difficult to accurately determine the removal efficiency on a percentage basis. Based on large variations in contaminant concentration found at the site, ca two orders of magnitude (see later Figure 12 and Appendix I), the error in determining cadmium removal will be even higher, thus preventing to draw correct conclusions on cadmium removal at the site.

Table 3 shows that most stronger acids, at higher concentrations (e.g., citric oxalic and salicylic) or combination of these acids will be efficient in removing cadmium if used as leachant in the electrokinetic process. However, acetic acid exhibited the least leaching power for cadmium. The results confirm that the leachant to be used at the site will be determined by the chromium extraction capability from soil and not cadmium.

5. Control of Soil Swelling on Addition of Additives to CSSA O-1 Soil

In the batch leachability tests it was found that when citric acid was added to the CSSA O-1 soil, soil swelling occurred. There was a concern that the swelling would have adverse effects relative to maintenance of the electrokinetic process as well as "bulging upward" of the soil within the treatment site. Although this could be considered beneficial from the aspect that reagents can be brought into close contact with the contaminants, the tests were performed to find the ways of controlling the soil swelling during leachant addition.

It was found that addition of acids to the soil such as oxalic, hydrochloric, nitric and/or formic acid will not cause swelling of the soil taken from the CSSA O-1 site. However, it was observed that oxalic acid can form a hard calcium oxalate precipitate which can increase soil resistance and was therefore not considered to be compatible with the electrokinetic soil processing. Table 4 summarizes the results of testing the soil swelling. The swelling was determined by measuring the change in volume of the soil occupying the testing vial. The same result was obtained when testing was performed in the field at CSSA O-1 site.

The results suggested that an ideal leachant for soil at CSSA O-1 site should be prepared by mixing an acid (at lower concentrations) which does not cause swelling of the soil and citric acid (at higher concentrations) which will serve as chromium complexing agent. This mixture can entirely reduce soil swelling and provide an efficient chromium removal. Table 4 shows that the presence of only 4.6 % of hydrochloric acid in the mixture with 20 % citric acid did not cause swelling of soil.

The above test determined that hydrochloric acid should be used in combination with citric acid as a mixed conditioning solution for the soil at CSSA O-1 site. This solution provided solubilization of heavy metal as well as calcium salts and was environmentally acceptable because addition of chlorides to the soil is not harmful compared to addition of nitrates (nitric acid) to the soil.

Table 4. Swelling of CSSA O-1 soil samples in contact with different acids.

Concentration of acids in the leachate	Soil swelling (Yes/No)
40 % citric	YES
20 % citric + 18.5 hydrochloric	NO
20 % citric + 9.2 % hydrochloric	NO
20 % citric + 4.6 % hydrochloric	NO
15 % citric + 9.2 % hydrochloric	NO
10 % citric + 9.2 % hydrochloric	NO
5 % citric + 9.2 % hydrochloric	NO
50 % formic	NO
50 % formic + 18.5 % hydrochloric	NO
25 % formic + 9.2 % hydrochloric	NO
12.5 % formic + 4.6 % hydrochloric	NO
10 % formic	NO

6. Electrokinetic Removal of Chromium from CSSA O-1 Soil

Electrokinetic experiments were performed in the soil test bed described in the Experimental Section. Homogenized soil taken from the CSSA O-1 site was used in the experiments. Starting concentration of chromium in the soil was 630 ppm. Pulsed voltage was applied to the soil with On/OFF periods equal to 20s/2s. Voltage amplitude was regulated and was in the range 50 - 150 V. The current changed during the experiment and was in the range between 0.2 A - 1.1 A. As chemical changes occurred in the soil, e.g., acidification of soil, moisture changes, the voltage amplitude was increased or reduced to keep the current between 0.4 and 1.0 A. This current range provided an optimum operation of the electrokinetic process and did not cause overheating of the electrode wells.

The pH in the cathode well was controlled by addition of citric acid. A mixture of citric acid and oxalic acid was added at the beginning of the test (during the first week of the run) but it was found that this caused a precipitation of calcium oxalate, a hard precipitate which had to be removed from the cathode well. After cleaning of the cathode well only citric acid was added to

the cathode well. The experiment was monitored by taking soil core samples at five locations between the electrode wells. Samples were taken after each week of continuous process operation. Soil core samples were analyzed for chromium, moisture content and pH.

The changes in soil pH between the electrode wells indicated the advancement of the acid front from the anode toward the cathode and acidification of the soil during the process.

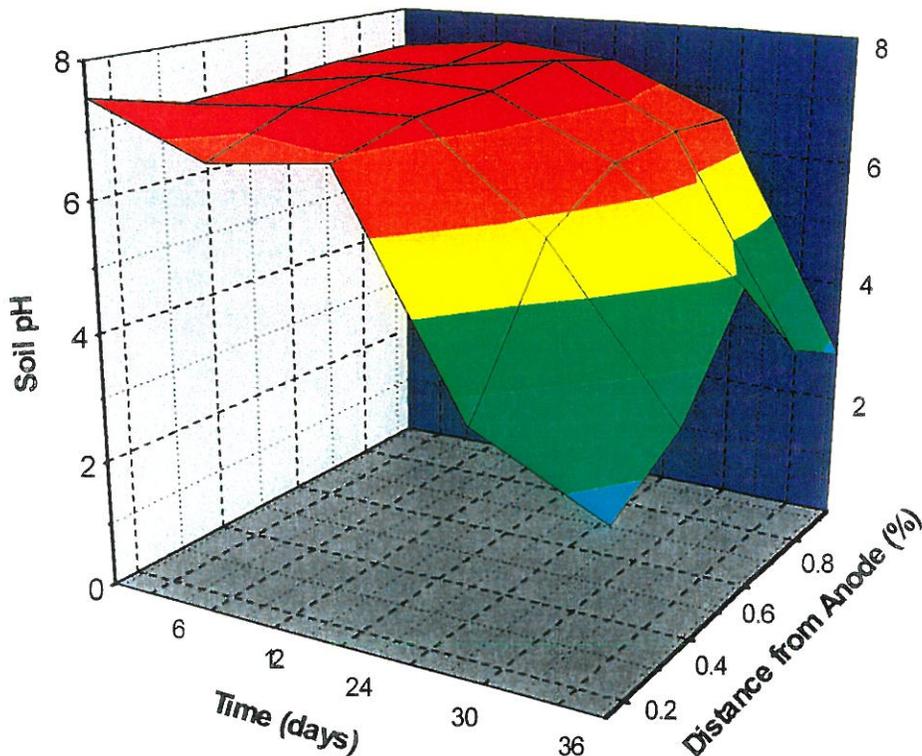


Figure 8. Changes in soil pH during the electrokinetic treatment in the soil bed between the electrodes.

Figure 8 shows changes in soil pH throughout the soil during the entire electrokinetic treatment of soil. Two percent citric acid was added to the cathode well during first 19 days of treatment. The 3 D graph in Figure 8 shows that pH of soil was not changed significantly within that period. Therefore, from day 19, more concentrated citric (40 %) was added to both anode and cathode wells. The electroosmotic flow from the anode toward the cathode helped in distribution of citric acid in soil. Batch experiments have shown that to achieve removal of chromium contaminant from soil, the soil pH had to be lowered. To speed up the soil acidification, citric acid was injected in the soil between the wells. The effect of soil acidification is obvious after 3 weeks of operation (cf., Fig. 8). The soil pH achieved after ca five weeks of continuous treatment was 2 - 3 throughout the soil.

The electroosmotic flow rate in the cell was in the range between 200 - 1,000 ml per day. As the process and soil acidification progressed, the electroosmotic flow decreased and the consumption of the acid at the anode decreased. It finally ceased after ca 25 days. This was expected because the soil acidification decreased the negative charge on soil causing the electroosmotic flow from the anode toward the cathode to decrease due to a decrease in the

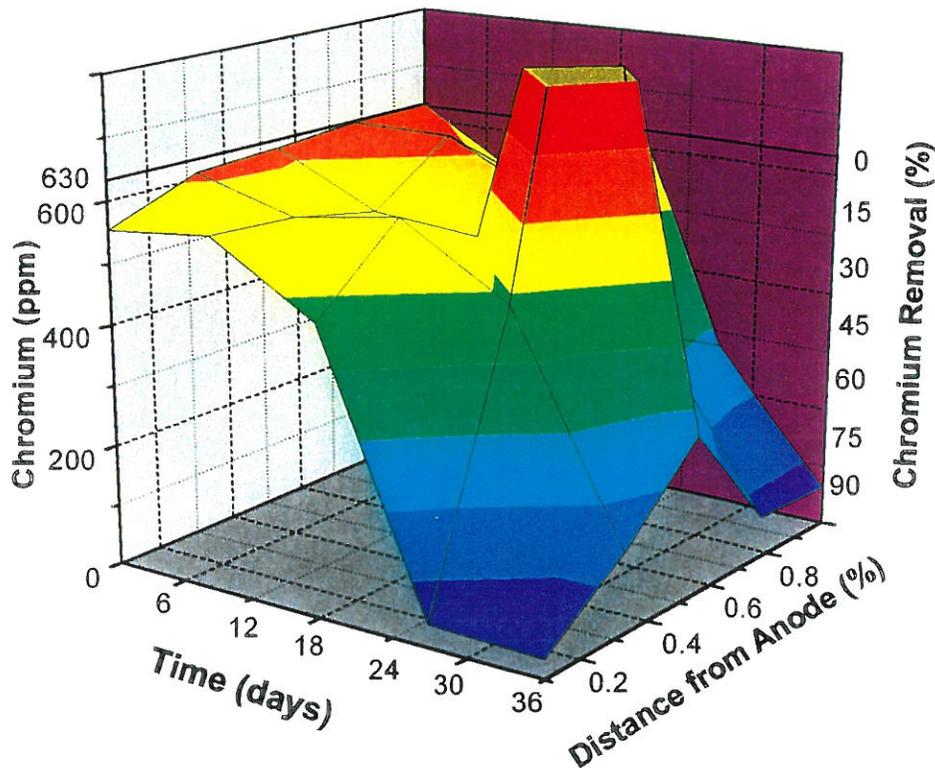


Figure 9. Removal of chromium from soil between the electrodes during the electrokinetic treatment in the soil bed.

ζ -potential on soil particles. The cessation of the electroosmotic flow after acidification of the soil is *beneficial for chromium removal* because chromium is in the anionic form and moves toward the anode, i.e., in the opposite direction of the electroosmotic flow. Thus, the electroosmotic flow from the anode toward the cathode slows down the chromium removal.

Figure 9 shows removal of chromium contaminant from the CSSA O-1 soil during the entire electrokinetic treatment. Comparing Figure 8, the changes in soil pH and Figure 9, removal of chromium, it is clear that very little chromium was removed from soil within first two weeks when pH of soil was close to neutral. Acidification of soil and distribution of citric acid, a chromium complexing agent, facilitated chromium solubilization, transport and removal from soil.

Chromium movement started after 21 days of the treatment and chromium was accumulated toward the center of the soil bed, exceeding the starting (630 ppm) concentration of chromium in the middle of the soil bed (maximum was 1359 ppm, cf., Fig. 9). This presents an expected pattern of chromium movement throughout the soil. The chromium further moved toward the anode, and after 36 days of the electrokinetic treatment the total removal was in the range between 60 % (in the center of the bed) and 94 % (near the electrode wells).

After the treatment, the soil was sectioned in three portions, soil near the anode, middle of the cell, and soil near the cathode. Each soil sample was homogenized and analyzed to determine total amount of chromium remaining in soil. Figure 10 clearly demonstrates **highly efficient removal of chromium from CSSA O-1 soil**. In 1/3 portion of soil near the cathode, 99.8% removal was achieved. In the middle of the cell, the removal was 84%. Slightly lower removal (64%) near the anode indicated that chromium was transported and accumulated toward the anode. However, it is expected that with prolonged treatment, removal of chromium below target chromium concentrations could be achieved. The movement and accumulation of chromium toward the anode well indicated that chromium was in soil in the **anionic form**. Its movement in the soil toward the positive anode was entirely controlled by electromigration and dielectrophoresis.

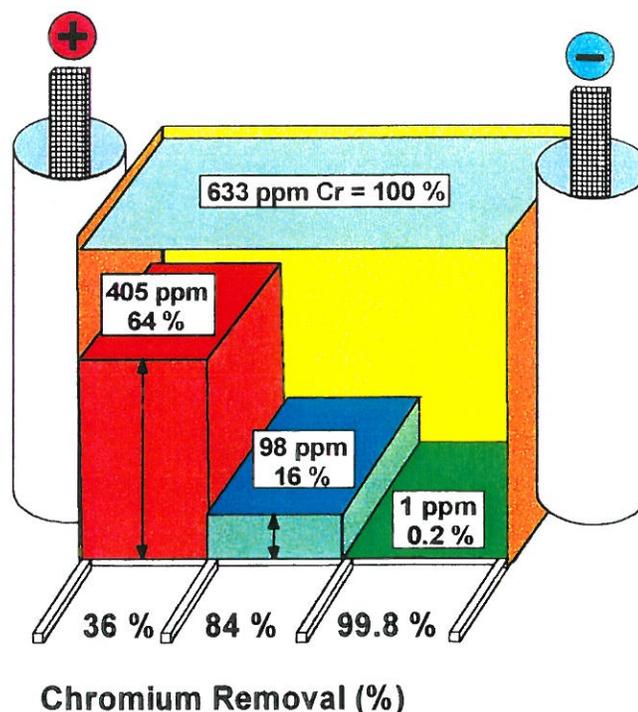


Figure 10. Removal of chromium in the soil test bed after 36 days of electrokinetic treatment. Starting chromium concentration was 633 ppm in uniformly homogenized soil taken from CSSA O-1 site.

B. Field Scale Treatability Study

1. Process Operation and Monitoring

A relatively low voltage had to be applied to the field to achieve reasonable working currents in the electrode wells. Total voltage applied to the field was 14.0 V and current per anode was in the range between 2.5-3.0 A and at the cathodes 8-10 A. This yielded total current to the field of 18-20 A. Current and voltage applied were very stable and stayed within these limits during the entire process operation. Pulsing regime applied was: on/off=20 s/5s. The process was turned on August 15, 1997 and was shut down on December 23, 1997. The total operation time was three months (89 days). The energy consumption during this period was on average 6,048 Wh per day (15.5 A x 14 V x 24 h). This yields the total energy consumed during the process operation of 538.2 kWh (6.048 kWh x 89 days).

The base produced electrochemically in the cathodes was neutralized by addition of a mixture of citric acid and hydrochloric acid. In the first month of operation a mixture of ca 4-5 % hydrochloric and 10 % citric acid was used as soil conditioning solution. Based on the finding from the bench scale study, soil acidification was most critical step in treatment of soil at CSSA O-1, containing high limestone content. To accelerate this process, the concentration of citric acid was reduced in the mixture to ca 4-5 % and hydrochloric acid was used at 10 - 15 %. This solution was used throughout entire field test. The soil conditioning solution was added as well to the anode wells. The addition to the cathode wells was based on the pH control in the cathodes, and conditioning solution was added whenever pH exceeded a preset value (pH = 2-3). In the anode wells, the addition of the conditioning solution was based on the low liquid level sensor mounted in the wells. The electrochemically produced acid in the anodes contributed to the overall acidification of the soil.

To further expedite the soil acidification, additional injection wells were mounted between the electrode wells. Both horizontal and vertical injection wells were installed. The acid to these wells was added through a solenoid valve with the flow rate adjusted to the soil hydraulic permeability. The location and distribution of these wells is shown in Figure 11.

Table 5 shows consumption of citric acid and hydrochloric acid for during each month of operation.

Table 5. Consumption of chemicals in the electrokinetic treatment of soil at CSSA O-1.

Time Period (months)	Citric acid (Lb)	Hydrochloric acid (31%) (Gallons)
3	3,300	1,210

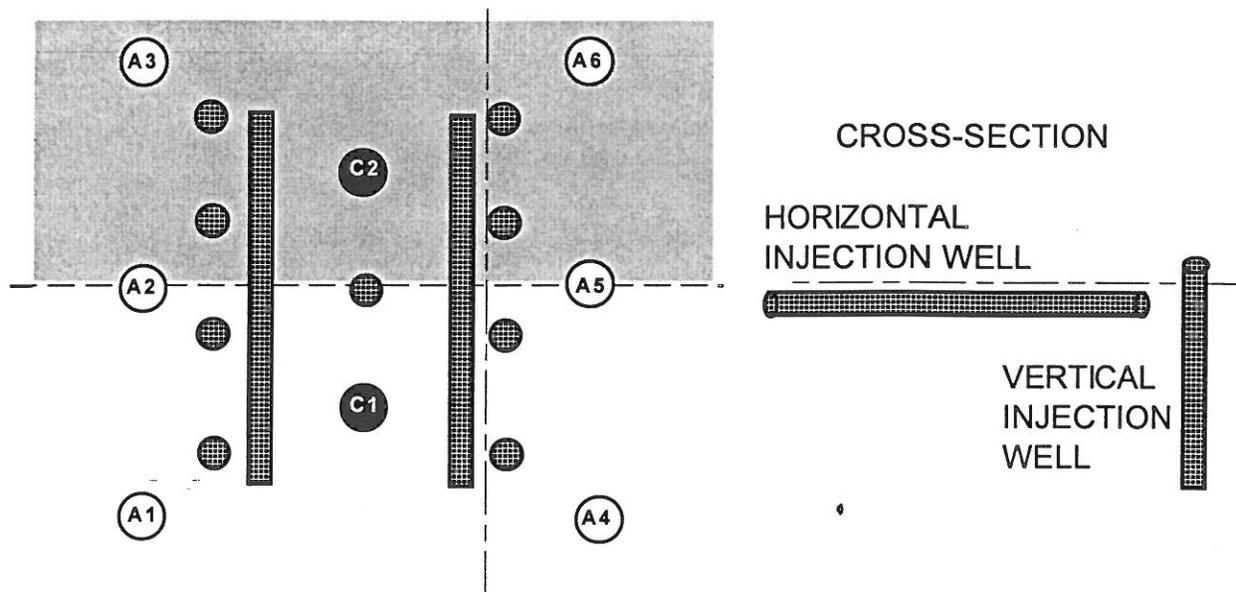


Figure 11. Position and distribution of injection wells for injecting soil-conditioning solution.

2. Chromium Contaminant Transport and Removal from Soil

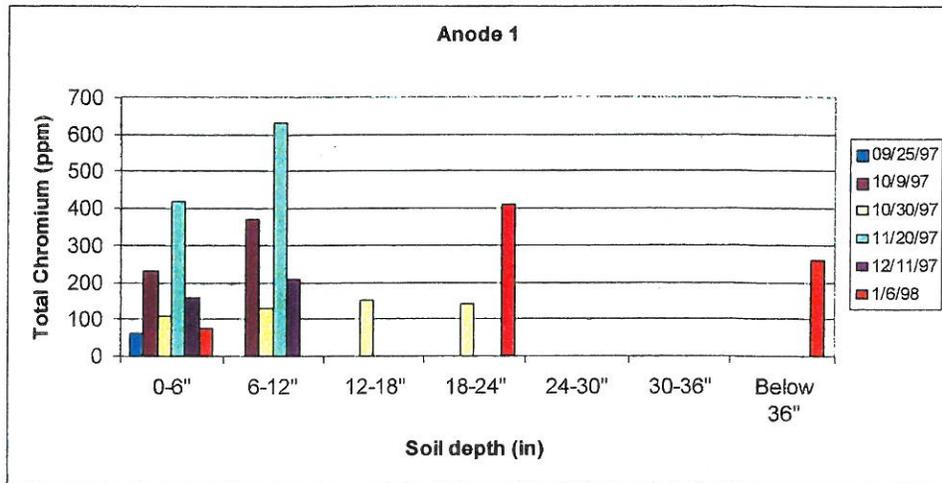
Core samples were taken from the site in accordance with the sampling plan shown in Figure 3. In the preliminary investigation of the samples taken from the site, it was determined that the contamination at the site is very heterogeneous, both laterally and vertically (in depth). To minimize the error during the core sampling and to establish proper monitoring of the process, Lynntech, Inc. adopted a methodology, which is based on sampling process "control zones". Two such control zones (profiles) were chosen between: (i) cathode well – middle point – anode well 6, and (ii) cathode well 1 – middle point – anode well 1. In addition, core samples were taken in the vicinity of each well during each sampling period (ca 1 ft from the well). The core samples are taken every three weeks of operation in close proximity to the initial sampling locations, as shown in Figure 3. This sampling pattern allows monitoring changes in chromium in time and in space at several sampling points. The method provides an accurate determination of the transport of contaminants in soil. Because the contaminants can accumulate during the process at certain locations in soil, e.g., near the wells, and can exceed the initial concentration at that location, it is extremely important to understand the trends of movement of contaminants in soil. They can move toward the anodes or toward the cathodes depending on their charge in soil. Frequent soil sampling, as the one implemented in this projected (every 20-22 days), provides a tool for monitoring the dynamic of the process and basis for predicting the duration of the process.

Figure 12 consists of 10 graphs, which summarize the results of chromium analysis performed on soil core samples taken during the process operation. The data at the end of the process were obtained by sampling the trenches excavated on January 6, 1997, as shown in Figure 3. The data are grouped in the graph for each particular depth, e.g., 0-6", 6-12" ..., and changes in chromium in time are shown for a particular depth. The samples were measured so that the core samples were sliced in half-foot sections and homogenized. Tables of raw analytical data for chromium results in the field are given in Appendix I.

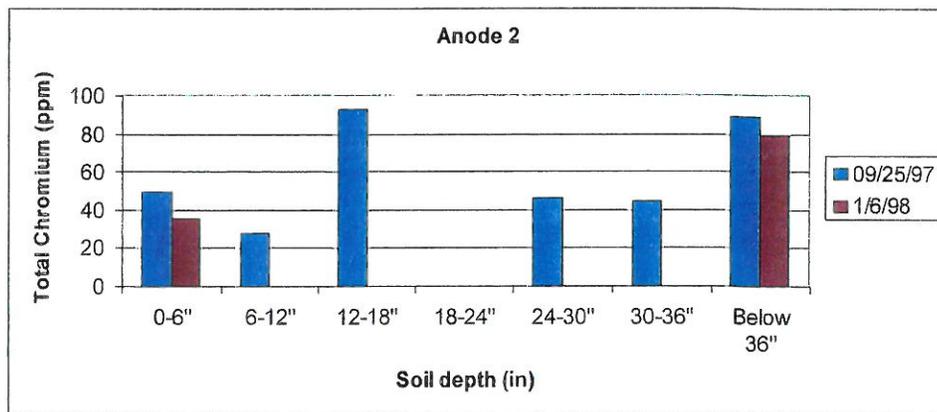
Results show that the starting chromium concentration was higher deeper in soil, particularly at 3 feet and below (cf., anode wells 1,2,4,6 and middle points) compared to the surface contamination. It seems that the chromium concentration at these depths was not much affected by the process, because the chromium level remained relatively high after the process at several sampling points (particularly trench samples). The pH of deep soil samples showed no significant acidification of soil below 3-4 feet. Most of the samples had a pH in the range between 6.0-7.5. (Starting soil pH was 7.5 – 8.5). Based on the bench scale study, if no efficient acidification of soil was established, removal of chromium from CSSA O-1 soil will be minimal (cf., Fig. 8 and 9). It seems that the acid produced electrochemically and transported electrokinetically through the soil was not enough to acidify the soil at 3-4 feet depth. The acid injected through the injection wells did not reach 4 ft during the process operation. From another point of view, this result shows that there is no concern that the contaminants were potentially mobilized below the limestone bedrock, underlying the treatment area at the depth of 3-4 ft.

Because most core samples were successfully taken at the depth from 0-24 inches, a detailed analysis of chromium transport and removal is given below for that region.

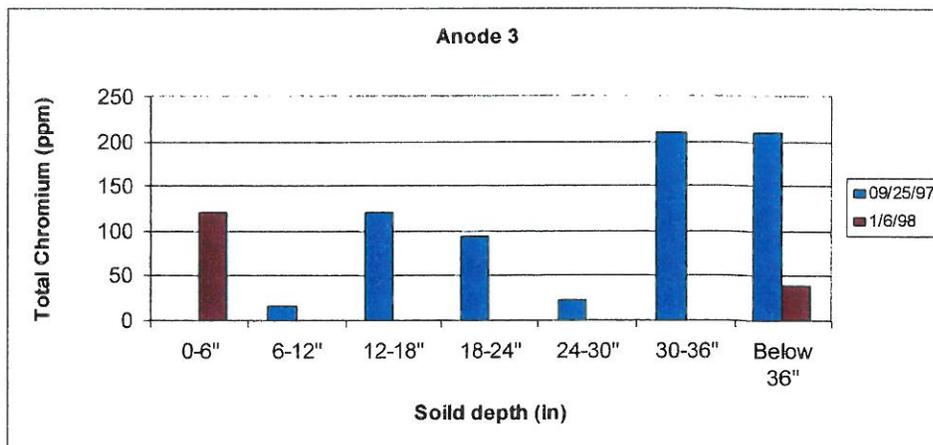
Three dimensional graphs (3D) were produced from the data obtained from cores taken between the two control zones (profiles) at different time intervals (sampling events). On the x-axes the process time is plotted, and on y-axes the data are given for samples taken at different locations along the profile or at certain distance from the cathode. Corresponding chromium concentrations are given on the z-axes. Thus, these graphs allow determination of temporal and spatial changes in contaminant concentration in soil. A comparison between 3D graphs obtained for the layer 0-6" (cf., Figure 13) and 6-12" (Figure 14) along the profile cathode 1 – anode 1 clearly shows same trends in chromium removal from soil. Thus, at both depths, high chromium spot, visible at the beginning of the process, approximately in the middle between the electrodes, disappeared, indicating an efficient removal of chromium. Both graphs demonstrate that chromium accumulated toward both the anode and cathode after ca 1.5 months of operation and chromium concentration in the middle of the treatment area significantly decreased. This points out that chromium was most probably transported by electromigration toward the anode and by dielectrophoresis and electroosmosis toward the cathode. Approaching the end of the process, chromium removal was highest near the anode 1.



(a)

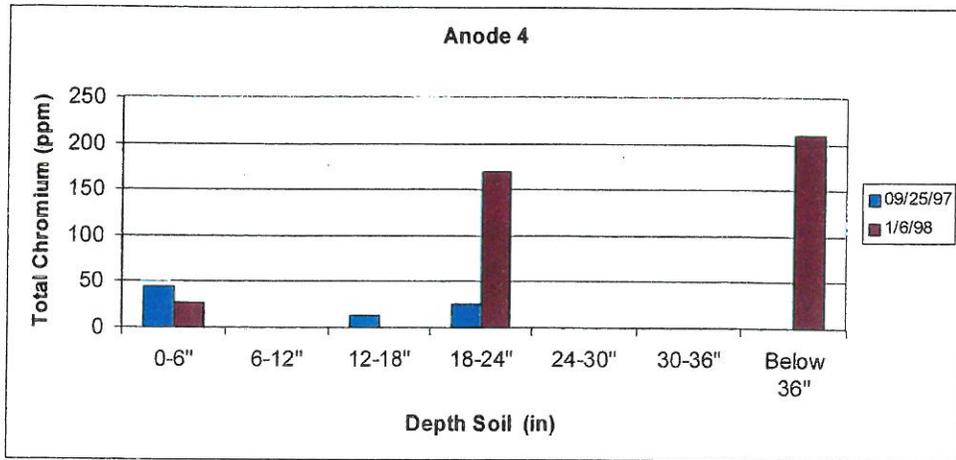


(b)

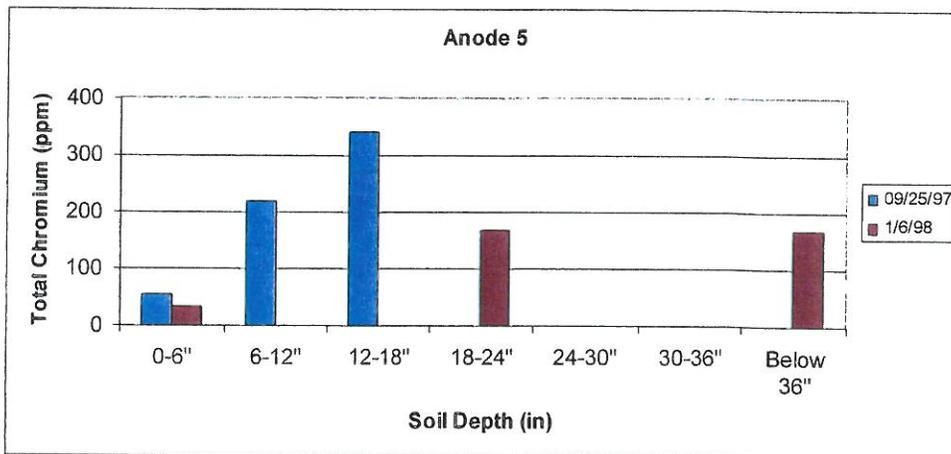


(c)

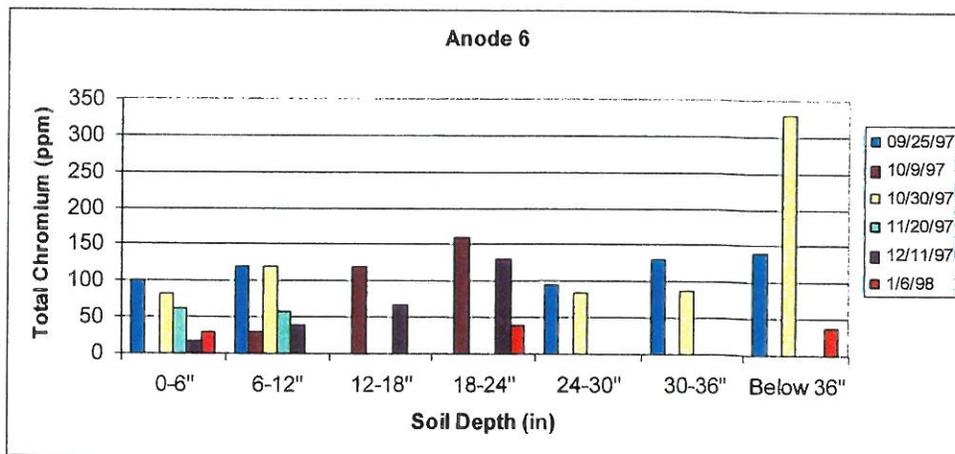
Figure 12. Summary of chromium analysis of core samples taken during the course of electrokinetic soil remediation at CSSA O-1 site at different depth.



(d)

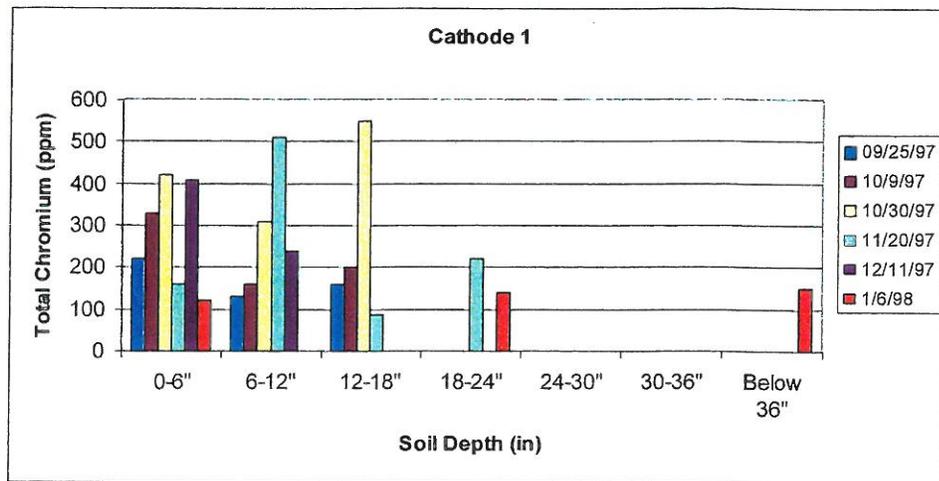


(e)

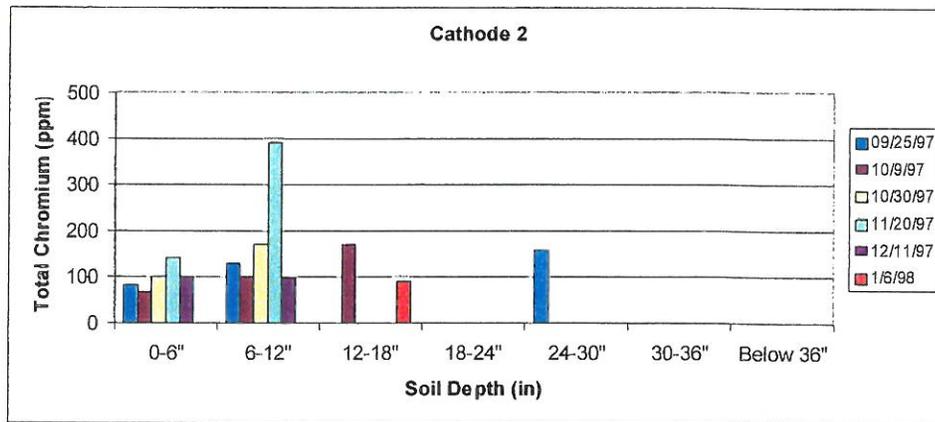


(f)

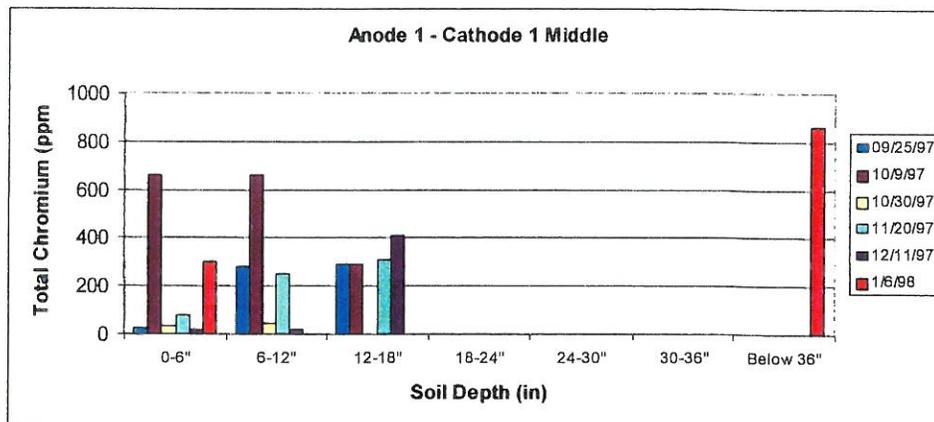
Figure 12. Continuation.



(g)

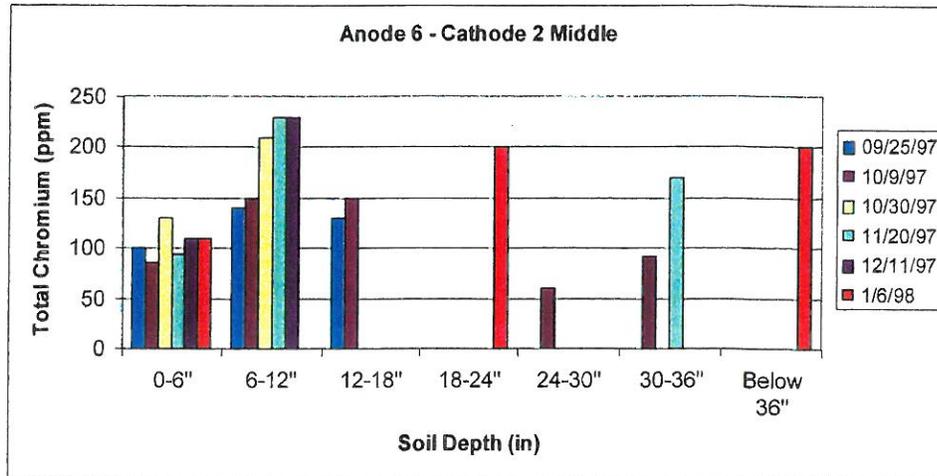


(h)



(i)

Figure 12. Continuation.



(j)

Figure 12. Conclusion.

3. Correlation Between Chromium Removal and Soil Acidification

Figure 15 shows pH values corresponding to chromium data obtained for samples taken at 0-6" depth. Comparing the pH changes (cf., Fig. 15) and chromium concentration (cf., Fig. 13), a clear correlation between pH and chromium removal was obtained. The 3D graphs demonstrate that the soil was most successfully acidified near the anode (down to pH 2-3) where an electrochemically produced acid entered the soil in addition to the acid injected through the electrode wells. At these locations an efficient chromium removal was obtained.

Comparison of figures 16 and 17 demonstrate the same type of correlation between pH and chromium removal for the second profile taken as process control zone between the anode well 6 and cathode well 2. The changes in pH (cf., Fig. 17) near the anode in time closely follow the changes in chromium removal in the vicinity of that electrode (cf., Fig 16). The pH was slowly decreasing during the process and a decrease in concentration of chromium in that region demonstrates the dependence of chromium removal on soil acidification. The pH in the middle between the anode 6 and cathode 2 and toward the cathode 2 remained mostly unchanged, ca 6-7.5. In that region no significant chromium removal was obtained. Two maxima in chromium concentration could indicate some dielectrophoretic concentration of chromium toward the cathode.

Figure 18 clearly depicts the correlation between soil acidity and chromium concentration in the vicinity of the anode 6. The comparison is shown for two depths (cf., Fig 18a and 18b), where an almost linear dependence of chromium removal on soil pH was obtained (cf., Fig 19.).

Table 6 shows average percentages of removal of chromium for different regions within the test area. The average removal was calculated by comparing the initial value of chromium (September 25, 1997) with the value obtained for samples taken at the end of the process (January 6, 1997). The averaging was performed for all the points considered being equivalent in terms of the electric field strength, e.g., near anodes, near cathodes and in the middle of the area between the electrode wells.

Table 6. Average percentage removal of chromium within the CSSA O-1 area after three months of the electrokinetic treatment.

Soil Region	Average Removal of Chromium %
Near Anodes	34
Middle Region Between Anodes and Cathodes	No measurable removal was obtained
Near Cathodes	13

The concentration of chromium found in the electrode wells and effluent was in the range between 10 – 1,000 ppm. This indicated that most of chromium was concentrated on the packing material of the electrode wells. Packing material surrounding each well was analyzed and chromium was indeed found in all packing including all the anode and cathode wells. The chromium concentration ranged from 10 – 30 ppm. This indicated that chromium was concentrated during the process at the well walls as expected.

C. Process Cost Estimates

Most of the published estimates for *energy expenditure* during the electrokinetic soil processing are based on laboratory estimates for model soils and not for natural contaminated soils. Estimated energy costs for the electrokinetic soil remediation using DC electric fields applied are in the range of \$20-30 per ton of soil. The electrokinetic process used in this project utilizes pulsed electric field with ON/OFF periods of 15-20 s/3-5 s which can bring an overall savings in energy expenditure of 25 % compared to DC based electrokinetic processes. In previous studies it was found that the application of pulsed electric fields, utilizing both DC and AC electrokinetic phenomena in soil, can bring up to 20-30% faster removal compared to DC electrokinetics. Any improvement in removal of the contaminants from soil by electrokinetics means shorter time of process operation and consequently lower energy and overall costs.

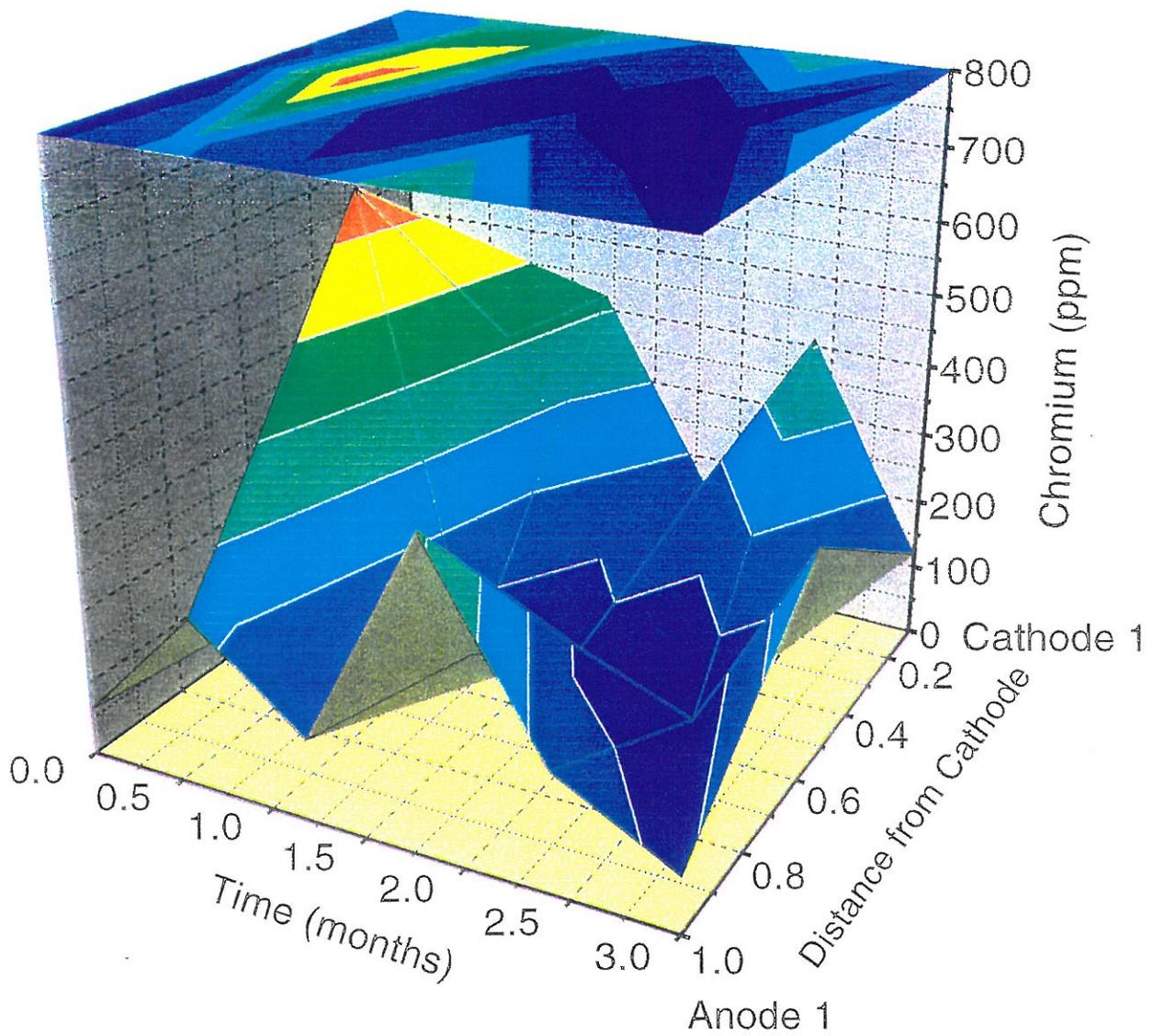


Figure 13. Temporal and spatial changes in chromium concentration between anode 1 and cathode 1. Depth: 0-6 inches.

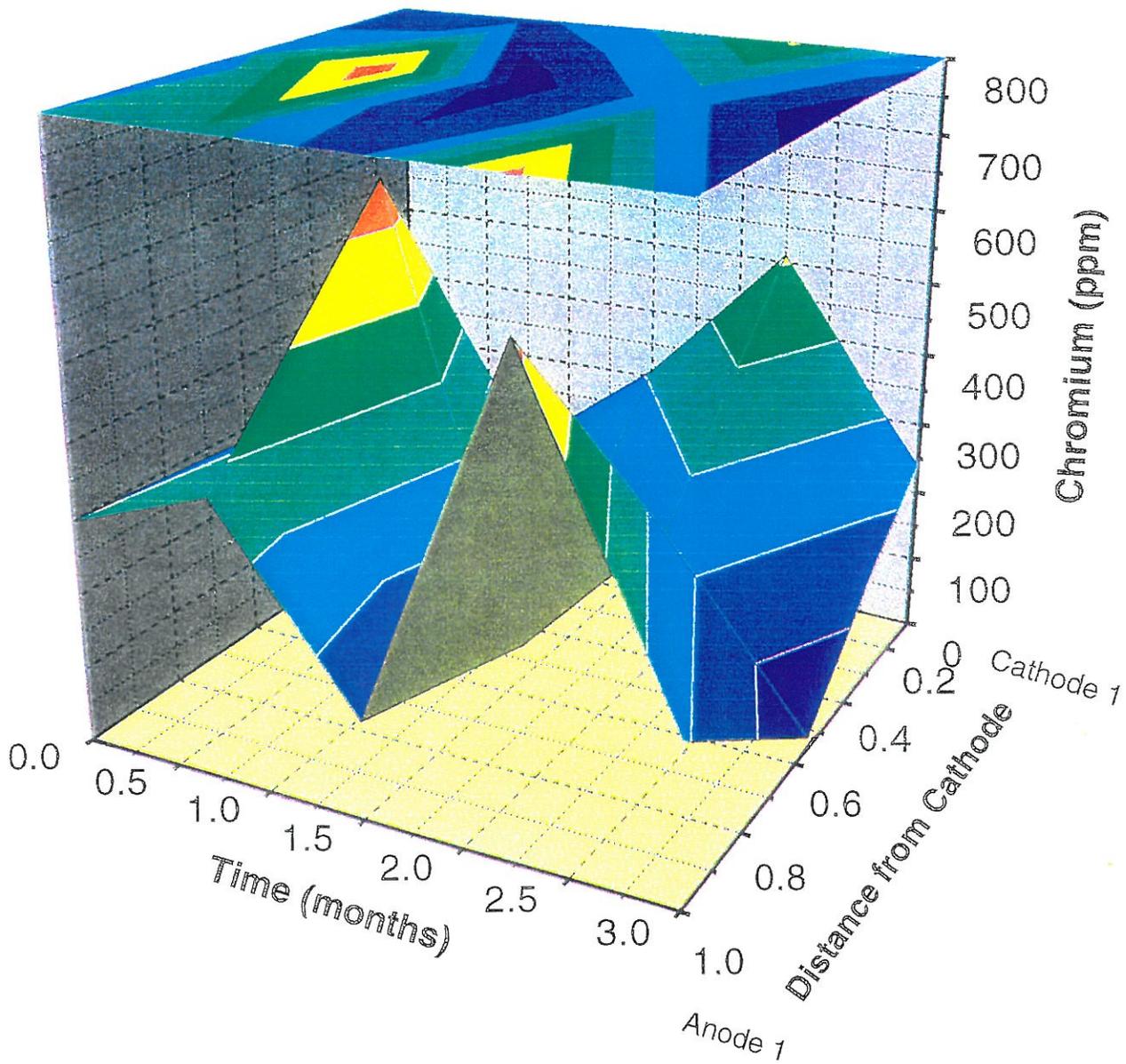


Figure 14. Temporal and spatial changes in chromium concentration between anode 1 and cathode 1. Depth: 6-12 inches.

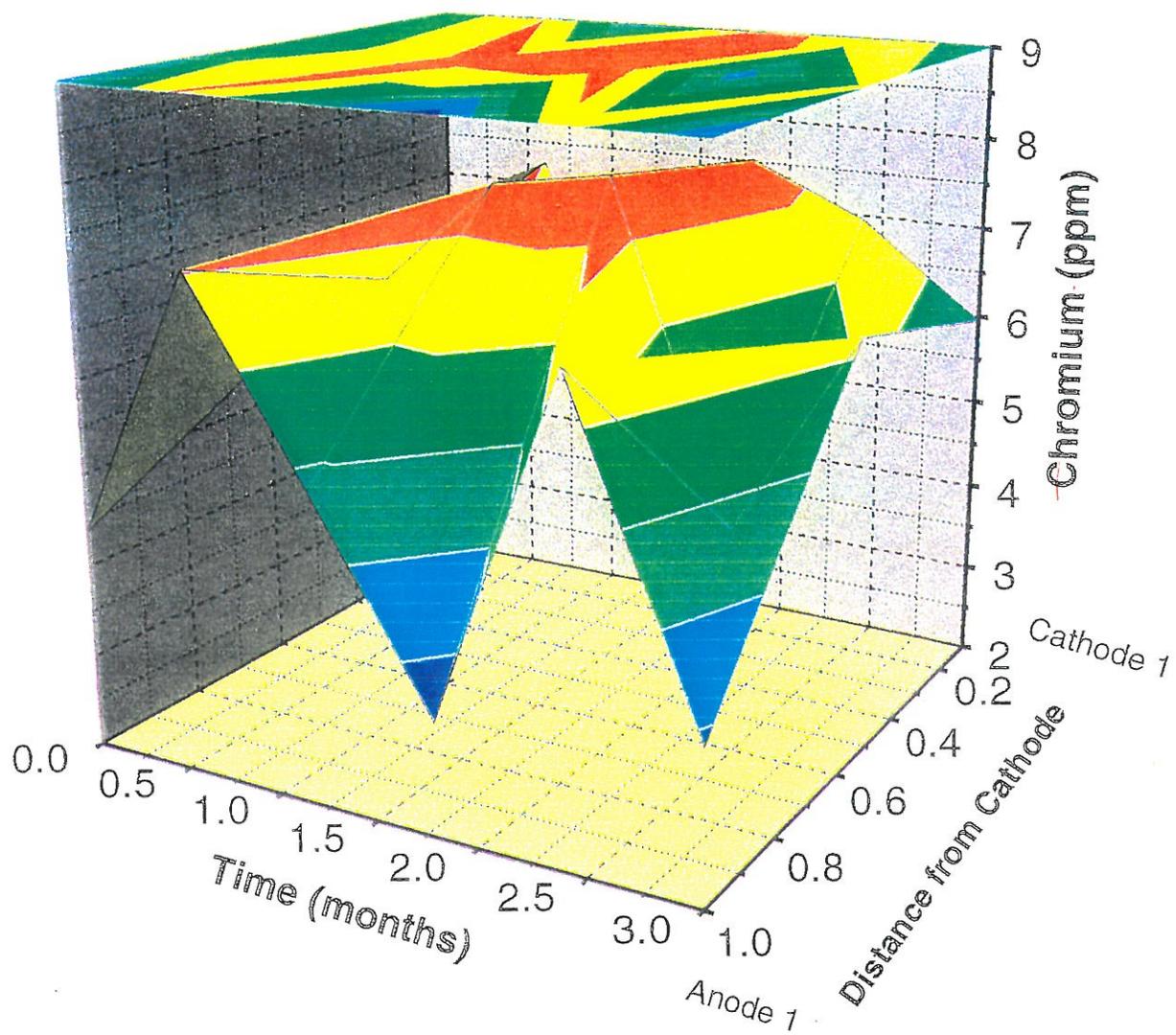


Figure 15. Temporal and spatial changes in soil pH between anode 1 and cathode 1.
Depth: 0-6 inches.

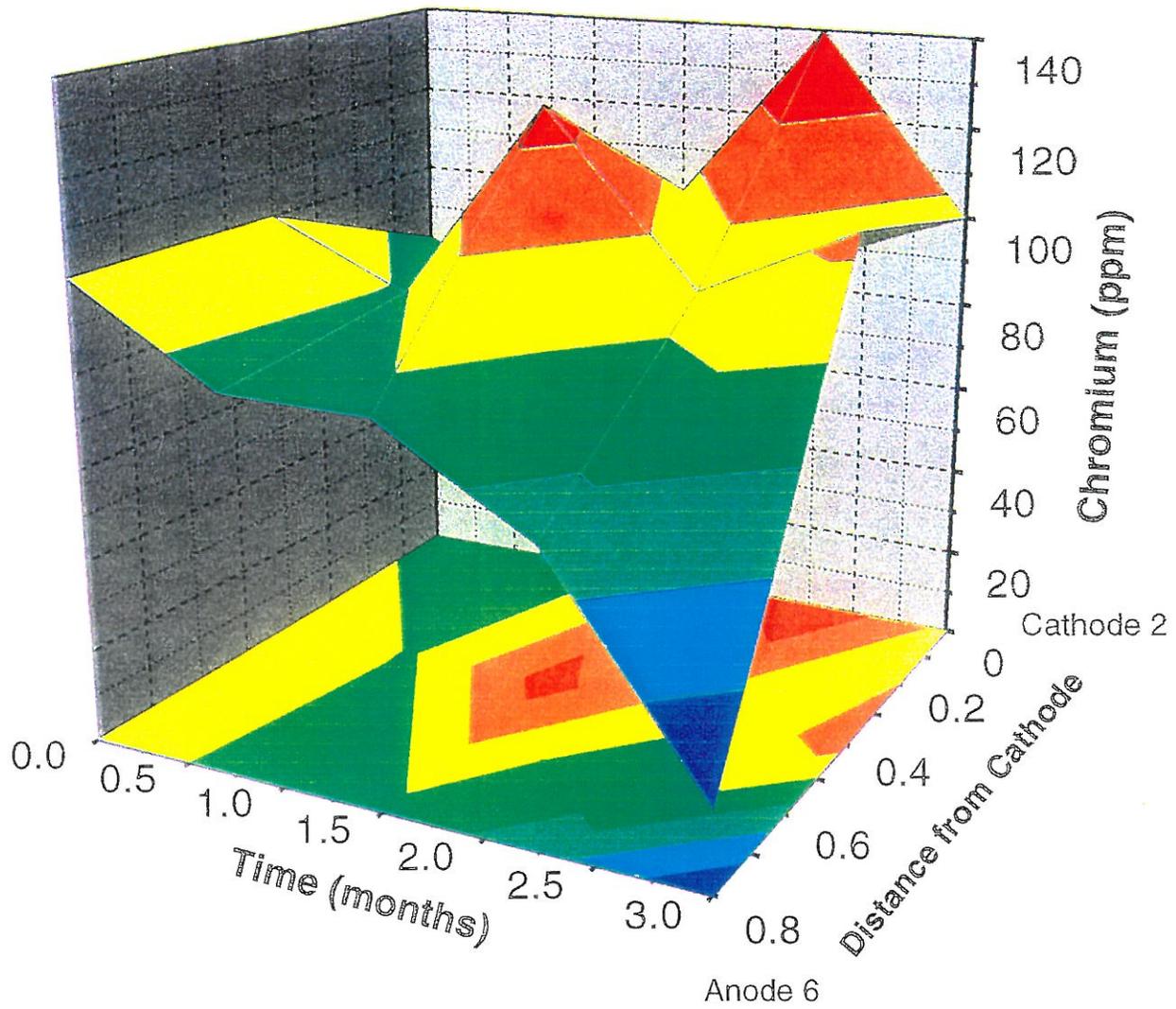


Figure 16. Temporal and spatial changes in chromium concentration between cathode 2 and anode 6.
Depth: 0-6 inches.

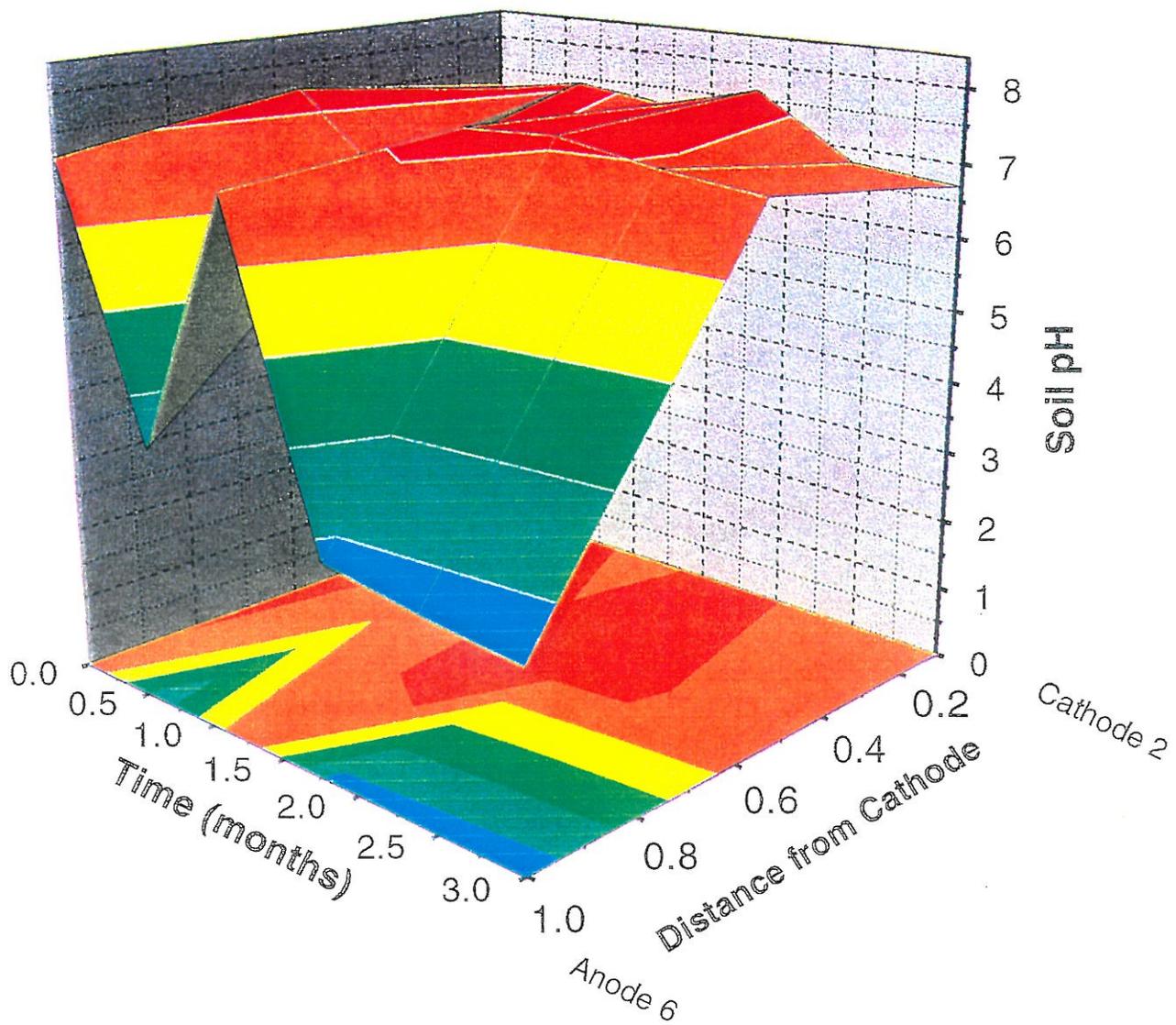


Figure 17. Temporal and spatial changes in pH between cathode 2 and anode 6. Depth: 0-6 inches.

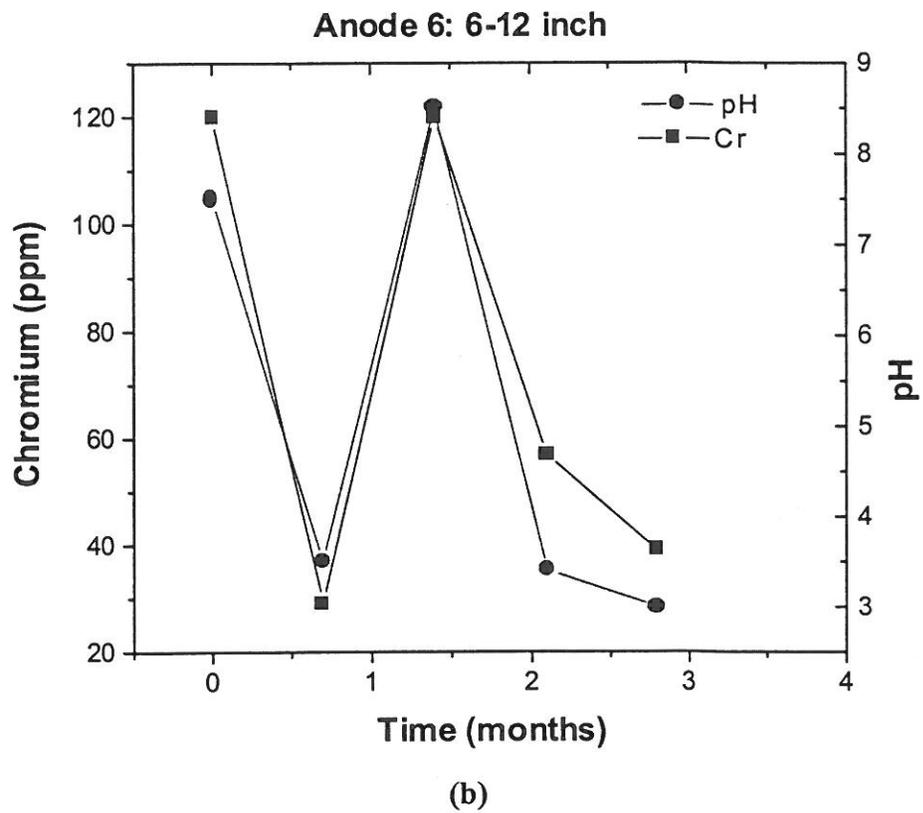
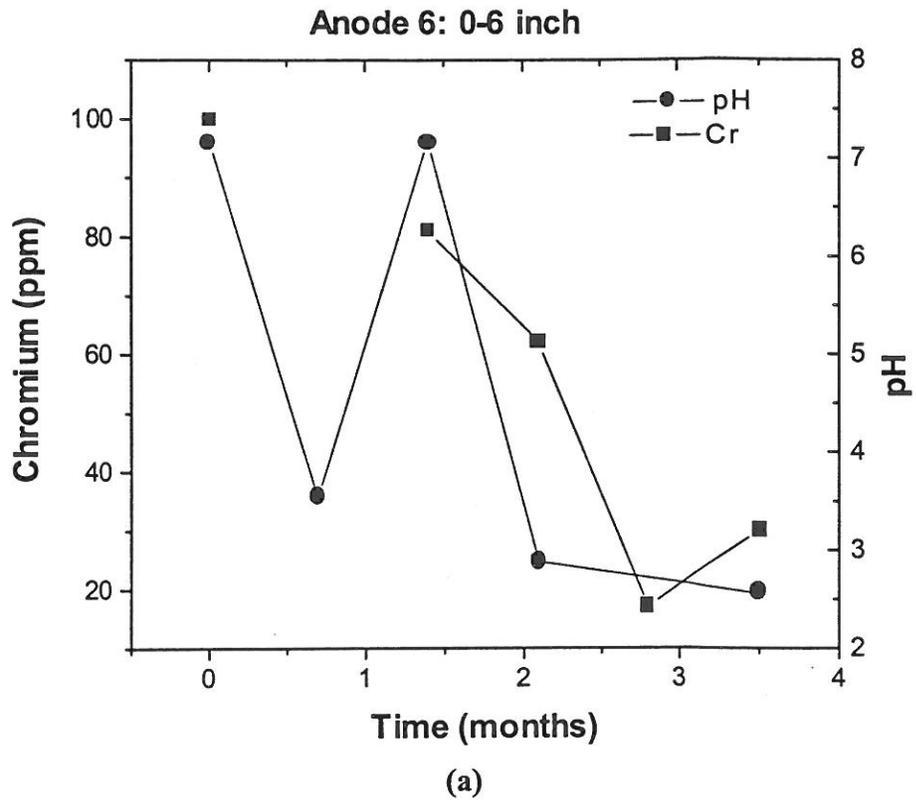


Figure 18. Correlation between pH and chromium removal in soil in the vicinity of the anode 6 at two different depth: (a) 0-6 inches, and (b) 6-12 inches.

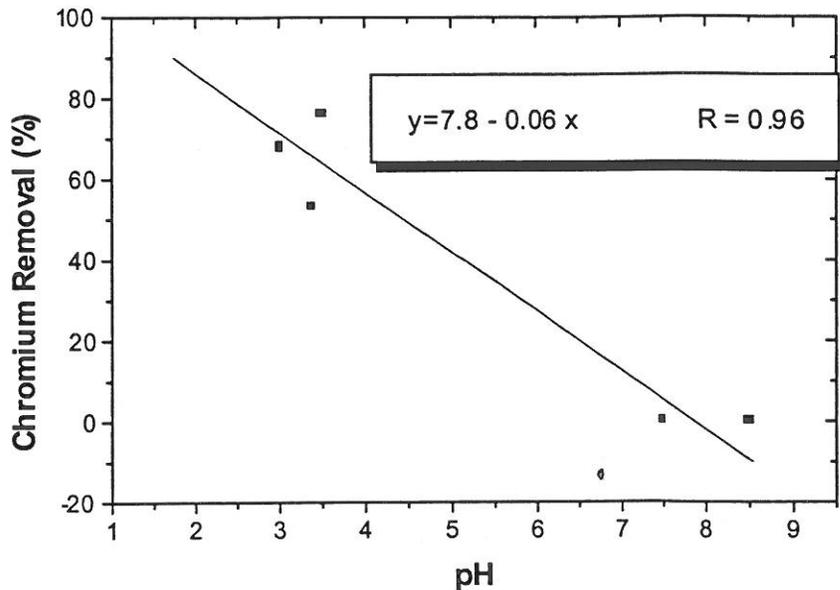


Figure 19. A linear correlation between pH and chromium removal in soil calculated from Figure 17 b.

Operating Costs

The total operating cost calculated here is based on the energy consumption during three months of the process operation and cost for chemicals used in the process.

Energy cost:

Total energy consumption: 538 kWh (cf., Section IV B).

Estimated soil volume treated: $6 \text{ ft} \times 7 \text{ ft} \times 4 \text{ ft} = 168 \text{ ft}^3 \times 0.0283 \text{ m}^3/\text{ft}^3 = 4.7 \text{ m}^3$

Taking bulk density of soil of 1.85 g/cm^3 (and assuming 30 % porosity):

Total mass of soil treated: 8.69 t.

Energy consumption per tone of soil:

$$538 \text{ kWh}/8.7 \text{ t} = 61.8 \text{ kWh/t}$$

Assuming the energy cost of $\$0.1/\text{kWh}$, total energy cost per tone of soil was $\$6$.

Chemicals cost:

Total amount of citric acid added: 3,300 Lb (60 bags x 55 Lb). (For chemicals consumption see Section IV B).

Citric acid cost: 60 bags x \$46/bag = \$2,760.

Total amount of hydrochloric acid used: 1,210 Gallons (22 drums x 55 Gallons).

Hydrochloric acid cost: 22 drums x \$66/drum = \$1,452.

Total cost for chemicals: \$4,212.

Chemicals cost per tone of soil: \$4,212/8.69 t = \$484/t.

Total operation cost per tone of soil (chemicals + energy): \$484 + \$6 = \$490/t

The above estimate shows that the energy cost was only 2.1 % of the total operation cost. The operation cost of \$490 per tone of soil was entirely affected by large amount of chemicals used to acidify the soil. This cost is still not as high as the cost for excavation and incineration of soil (typically \$1,000 – \$1,500 per tone of soil). However, taking into account low removal efficiency achieved at the CSSA O-1 site, and eventual need to extend the process operation for longer periods of time, this high cost is prohibitive for efficient operation of in situ electrokinetic soil processing at this site. A high consumption of acids was due to a high limestone content. If larger rocks were separated from the soil, the consumption of acid will be drastically minimized and the process could turn to be economical. This suggests that an on-site electrokinetic treatment of soil in a container (dumpster) may be a feasible approach for the site remediation. In this way, the larger rocks, a source of limestone, could be separated before transfer of soil to the process vessel, and process operated with minimized consumption of acid. Such a process will be comparable to an on-site soil washing, however it will be significantly enhanced by the electrokinetic contaminant and reagent transport through the soil.

V. Conclusions and Recommendations

Based on the results of the bench scale and field scale treatability study performed, the following conclusions/recommendation for the at CSSA O-1 site were made:

1. The soil at the CSSA O-1 site showed a very high buffering capacity due to high limestone content. This required that a mixture of an inorganic acid, hydrochloric acid and an organic acid, citric acid be used as the soil conditioning solution which was added to the electrode and injection wells during the process operation. Hydrochloric acid was used to enhance the process of soil acidification and citric acid to enhance the solubility of heavy metal contaminants in soil. The electrokinetic distribution of this acid to the soil was performed in addition to the electrochemical acidification of the soil by the acid produced in the anode wells.
2. The efficiency of the electrokinetic removal of chromium, main contaminant at the site, obtained from the bench scale tests was extremely high. After 36 days of treatment, up to 99.8 % chromium was removed in one third of soil bed (near the cathode). The remaining concentration of chromium was 1 ppm, well below the target closure value of 39 ppm. The results demonstrated accumulation and transport of chromium in the direction of the anode, indicating that chromium was in the form of anions in the soil and was negatively charged. Chromium removal in the central region was 84 % and in the region near the anode was 64%. It is believed that with prolonged treatment, the removal below the regulatory limits could be achieved throughout the whole mass of soil. The bench scale results demonstrated a clear correlation between the acidity of soil achieved during the process and chromium removal. Efficient chromium removal could be obtained when the soil was acidified to ca pH =2 – 3.
3. Electrokinetic remediation at CSSA O-1 site was performed in a continuous three months field test. The field test results demonstrated much lower efficiency in chromium removal compared to bench scale tests. Chromium removal was entirely dependent on the efficiency of soil acidification. To enhance the acid distribution in soil, the acid conditioning solution was added to the anodes and cathodes wells as well as through a series of horizontal and vertical injection wells.
4. Because the contaminant distribution at the site was extremely heterogeneous, both laterally and vertically, a sampling method, which utilizes process “control zones”, was used to recognize the trends in the contaminant transport and/or removal from soil. This method involved frequent sampling at predetermined locations between the wells at regular time

intervals, every 20-22 days. Thus, it was possible to obtain temporal and spatial distribution of contaminants in soil during the process.

5. Using the method described in 4., a clear correlation between chromium removal and soil pH was verified and demonstrated to be valid for the field test. An almost linear dependence of chromium removal on soil pH was obtained. Highest chromium removal, 34 %, was obtained near the anodes where soil was acidified down to $\text{pH} = 2 - 4$. Only 13 % chromium was removed near the cathode. Removal of chromium near the cathode indicated that transport of negatively charged chromium in that region was exclusively by dielectrophoresis and electroosmosis.
6. Process cost estimate showed that the energy expenditure cost was very low, only \$6/t of soil. This cost was only 1-2% of the total cost, which was entirely dominated by the cost of chemicals used in the process. Total cost for the process operation was \$490 per ton of soil. This cost is too high considering that the process needed to be further prolonged to achieve removal goals of the project.
7. It is recommended that a potential on-site electrokinetic treatment of soil from CSSA O-1 site could be feasible if the soil is transferred into a container and treated within the container after the removal of large limestone rocks. It is believed that the large consumption of acid was due to the rocks present in soil which decomposition during the acidification contributed to the high consumption of chemicals. By removing larger size soil material, containing limestone, the on-site electrokinetic treatment in the container may be feasible and more efficient approach than applying simple soil washing process. This recommendation is supported by extremely low energy cost of the electrokinetic process in which mineral and organic acids are utilized as soil conditioning solutions.

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APPENDIX I

This Appendix I contains: (i) tables of raw analytical data for contaminant concentrations in the samples taken during the operation of the electrokinetic process in the field; (ii) two tables of the analysis of standard NIST reference soil samples performed by EnviroTech Mid-Atlantic Laboratories (Tables 3 and 4 in Appendix); (iii) a list of QA/QC control data for analytical measurements of metal concentration in the soil samples taken from the field; (iv) a letter from Buchanan Soil Mechanics laboratory where soil mechanical analyses were performed stating that the standard ASTM methods were used in the analysis of soil samples taken from CSSA 0-1.

The data presented in Tables of raw analytical data correspond to the locations sampled as marked in Figure 3 in the text. Labels A1 – A6 correspond to core samples taken in the vicinity (6-12”) of the anode wells, labels C1 and C2 correspond to the samples taken near the cathode wells and data labeled C2 – Mid – A6 correspond to the core samples taken in the middle portion of the soil along the profile cathode 2 and anode 6.

**SUMMARY OF ANALYTICAL DATA FOR CHROMIUM DETERMINATION
IN SAMPLES OBTAINED FROM CSSA 0-1 SITE DURING ELECTROKINETIC
TREATMENT PROCESS**

Data are given for each location, time of sampling and depth. Details for labeling are given in Figure 3.

A1 - A6 : core samples taken 6"-12" from the anode wells.

C1 and C2: core samples taken 6"-12" from the anode wells.

A6-Mid-C2: core samples taken in the middle portion of the soil along the profile anode 6 and cathode 2

A1-Mid-C1: core samples taken in the middle portion of the soil along the profile anode 1 and cathode 1.

Core samples are sliced into 1/2 ft sections and analyzed where enough samples was collected.

All data are given as total ppm Cr (mg/kg Cr).

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A1	09/25/97	63						
	10/9/97	230	370					
	10/30/97	110	130	150	140			
	11/20/97	420	630					
	12/11/97	160	210					
	1/6/98	75			410			260

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A2	09/25/97	50	28	93		46	45	89
	1/6/98	36						79

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A3	09/25/97		17	120	94	23	210	210
	1/6/98	120						38

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A4	09/25/97	44		14	26			
	1/6/98	27			170			210

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A5	09/25/97	55	220	340				
	1/6/98	34			170			170

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A6	09/25/97	100	120			95	130	140
	10/9/97		29	120	160			
	10/30/97	81	120			84	88	330
	11/20/97	62	57					
	12/11/97	17	39	67	130			
	1/6/98	30			39			37

**SUMMARY OF ANALYTICAL DATA FOR CHROMIUM DETERMINATION
IN SAMPLES OBTAINED FROM CSSA 0-1 SITE DURING ELECTROKINETIC
TREATMENT PROCESS - CONTINUATION.**

Data are given for each location, time of sampling and depth. Details for labeling are given in Figure 3.

A1 - A6 : core samples taken 6"-12" from the anode wells.

C1 and C2: core samples taken 6"-12" from the anode wells.

A6-Mid-C2: core samples taken in the middle portion of the soil along the profile anode 6 and cathode 2

A1-Mid-C1: core samples taken in the middle portion of the soil along the profile anode 1 and cathode 1.

Core samples are sliced into 1/2 ft sections and analyzed where enough samples was collected.

All data are given as total ppm Cr (mg/kg Cr).

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
C1	09/25/97	220	130	160				
	10/9/97	330	160	200				
	10/30/97	420	310	550				
	11/20/97	160	510	87	220			
	12/11/97	410	240					
	1/6/98	120			140			150

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
C2	09/25/97	82	130			160		
	10/9/97	68	100	170				
	10/30/97	100	170					
	11/20/97	140	390					
	12/11/97	100	97					
	1/6/98			92				

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A6-C2 Mid	09/25/97	100	140	130				
	10/9/97	86	150	150		60	92	
	10/30/97	130	210					
	11/20/97	94	230				170	
	DUPLICATE 11/20/97	110	270					
12/11/97	110	230						
1/6/98	110			200				200

Location	Date	0-6"	6-12"	12-18"	18-24"	24-30"	30-36"	Below 36"
A1-C1 Mid	09/25/97	25	280	290				
	10/9/97	660	660	290				
	10/30/97	31	47					
	11/20/97	79	250	310				
	12/11/97	17	14	410				
	1/6/98	300						860

Table 3
Results of Analysis of NIST Standard Reference Material 2704
"River Sediment" Using Method 3050B ($\mu\text{g/g} \pm \text{SD}$)

Element	Atm. Pressure Microwave Assisted Method with Power Control	Atm. Pressure Microwave Assisted Method with Temperature Control (gas-bulb)	Atm. Pressure Microwave Assisted Method with Temperature Control (IR-sensor)	Hot-Plate	NIST Leachable Concentrations Using Method 3050	NIST Certified Values for Total Digestion ($\mu\text{g/g} \pm 95\% \text{ CI}$)
Cu	101 \pm 7	89 \pm 1	98 \pm 1.4	100 \pm 2	2700	98.6 \pm 5.0
Pb	160 \pm 2	145 \pm 8	145 \pm 7	148 \pm 1	5100	161 \pm 17
Zn	427 \pm 2	411 \pm 3	405 \pm 14	427 \pm 5	5900	438 \pm 12
Cd	NA	3.5 \pm 0.86	3.7 \pm 0.9	NA	20	3.45 \pm 0.22
Cr	82 \pm 3	79 \pm 2	85 \pm 4	89 \pm 1	19	135 \pm 5
Ni	42 \pm 1	38 \pm 1	38 \pm 4	44 \pm 2	10.1	44.1 \pm 3.0

NA - Not Available

Table 4
Results of Analysis of NIST Standard Reference Material 2710
"Montana Soil (Highly Elevated Trace Element Concentrations)" Using Method 3050B
($\mu\text{g/g} \pm \text{SD}$)

Element	Atm. Pressure Microwave Assisted Method with Power Control	Atm. Pressure Microwave Assisted Method with Temperature Control (gas-bulb)	Atm. Pressure Microwave Assisted Method with Temperature Control (IR-sensor)	Hot-Plate	NIST Leachable Concentrations Using Method 3050	NIST Certified Values for Total Digestion ($\mu\text{g/g} \pm 95\% \text{ CI}$)
Cu	2640 \pm 60	2790 \pm 41	2480 \pm 33	2910 \pm 59	2700	2950 \pm 130
Pb	5640 \pm 117	5430 \pm 72	5170 \pm 34	5720 \pm 280	5100	5532 \pm 80
Zn	6410 \pm 74	5810 \pm 34	6130 \pm 27	6230 \pm 115	5900	6952 \pm 91
Cd	NA	20.3 \pm 1.4	20.2 \pm 0.4	NA	20	21.8 \pm 0.2
Cr	20 \pm 1.6	19 \pm 2	18 \pm 2.4	23 \pm 0.5	19	39*
Ni	7.8 \pm 0.29	10 \pm 1	9.1 \pm 1.1	7 \pm 0.44	10.1	14.3 \pm 1.0

NA - Not Available * Non-certified values, for information only.

3050B - 10

Revision 2
December 1996



EnviroTech Mid-Atlantic Laboratories

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December 30, 1997
Page 1 of 7

Client Contact

Attn.: John Van Hyfte
Fax No.: 409-764-7479

Report Information

ETMA Project #: 16960
Date ETMA Rec'd: 12/18/97

Client Information

Name: Lynntech
Address: 7610 Eastmark Drive, Suite 105
College Station, TX 77840

Sample Information

Client Project: -
Client Project #: -
P.O. #: -

Sample Identification

Sample submitted and identified by client:

Sample	Field Identification	Matrix	Date	Time Collected
16960A	C1 B1	Soil	-	-
16960B	C1 B2	Soil	-	-
16960C	C1 B3	Soil	-	-
16960D	C2 B1	Soil	-	-
16960E	C2 B2	Soil	-	-
16960F	C2 B	Soil	-	-
16960G	C3 B1	Soil	-	-
16960H	C3 B2	Soil	-	-
16960I	C4 B1	Soil	-	-
16960J	C4 B2	Soil	-	-
16960K	C5 B1	Soil	-	-
16960L	C5 B2	Soil	-	-
16960M	C6 B1	Soil	-	-
16960N	C6 B2	Soil	-	-
16960O	C6 B3	Soil	-	-
16960P	C6 B4	Soil	-	-
16960Q	C7 B1	Soil	-	-
16960R	C7 B2	Soil	-	-

All analyses were performed in accordance with EPA methods referenced in Code of Federal Regulations, Section 40 Part 136, "Methods for Chemical Analysis of Water and Wastes", EPA 600/4-79 revised March 1983 and/or "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods", SW-846, 3rd Edition.

Client Project: -
 Client Project #: -
 P.O. #: -

Sample Identification Continued

Sample submitted and identified by client:

Sample	Field Identification	Matrix	Date	Time Collected
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16960T	C8 B2	Soil	-	-
16960U	C8 B3	Soil	-	-
16960V	C8 B4	Soil	-	-
16960W	C9 B1	Soil	-	-
16960X	C10 B1	Soil	-	-
16960Y	C10 B2	Soil	-	-
16960Z	C11 B1	Soil	-	-
16960A ²	C11 B2	Soil	-	-
16960B ²	C12 B1	Soil	-	-
16960C ²	C12 B2	Soil	-	-
16960D ²	C12 B3	Soil	-	-
16960E ²	C13 B1	Soil	-	-
16960F ²	C13 B2	Soil	-	-
16960G ²	C13 B3	Soil	-	-
16960H ²	C14 B1	Soil	-	-
16960I ²	C14 B2	Soil	-	-
16960J ²	C15 B1	Soil	-	-
16960K ²	C15 B2	Soil	-	-
16960L ²	C15 B3	Soil	-	-
16960M ²	C16 B1	Soil	-	-
16960N ²	C16 B2	Soil	-	-
16960O ²	C17 B1	Soil	-	-
16960P ²	C17 B2	Soil	-	-
16960Q ²	C18 B1	Soil	-	-
16960R ²	C18 B2	Soil	-	-
16960S ²	C18 B3	Soil	-	-
16960T ²	C19 B1	Soil	-	-
16960U ²	C19 B2	Soil	-	-
16960V ²	C19 B3	Soil	-	-
16960W ²	C20 B1	Soil	-	-
16960X ²	C20 B2	Soil	-	-
16960Y ²	C20 B3	Soil	-	-
16960Z ²	C21 B1	Soil	-	-
16960A ³	C21 B2	Soil	-	-
16960B ³	C22 B1	Soil	-	-
16960C ³	C23 B1	Soil	-	-
16960D ³	C23 B2	Soil	-	-
16960E ³	C24 B1	Soil	-	-
16960F ³	C24 B2	Soil	-	-
16960G ³	C25 B1	Soil	-	-
16960H ³	C25 B2	Soil	-	-
16960I ³	C25 B3	Soil	-	-
16960J ³	C26 B1	Soil	-	-
16960K ³	C26 B2	Soil	-	-

Client Project: -
Client Project #: -
P.O. #: -

Sample Identification Continued

Sample submitted and identified by client:

Sample	Field Identification	Matrix	Date	Time Collected
16960L ³	C27 B1	Soil	-	-
16960M ³	C28 B1	Soil	-	-
16960N ³	C28 B2	Soil	-	-
16960O ³	C29 B1	Soil	-	-
16960P ³	C29 B2	Soil	-	-
16960Q ³	C29 B3	Soil	-	-
16960R ³	C29 B4	Soil	-	-
16960S ³	C30 B1	Soil	-	-
16960T ³	C30 B2	Soil	-	-
16960U ³	C31 B1	Soil	-	-
16960V ³	C31 B2	Soil	-	-

Client Project: -
 Client Project #: -
 P.O. #: -

Analysis	LOQ	16960A	16960B	16960C	16960D	16960E
Total Metals (mg/kg)						
Chromium (Cr)	0.5	420	310	550	84	88

Analysis	LOQ	16960F	16960G	16960H	16960I	16960J
Total Metals (mg/kg)						
Chromium (Cr)	0.5	330	100	170	31	47

Analysis	LOQ	16960K	16960L	16960M	16960N	16960O
Total Metals (mg/kg)						
Chromium (Cr)	0.5	81	120	110	130	150

Analysis	LOQ	16960P	16960Q	16960R	16960S	16960T
Total Metals (mg/kg)						
Chromium (Cr)	0.5	140	130	210	160	510

Analysis	LOQ	16960U	16960V	16960W	16960X	16960Y
Total Metals (mg/kg)						
Chromium (Cr)	0.5	87	220	170	110	270

Analysis	LOQ	16960Z
Total Metals (mg/kg)		
Chromium (Cr)	0.5	85

LOQ - Limit of Quantitation BLQ - Below Limit of Quantitation LOD - Limit of Detection BLD - Below Limit of Detection
 J - Estimated Value NOTE: Soil results are reported on a dry weight basis unless otherwise noted.

Client Project: -
 Client Project #: -
 P.O. #: -

Analysis	LOQ	16960A ²	16960B ²	16960C ²	16960D ²	16960E ²
Total Metals (mg/kg)						
Chromium (Cr)	0.5	120	62	57	*	58

Analysis	LOQ	16960F ²	16960G ²	16960H ²	16960I ²	16960J ²
Total Metals (mg/kg)						
Chromium (Cr)	0.5	420	630	140	390	79

Analysis	LOQ	16960K ²	16960L ²	16960M ²	16960N ²	16960O ²
Total Metals (mg/kg)						
Chromium (Cr)	0.5	250	310	94	230	160

Analysis	LOQ	16960P ²	16960Q ²	16960R ²	16960S ²	16960T ²
Total Metals (mg/kg)						
Chromium (Cr)	0.5	210	18	17	32	16

Analysis	LOQ	16960U ²	16960V ²	16960W ²	16960X ²	16960Y ²
Total Metals (mg/kg)						
Chromium (Cr)	0.5	15	16	4.3	5.3	12

Analysis	LOQ	16960Z ²
Total Metals (mg/kg)		
Chromium (Cr)	0.5	5.6

Client Project: -
 Client Project #: -
 P.O. #: -

Analysis	LOQ	16960A ³	16960B ³	16960C ³	16960D ³	16960E ³
Total Metals (mg/kg)						
Chromium (Cr)	0.5	3.9	2.5	110	230	13

Analysis	LOQ	16960F ³	16960G ³	16960H ³	16960I ³	16960J ³
Total Metals (mg/kg)						
Chromium (Cr)	0.5	4.1	17	14	410	9.8

Analysis	LOQ	16960K ³	16960L ³	16960M ³	16960N ³	16960O ³
Total Metals (mg/kg)						
Chromium (Cr)	0.5	5.5	160	8.7	4.1	18

Analysis	LOQ	16960P ³	16960Q ³	16960R ³	16960S ³	16960T ³
Total Metals (mg/kg)						
Chromium (Cr)	0.5	39	67	130	410	240

Analysis	LOQ	16960U ³	16960V ³
Total Metals (mg/kg)			
Chromium (Cr)	0.5	100	97

Client Project: -
 Client Project #: -
 P.O. #: -

Quality Control Data

Analysis	%STD	%Spike	%RD	Method #	Analyst	Date Analyzed
Total Metals						
Chromium (Cr) (A-J)	99	96	2.4	6010A	J. Reid	12/26/97
Chromium (Cr) (K-T)	102	85	<1.0	6010A	J. Reid	12/26/97
Chromium (Cr) (U-E ²)	91	92	2.2	6010A	J. Reid	12/26/97
Chromium (Cr) (F ² -O ²)	98	100	3.1	6010A	J. Reid	12/26/97
Chromium (Cr) (P ² -Y ²)	97	98	1.4	6010A	J. Reid	12/26/97
Chromium (Cr) (Z ² -I ³)	94	93	1.4	6010A	J. Reid	12/26/97
Chromium (Cr) (J ³ -S ³)	92	105	<1.0	6010A	J. Reid	12/26/97
Chromium (Cr) (T ³ -V ³)	99	99	<1.0	6010A	J. Reid	12/26/97



C. Brian Kidd
 Laboratory Director



Reviewed By

Buchanan/Soil Mechanics, Inc.

Consulting Engineers

Bryan, Texas

206 North Sims, 77803/P.O. Box 672, 77806/(409) 822-3767/Fax (409) 822-7604

Spencer J. Buchanan, P.E. (1903-1982)

Philip N. Buchanan, Ph.D., P.E.

Edsel J. Burkhart, P.E.

July 22, 1998

Mr. John Van Hyfte
LYNNTECH, INC.
7610 Eastmark Drive, Suite 105
College Station, Texas 77840

Reference: Soil testing: report transmitted July 21, 1998
B/SMI Project No. 981912

Dear Mr. Van Hyfte:

You asked for identification of test procedures used for the tests reported July 21. The procedures used are contained in the ASTM Standards (including in the term Standards documents identified as Specification for . . . (SPE), Standard Practice for . . . (SP), Standard Test Method for . . . (STM), and Test Method for . . . (TM), except that the permeability to water was determined using a procedure of the U.S. Army Corps of Engineers, all as listed below.

The **SIEVE ANALYSIS** sieve analysis as reported was performed using applicable parts of the following Standards, including applicable referenced Standards:

1. ASTM D 421, SP Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants, or ASTM D 2217, SP Wet Preparation of Soil Samples for Particle-Size Analysis.
2. ASTM C 136, STM Sieve Analysis of Fine and Coarse Aggregate, and/or ASTM D 422, STM Particle-Size Analysis of Soils.

The **OPTIMUM MOISTURE/DENSITY RELATIONSHIP** as reported was performed using applicable parts of the following Standard, including applicable referenced Standards:

ASTM D 698, TM Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³)), particularly Procedure A.

The Atterberg liquid limit (LL) and plastic limit (PL) and plasticity index (PI) and the percent passing the No. 200 sieve (**PASSED NO. 200 SIEVE**) are also reported on the same sheet as the **OPTIMUM MOISTURE/DENSITY RELATIONSHIP**. The tests underlying these results were performed using applicable parts of the following Standards, including applicable referenced Standards:

1. ASTM D 4318, STM Liquid Limit, Plastic Limit, and Plasticity Index of Soils.
2. ASTM D 1140, STM Amount of Material in Soil Finer Than the No. 200 (75- μ m) Sieve.

The **SUMMARY OF LABORATORY TEST DATA** contains a report of Specific Gravity and the permeability to water at a particular molded density and moisture content (**k**), sometimes also known as the Engineer's coefficient of permeability, and also contains reports of test data sheet as the **OPTIMUM MOISTURE/DENSITY RELATIONSHIP**. The tests underlying the results which appear only on the **SUMMARY OF LABORATORY TEST DATA** were performed using applicable parts of the following Standards, including applicable referenced Standards:

1. ASTM D 854, STM Specific Gravity of Soils.
2. U.S. Army Corps of Engineers Procedure: PERMEABILITY TEST WITH CONSOLIDOMETER, contained in Appendix VII, Engineer Manual 1110-2-1906, 30 November 1970. This procedure is or was the accepted laboratory procedure of the Texas Department of Health having applicability to soil liners for landfills.

In general, compliance with the published Standards in the laboratory was substantial rather than strict, that is, there are in all or nearly all cases some (believed immaterial) departures from the black letters of the published procedures in the actual laboratory procedures.

More information is available. I trust this meets your needs for the time being. If you need more information, please let me know.

Sincerely,

BUCHANAN/SOIL MECHANICS, INC.

Robert E. Bigham



Work Plan

0-1 Treatability Study at Camp Stanley Storage Activity, Boerne, TX

Prepared for:

Parsons Engineering Science, Inc.
Contractor to Air Mobility Command

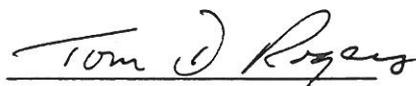
Submitted by:

Lynntech, Inc.

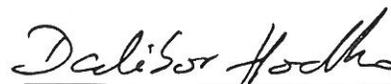
Subcontract 728487-3000-00

April 28, 1997

Revised June 10, 1997



Tom D. Rogers
Project Manager
Lynntech, Inc.



Dalibor Hodko
Principal Investigator
Lynntech, Inc.

1. Introduction

Lynntech, Inc. under a subcontract agreement with Parsons Engineering Sciences, Inc., is conducting a treatability study and a field demonstration of electrokinetic soil remediation technology to evaluate its process feature, remediation efficiency and cost effectiveness for removing chromium (Cr) and cadmium (Cd) from contaminated soil at the O-1 site, Camp Stanley Storage Activity (CSSA), Boerne, TX. The work being performed by Lynntech, Inc. is a subpart of a larger scope of environmental remediation work being performed by Parsons ES, Inc., at CSSA. As the Prime Contractor for this work at CSSA, Parsons ES Inc., will coordinate activities at the site related to the field demonstration of Lynntech's electrokinetic soil processing technology.

The demonstration will consist of two parts: (i) bench scale treatability study, and (ii) a demonstration of the process operation in the field pilot test. An area approximately 6' x 7' will be treated at O-1 CSSA site. The depth of treatment will be 3-4 feet. The field test will be conducted continuously for ca 2 months. It is anticipated that the work shall be completed on August 31, 1997 including all the required deliverables in the project.

The start date for the project is April 07, 1997. A Health and Safety Plan, as well as this Work Plan will be delivered according to the Scope of Work (SOW), within 20 days of the execution of the Subcontract. Samples of contaminated soil will be then collected at the O-1 site, and bench scale treatability study performed using the soil from the site. It is anticipated that the field test will start on June 07 and will be conducted through August 08, 1997. Demobilization of equipment upon completion of field pilot test and disposal of investigation derived waste (IDW) will be completed on August 13, 1997. A final data report which will include data reduction and results of the bench scale treatability study and field test, system design, and any graphs/tables that are necessary for conclusions will be delivered on August 31, 1997.

The overall objectives of the project are:

- To demonstrate the effectiveness of Lynntech's in situ electrokinetics soil treatment system for heavy metal removal at the Camp Stanley Storage Activity (CSSA) oxidation pond (SWMU 0-1);
- To establish a technical knowledge base for assessing the method's potential to be used as a full scale treatment method.
- To establish cost and performance criteria and demonstrate the minimal environmental impact of the method.

subcontractor, shall provide all the goods, services and personnel to successfully complete the work detailed in this Work Plan.

5. Description of Activities and Tasks

A bar graph schedule describing all the Tasks and activities (meetings, project reviews and reports) to be accomplished during the project performance is shown in Figure 1. The anticipated dates for accomplishing each Task are marked in the Figure. Key elements of each task shown in the schedule are described below in chronological order. Key personnel involved in the performance of each Task is shown in the outline of the work plan schedule.

5.1. Project Startup

The project started by discussing the details of project organization and performance between the Contractor's and Lynntech's representatives at the Startup Meeting held at CSSA facility, Boerne, TX, on April 11, 1997. Project management and organization was presented by Dr. Tom D. Rogers, Lynntech's Project Manager. A short presentation of the basic technical aspects of the technology was given by Dr. Dalibor Hodko, the Project Scientist. Utility requirements, source of water and electricity needed for the field pilot test, were discussed at the meeting. The meeting included a site visit, where several soil samples from the O-1 contaminated area were taken by Ken Rice, the Task Manager for the project.

5.2. Development and Approval of the Work Plan and the Health & Safety Plan

Within 20 days of contract implementation, Lynntech will formally present the Project Work Plan accompanied by a Health and Safety Plan. Drs. Hodko and Rogers shall schedule a meeting with the Contractor for presentation of these plans. Following approval of these plans by the Contractor, Lynntech shall immediately proceed to implement the technical tasks of the project.

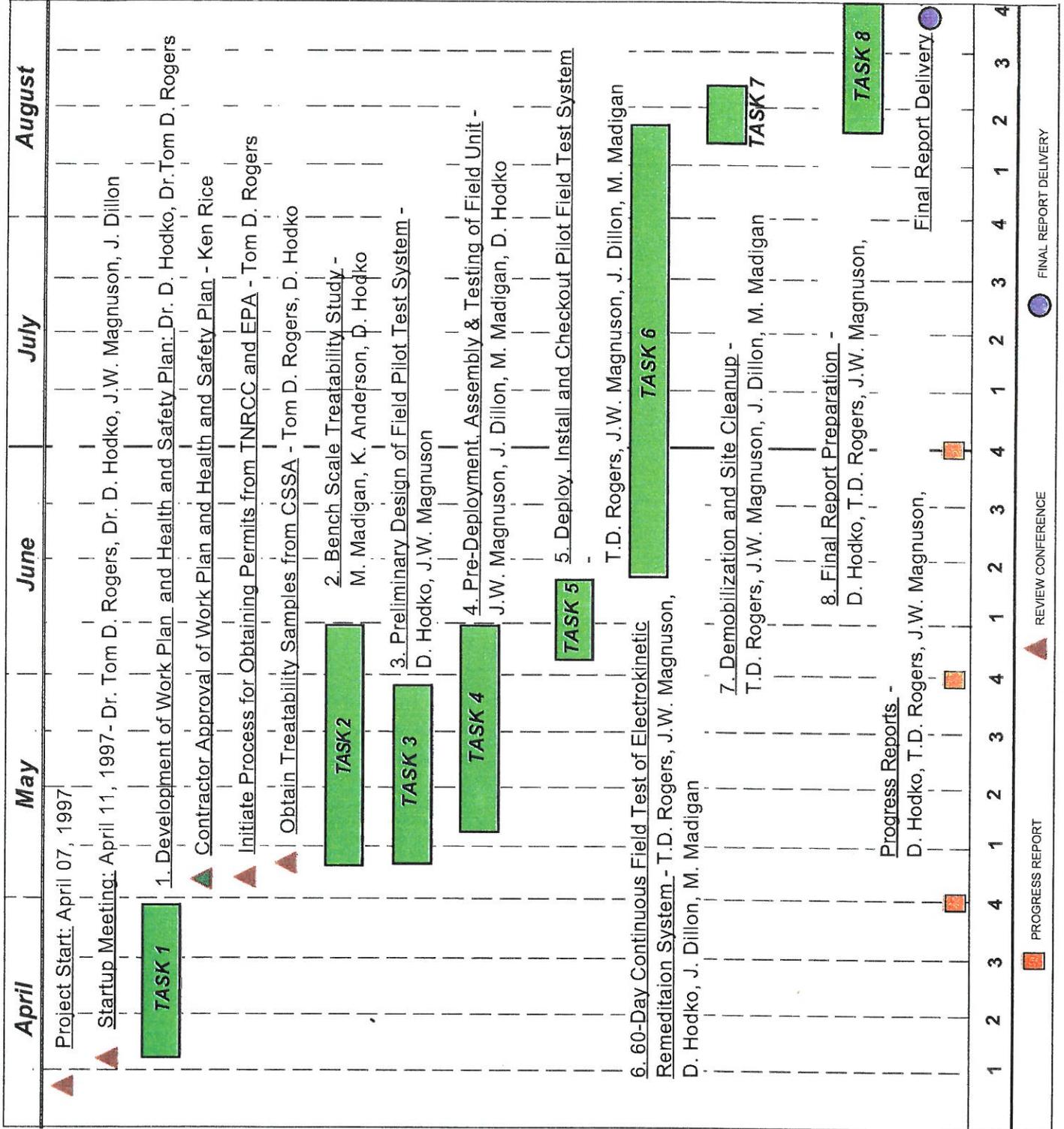
5.3. Notification for Performance of the Field Treatability Study

A Letter of Notification for intent to perform treatability studies shall be prepared not later than May 04, 1997, and forwarded to the Texas Natural Resource Conservation Commission (TNRCC) and to EPA Region 6 in accordance with requirements of 40 CFR Section 261.4(e)-(f) for hazardous materials.

5.4. Obtain Soil Samples From CSSA for Bench-Scale Treatability Studies

Collection of appropriate soil samples from the site shall be performed by Drs. Hodko and Rogers. These samples shall include bulk soil samples for carrying out various bench scale tests.

Figure 1. Work Plan Schedule



Documentation shall accompany these samples and it is planned that upon completion of the bench scale studies, all soil samples shall be returned to the site. The following samples will be taken:

- (i) Bulk soil sample, ca 20 Lb, from the contaminated area at a depth of ca 3.5 ft, where highest chromium and/or cadmium concentration has been found. This soil will be used in a bench scale electrokinetic soil bed for testing the conditions for removal of contaminants;
- (ii) Two core samples, 1" in diameter, one from the non-disturbed area and one from the disturbed area (excavated in 1996 investigations and later returned to the pit) will be taken. These samples will be used for soil chemical and mechanical analysis (classification, pH, chlorides, sulfate, nitrates, moisture content, density), and
- (iii) Shelby tube non-disturbed samples, 2" in diameter, for soil hydraulic permeability analysis.

5.5. Bench Scale Treatability Study

This task is a key aspect of the project because the test results pertaining the physical aspects of the soil and the chemical nature of the soil and the contaminants provide specific information for design of electrode wells, determining electronic monitoring requirements, type of anode and cathode well fluids, pH control, plumbing and fluid delivery system, and system automation control requirements. As this data becomes available, work in support of Tasks 6 (design of the field pilot test system) and 7 (assembly and testing of the field system) shall proceed in parallel.

The bench scale study will consist of:

- (i) Determining chemical, geophysical and mechanical characteristics of soil from the CSSA O-1 site.
- (ii) Determining the optimum additives to the electrode wells for enhancing the solubilization of chromium and cadmium in soil at O-1 site.
- (iii) Determining electrokinetic contaminant transport in a 20 Lb soil test bed.

5.5.1. Chemical and Geophysical Analysis of Soil from the O-1 Site

Chemical soil analysis including soil pH determination and analysis of chlorides, sulfates and nitrates (EPA 150.1, EPA 325.3, EPA 375.4.0, EPA 353.3) will be performed at Lynntech's analytical laboratory. *Quality assurance/quality control* (QA/QC) procedures as well as analytical procedures according to the standard ASTM and EPA tests necessary to perform a

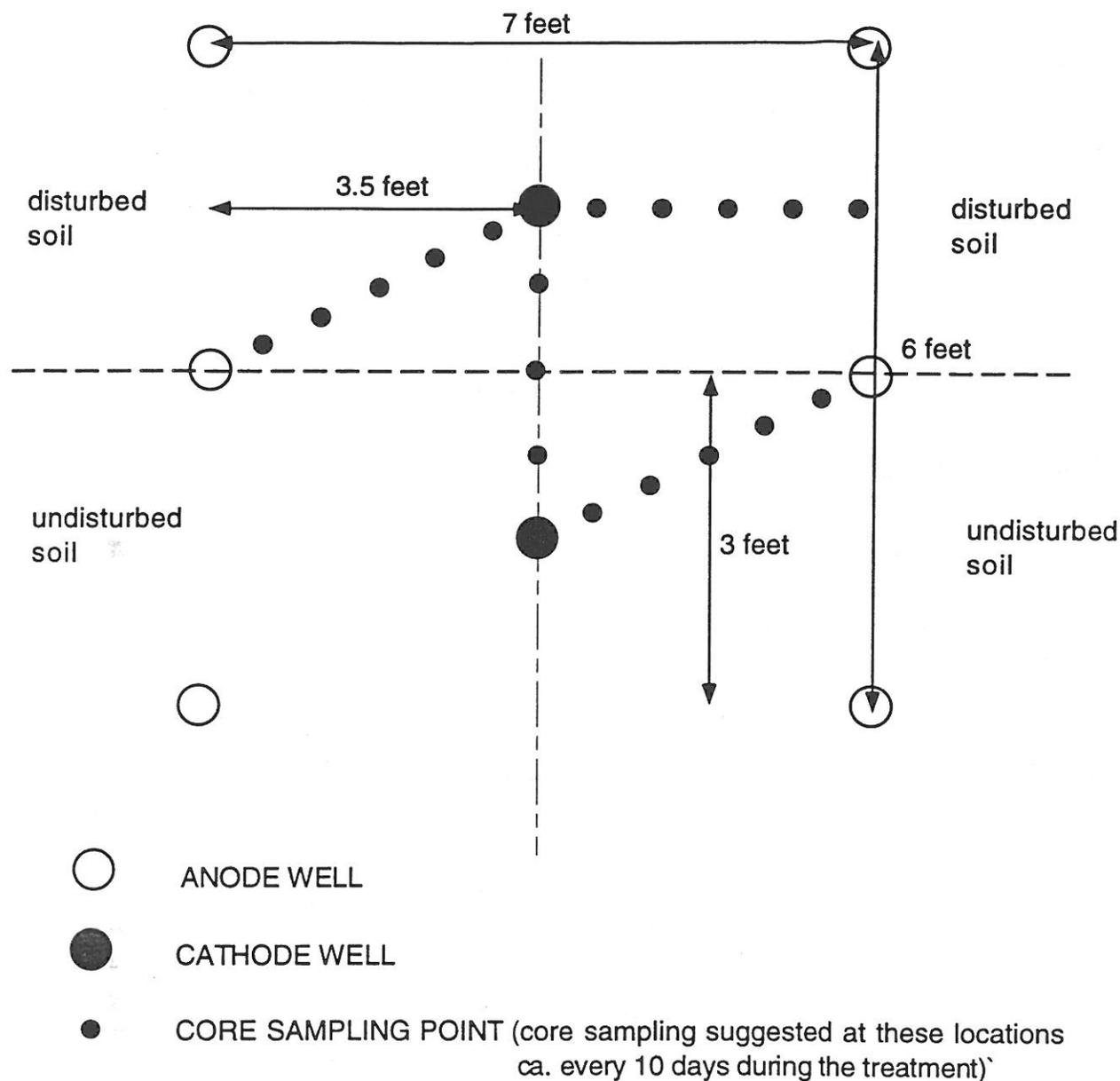


Figure 2. Schematic of electrode well and core sampling locations for CSSA O_1 Site.

homogenized to achieve uniform contaminant distribution in the soil bed. This is necessary to obtain clear profiles of contaminant removal from soil in time and to determine an average removal efficiency for given electrical and chemical treatment conditions. The experiments will be performed in a soil bed furnished with two electrode wells and all necessary fittings and sensors for fluid management and control. The soil samples and solution samples from the wells will be taken on a weekly basis. It is envisaged that the electrokinetic test will be conducted for 4-5 weeks. Soil samples will be taken by coring ca 0.5 cm diameter cores in the soil at five locations between the electrodes wells. The soil core samples will be taken to a depth of 4 feet. Figure 2 shows a schematic of electrode wells distribution in the field and locations of core soil

These two concepts present the basis of our proprietary “**dc/ac electrokinetic process**”. In practice the process utilizes: (i) pulsed or half-wave rectified sinusoidal electric field, and (ii) a dual or multiple segmented layered well casing to enhance the soil remediation efficiency.

Data resulting from the bench scale tests will be used to establish specific requirements for electrode well construction, component interface and system operation parameters. Lynntech’s process operation unit, consisting primarily of the trailer which houses electronics for digital and analog data transfer and process control, is designed in such a way that it can be easily adapted to a variety of the fluid control conditions encountered at the contaminated sites. Thus, based on the data from the bench scale study where the direction of movement of each contaminant in soil is determined, an optimum process flow diagram will be designed. This will include the determination of the number of fittings, level and pH sensors and soil voltage probes needed for the electrode well construction. A full-scale anode well assembly and a cathode well assembly shall be constructed and tested in the laboratory. This task activity shall be carried out in parallel with Task 5 and Task 7. Figure 3 shows a site layout for Lynntech’s process operation in the field.

5.7 Pre-Deployment Assembly and Testing of Field Unit

Lynntech’s field unit is built to satisfy all the requirements for performing dc/ac electrokinetic soil processing: (i) generation of a pulsed or nonuniform electric field in the soil; (ii) stable electrodes; (iii) electrode wells; (iv) contaminant recovery; (v) well fluid management; and, (vi) management of the soil pH and voltage distribution in the soil. The main pilot system’s components are: (i) 16 -foot trailer which serves as a process operation and control unit; (ii) electrode well assemblies; (iii) chemicals and effluent storage tanks, and (iv) cables and pipes.

Electrode well design. Lynntech uses a proprietary electrode well construction that consist of a multilayered porous structures. The well design is based on a concept of coupled porous structures, which takes into account electrokinetic properties of each of the layer used in the well construction where soil is considered a part of the coupled structure. Thus, the electrode well design is fitted to the electrokinetic and hydraulic properties of the soil at the site. This allows to maximize electrokinetic transport in the soil. The walls of the wells are formed from a ceramic casing (4" dia) surrounded by a layer of clay (tightly packed kaolinite or bentonite). This wall has a low hydraulic permeability but a high electroosmotic permeability. The low hydraulic permeability prevents water loss ensuring fluid is maintained in the well, which is essential when carrying out electrokinetics in unsaturated soil. The high electroosmotic permeability of the ceramic/clay layers ensures that the water flow is controlled at the electrode wells. Another function of the well casing is to adsorb the contaminants. Metals extracted from the soil will be concentrated on a high surface area clay layer. This will decrease the concentration of

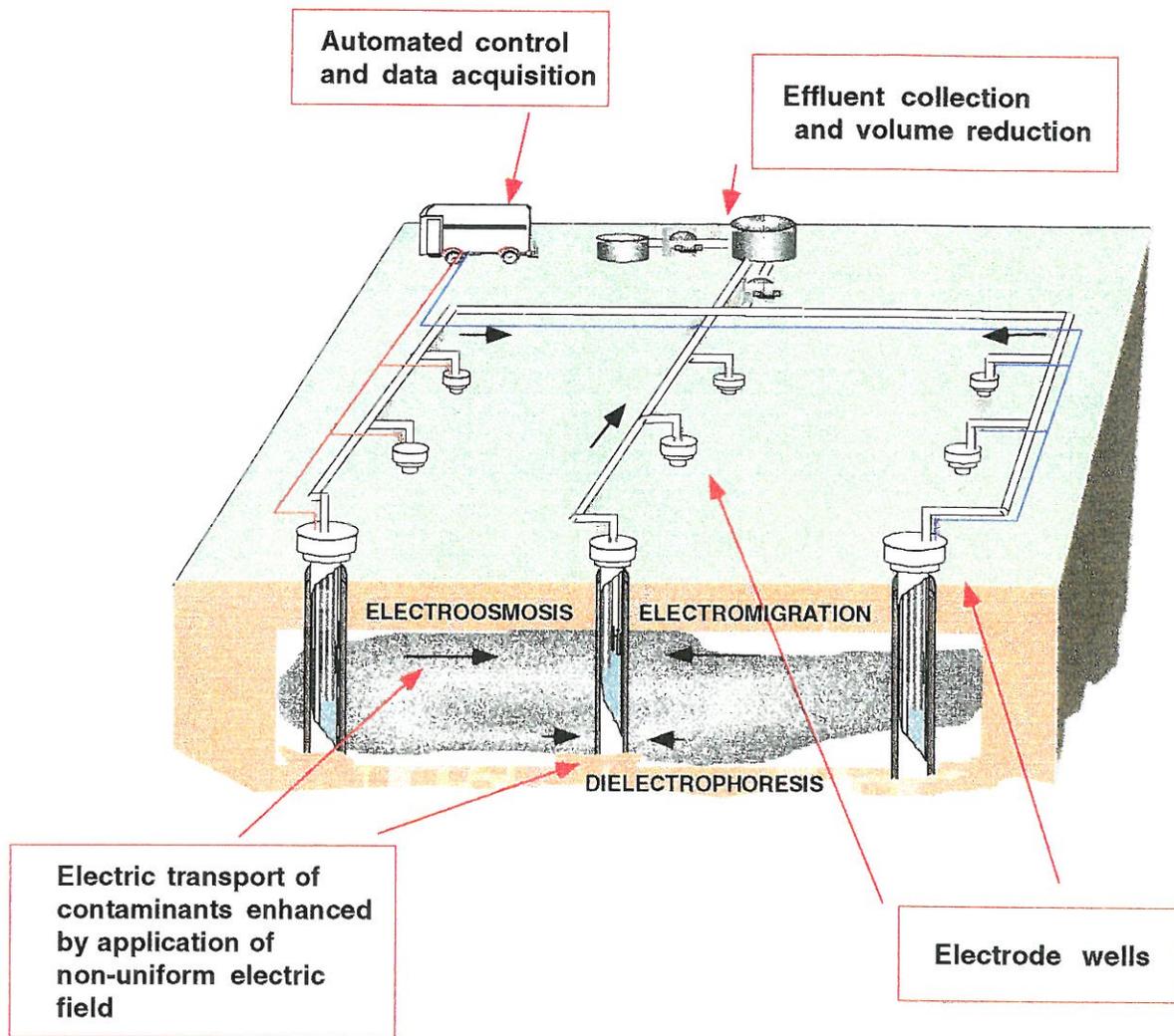


Figure 3. Site layout of Lynntech's dc/ac electrokinetic soil remediation process.

contaminants in the electroosmotic effluent from the cathodes. Contaminants can be periodically recovered from the clay by, for instance, acid washing.

Ceramic casing will be closed by a PVC box which serves as the well-cap. Each well box contains necessary electronics for monitoring and controlling the pH and temperature and solenoid valves for fluid addition or extraction. The cathode well boxes contain: a stainless steel cathode, a pH controller, a pH probe, a temperature probe, 4 - 20 mA temperature transmitter, high and low well solution level sensors, and three solenoid valves for controlling the addition of water, the addition of neutralizer/extractant and withdrawal of the effluent. The anode well boxes contain: a dimensionally stable electrode, iridium oxide coated titanium mesh, a temperature probe, 4 - 20 mA temperature transmitter, a low well solution level sensor, and one

valve for the addition of water or leachant. The level sensors can be easily rearranged to be used as high or low well solution level sensor. The well boxes are designed that can be easily adapted to the specific requirements of each site. This will be determined after the performance of bench scale study and once the final fluid flow diagram is established.

Electrode wells arrangement. A number of anode and cathode wells are positioned in rows. Cathode wells are surrounded by the anode wells so that each cathode is centrally positioned to several anode wells. Optimum distances between the wells will be determined experimentally in the field before the start of the field test. Our approach for determining optimum distances between the electrode wells is based on a simple field experiment where one anode and two cathodes are positioned in the soil at two different distances. The optimum distance is obtained from the following measurements performed in the field: (i) current is measured at different voltage pulses through the soil; (ii) electroosmotic flow rate is measured at two anode-cathode distances, and (iii) voltage profiles are measured at each porous layer included in the well construction, include the voltage drop across the soil.

Trailer. The trailer contains: (a) NEMA 4 box which houses electronics for process control and automated data acquisition (total up to 73 analog signals: 18 soil voltage probes, 10 temperature soil probes, 18 temperature probes, 18 current probes, 1 system total voltage probe, 6 pH probes; and 76 digital signals: 6 high and 18 low level sensors in the wells, high level sensor - alarm in the effluent tank, low level sensor - alarm for leachant solution, level sensor for automated fill-up of tap water into the water tank and digital lines for turning on/off solenoid valves and pumps; (b) rack housing up to for 4 x 10 kW power supplies; (c) computer system for data acquisition and process control; (d) necessary field portable analytical equipment, e.g., pH meter, apparatus for deionized water, balance, etc. All the analog and digital signals are electronically isolated from the computer system using in-house developed opto-isolation amplifier boards.

Storage tanks will be provided for (a) addition of water to the field through the anode wells (55 gallon barrel connected to the tap water pipe or similar); (b) addition of leachant/extractant in the cathode wells (55 gallon barrel); (c) effluent collection (in 55 gallon barrel, DOT approved), and (d) effluent storage (55 gallon barrels, DOT approved).

Cables and pipes. Each anode and cathode well will be connected to the trailer using one multipin electrical cable for energizing the electrodes, valves and pumps, for connection of analog signal probes and transferring digital signals from the computer. Solutions are transported using 1/2" PVC tubing, fittings and manual override valves. Most of the cables are ready for use and it is expected that no changes on cable construction will be needed.

Lynntech's electrokinetic field unit has previously been used for field purposes and is ready for deployment. It will require only minor software modifications to support specific aspects arising from requirements at the site. In conjunction with activities of Task 6, the operation control

system shall be configured and fully tested in readiness for field activities. This will include testing of the remote control operation of the system. The remainder of the anode and cathode wells required for the field test shall be constructed and tested following the requirements established in Task 7. Each anode and cathode assembly, including spares, shall be tested and verified prior to field deployment. Based on previous experience, this activity, ensures rapid startup of the field test.

5.8. Deploy, Install and Check-out of Pilot Field Test System

Because much of the electrokinetic field system has already been constructed and operated, deployment to CAAS, preparation of the site, preparation of holes in the site for insertion of electrode wells, plumbing and electronic integration and operational checkout is expected to be completed within 4-5 days. For deployment and field setup of the test system, Lynntech shall prepare and provide a detailed list of all equipment, materials and supplies required to support the field test and shall coordinate our arrival and entry with the Contractor and appropriate security and site management representatives. The deployment, installation and system check-out in the field will be performed by a crew of 3-4 people. These operations will be supervised by both Project Manager, Dr. Tom D. Rogers and Project Scientist, Dr. Dalibor Hodko.

5.9. 60-Day Continuous Field Test

Lynntech's electrokinetics system has been brought to an advanced state of engineering development that is capable of carrying out a wide range of full-scale electrokinetics remediation efforts at a variety of sites. This system will be used after adaptation to the requirements of the CSSA O-1 site. Lynntech plans to operate the electrokinetic pilot system for 60 days so as to maximize data recovery and to optimize development of trend data in terms of contaminant movement and removal. This data shall be derived from periodic core sampling within the test site and through monitoring of recovered well fluids which will contain metal ions removed from the soil (additional metal will be electrodeposited at the appropriate electrode). It is envisaged that several core samples will be taken during the process operation along one or two diagonal profiles between one or two anode/cathode electrode well pairs. Using this approach it is possible to monitor both spatial and temporal efficiency of the contaminant removal from soil. Thus, during the field test a series of core samples and well solution samples shall be collected and delivered to the Contractor for final chemical analyses.

A suggested sampling protocol is as follows: (i) obtain 1" diameter, 4' deep, core samples every two weeks during process operation to establish profiles of contaminant concentrations between a pair of anode/cathode wells, and (ii) sample the anode and cathode well pair solutions at the same intervals. Soil cores can be sliced into e.g., 1 foot sections and analyzed for chromium,

cadmium, and eventually organic contaminants. Apart from frequent soil and well sampling to establish the removal rate of contaminants, real time monitoring of other process parameters is performed. Our system allows automated monitoring and logging of: (i) electroosmotic flow in the cathodes; (ii) water and chemical consumption; (iii) current flowing in each well; (iv) voltage distribution in soil and across the electrode well walls; (v) pH and temperature of the wells and soil.

For support of the field test, Lynntech requires electrical power (220-240 VAC, 3 phase) at the site. The location of the transformer pole is at the discretion of the Contractor and Client. The service pole equipped with a 100 Amp disconnect box should be located about 50-60 feet from the site. Lynntech shall provide at least one 500 gallon polyethylene tank for storage of water. As discussed at the Startup meeting the transport of water from a suitable source will be provided by the Contractor. Lynntech plans to rent and place a portable 20-foot trailer at the test site for storage of equipment and supplies. Site personnel shall be equipped with a cellular telephone for communication and a cellular telephone shall be installed in the main instrument trailer and equipped with a recorder.

Lynntech plans to have at least one technical person stationed at the test site for daily inspection and/or servicing during the first week of operation. After that, the process will be monitored remotely from College Station via a modem line. The technical person will visit the site 2-3 time per week or as needed. The Project Manager and/or the Project Scientist shall visit the site at 2-3 week intervals or as needed. Daily communication between the Project Manager and the technical employee present at the site shall be maintained (includes weekends and holidays).

5.10. Demobilization and Site Cleanup

Upon termination of the field test, Lynntech shall remove and decontaminate all electrode well assemblies from the test site, fill the holes with non-contaminated fill dirt (or fill material specified by the Contractor) and return the surface configuration to its pre-test appearance. Upon vacating the site, no equipment, supplies or trash shall be left at the site. Lynntech shall coordinate site demobilization and cleanup with the Contractor. Investigation derived waste shall be collected at the locations determined by the Contractor who will properly dispose-off the waste.

5.11. Final Report Preparation

A detailed and comprehensive Final Report shall be prepared by Lynntech and delivered in a timely manner to the Contractor. The Project Manager shall coordinate the layout and organization of this report with the Contractor and a Draft copy shall be presented for review and approval. Lynntech plans to make available to the Contractor and the Client all relevant data

derived from both the bench study and the field pilot system test study. Relevant data will include: (i) chromium and cadmium removal efficiency from soil; (ii) energy consumption; (iii) additives consumption; (iv) water consumption; (v) pH changes in soil during the process; (vi) interpretation of the results obtained; (vii) cost estimates; (viii) evaluation of the feasibility for full-size field treatment.

The Project Manager and Principal Investigator shall schedule a project debriefing with the Contractor and Client to coincide with delivery of the Draft Final Report. Following approval of the Draft Final Report by the Contractor, Lynntech shall revise as appropriate and prepare the Final Report which will be delivered to the Contractor on or before August 31, 1987.