

**RESOURCE GUIDE FOR ELECTROKINETICS LABORATORY AND
FIELD PROCESSES APPLICABLE TO RADIOACTIVE AND
HAZARDOUS MIXED WASTES IN SOIL AND GROUNDWATER FROM
1992 TO 1997**

September 30, 1997

Prepared for:

U.S. Environmental Protection Agency
Office of Radiation and Indoor Air
Radiation Protection Division
Center for Remediation Technology and Tools
Washington, DC

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Preface

A goal of the Environmental Protection Agency/Office of Radiation and Indoor Air/Center for Remediation Technology and Tools (EPA/ORIA/CRTT) is to bring innovative remediation technologies for radioactive and hazardous mixed wastes to the Office of Air and Radiation. This involves investigating any techniques which show promise in meeting EPA cleanup standards for hazardous waste in soil and groundwater. The electrokinetic remediation technology utilizes electric currents to extract radionuclides, heavy metals, organics and hazardous mixed waste from a porous medium. This resource document compiles a list of all electrokinetic processes used on a patented, bench, pilot, field or conceptual scale from the period 1992 to 1997. It is intended to be used by anyone interested in learning about the work that has occurred in the field of electrokinetics or by environmental management and scientists responsible for identifying and selecting a remediation tool for use at sites containing radioactive materials.

The information obtained in this report, adheres to the approved Data Quality Objectives (DQO) and Quality Assurance Program Plan (QAPP) for this document. The information was obtained by the use of the Internet, other documents, and by information received from various facilities upon request. This report tried to be consistent in the information cited for each electrokinetic process. However, this depended upon the availability of information. Therefore, some electrokinetic processes may appear to be more descriptive than others. If more in-depth information (e.g. biodegradation effects, hydraulic conditions, transport, sorption, precipitation and dissolution reactions) is desired for a particular electrokinetic process, then it is advised to contact the facility directly.

This project is coordinated by the EPA/Office of Radiation and Indoor Air (EPA/ORIA). The principal authors are Barrett Riordan and Rohit Karamchandani from Jack Faucett Associates, Inc. EPA/ORIA acknowledges all reviewers for their valuable observations and comments.

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INTRODUCTION AND SUMMARY

The theory of applying electric current to the soil or groundwater for remediation of inorganic, organic, radioactive and heavy metal wastes is called electrokinetic remediation. It is also known as electroreclamation, electrokinetic soil processing and electrochemical decontamination. Figure 1 depicts a general illustration of an electrokinetic system.

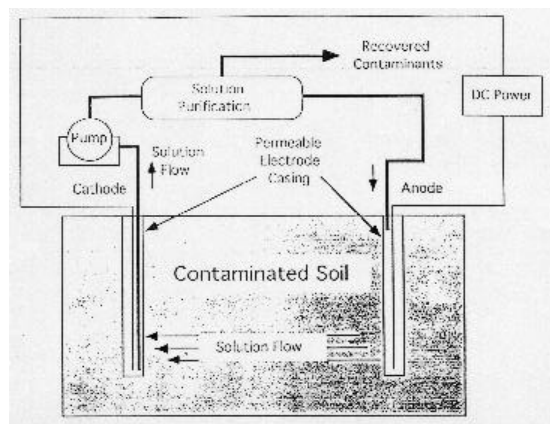


Figure 1: Schematic diagram of a typical electrokinetic processing system (Source: Electro Remediation Group, Ltd. and Lockheed Missiles and Space Co., Inc., Electrochemical Remediation of Contaminated Soil: A Technology Overview, 1993)

This figure shows a series of electrodes placed in the contaminated area. A small direct current (50-150 volts) is then applied between the electrodes. Because of the charge on soil, water and the contaminate, migration will occur towards the oppositely charged electrodes. In general, active electrodes in water cause an acid front at the anode and a base front at the cathode. The pH will drop at the anode and increase at the cathode. To prevent this pH imbalance, the electrodes are placed inside ceramic casings which are filled with a processing fluid. This processing fluid (also called surfactants and chelators) not only keeps a balance of pH at the anode and cathode, if chosen correctly, it also helps solubilize and move contaminants. Some processing fluids which have been used or considered are acetic acids, humic or gallic acids. The contaminant and processing fluid are then taken through a pump and recycling purification system where the contaminate is removed and the processing fluid is reused in the electrokinetic system.

There are five basic phenomena which together make up electrokinetic remediation. All have their

own properties and influences on the system but together work harmoniously to successfully remediate a contaminated area. They are diffusion, electrolysis, electroosmosis, electrophoresis and electromigration. If the area of interest is considered to be undisturbed before the electric current is applied, then the moment electricity enters the system diffusion begins. Diffusion is the process of redistributing the matter which lies between the electrodes. Electroosmosis is the movement of water under the electric field. This transport mechanism is necessary for contaminants to move towards electrode. The more saturated the soil, the easier electroosmosis will occur. Electrophoresis and electromigration are the movement of soil particles and contaminants respectively under an electric field. Because of the negative charge on soils, electrophoresis will be towards the anode. Depending upon the charge of the contaminate, electromigration can cause contaminate attraction towards either the anode or the cathode. Electrolysis is the chemical reaction which occurs around the electrodes. It can be properly manipulated with the appropriate chemical processing fluid as previously described.

The concept of electrokinetic remediation has been theorized in the form of electroosmosis since the early 1800s. However, application of electrokinetic remediation to a contaminated area is a fairly innovative technology dating back to the early 1970s in the United States and in Europe. In the United States, the approach was led by engineering and civil engineering laboratories and academic institutions. Technologically, the goal was to use electroosmosis to drive a flushing fluid between opposing anodes and cathodes. U.S. development work was boosted by an Oregon meeting in 1986 called by the U.S. Environmental Protection Agency (EPA). European researchers, however, focused on an entirely different approach. They used electromigration to desorb and then migrate anions and cations to their respective electrodes. Unlike the U.S. focus, much of the early European work was undertaken by electrochemical researchers. The techniques which resulted showed this difference in perspective.¹

Some contaminants that have been tested with electrokinetic remediation have been uranyl, thorium, radium, lead, cadmium, mercury, zinc, iron, magnesium, phenol, and BTEX compound (benzene, toluene and ethylene). Electrokinetic remediation rivals innovative and standard technologies (like soil excavation, incineration, vitrification, chemical stripping, phytoremediation, pressure flushing, soil washing, solidification/stabilization, chemical oxidation, air-stripping and impoundment) because of its efficacy of removal and its in situ and/or ex situ use. However, a limitation to this process is that the contaminate needs to be solubilize either by an acid front or by a processing fluid in order for the contaminate to be extracted. Table 1 provides an overview of the key factors for some of these technologies including electrokinetics.

This document attempted to list and describe all published work on electrokinetic remediation from 1992 to 1997. This work includes electrokinetic remediation being used commercially or on a bench, pilot, field or conceptual scale. There are three categories in this resource guide. The first category, Category A, lists all electrokinetic processes that are used as the remediation tool at a contaminated

¹ Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997.

site. Category B lists all electrokinetic processes that are being used on the bench, pilot or field scale. Finally, Category C lists all electrokinetic process that are in the conceptual development stage. Electrokinetic remediation being used abroad was also included in this resource guide. Information about each electrokinetic system includes the developers' name and address, technical description, status, cost and illustration (if available). This document should be used as a resource guide to understanding what work has been done in electrokinetic remediation as it applies to radioactive and hazardous mixed wastes so further research in this area can progress.

Table 1

Overview of in situ technologies for remediation of soils (Source: U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995)

TECHNOLOGY				
Evaluation Factor	Electrokinetics	Phytoremeditaion	Soil Flushing	Solidification/ Stabilization
Status	Full-scale applications in Europe Recently licensed in the United States	Pilot-scale Currently being field-tested in the United States and Europe	Commercial Selected at a number of Superfund sites	Commercial
Range of Metals Treated	Broad	Broad	Limited to inorganics (including radioactive contaminants)	Broad
Major Limiting Factor(s)	State-of-the-art	State-of-the-art Longer time required for treatment Crop yields and growth patterns	Potential contamination of the aquifer from residual flushing solution	Concern with long-term integrity
Site-Specific Considerations	Moisture level of soil Homogeneity of soil	Depth of contamination Concentration of contamination	Permeability of soil Groundwater flow and depth	Debris Depth of contamination

CATEGORY A

**Electrokinetic processes which are currently in use as remediation tools, either
in the United States or in other countries**

Table 2
Category A Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels before and after remediation	Treatment cost
Electrokinetics, Inc. (EK) — CADEX™ electrode system	kaolinite	not available	3 feet	not available	proprietary conditioning agents	30 feet by 60 feet Depth of 3 feet	lead	6-8 months	<u>Before</u> 1,000-5,000 ppm <u>After</u> not available	not available
Environmental & Technology Services (ETS)	clay-composed	not available	not available	10-15 amperes	not available	200 feet by 200 feet Depth of 70 feet	volatile organic compounds (VOCs), BTEX (benzene, toluene, ethylbenzene, xylene) compounds, total petroleum hydrocarbons (TPH)	3-12 months	<u>Before</u> VOC: 10-30 ppm BTEX: 100-2,200 ppm TPH: 3,000 ppm <u>After</u> VOC: < 0.1 ppm BTEX: < 40 ppm TPH: < 35 ppm	\$17-\$50 per ton
Isotron Corporation — ELECTROSORB™ Process	mixture of sand and kaolinite	not available	not available	not available	not available	not available	uranium, mercury	not available	<u>Before</u> mercury: 10-20 ppm <u>After</u> uranium: 50%-99% removal	not available

Table 2 (continued)
 Category A Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels before and after remediation	Treatment cost
Geokinetics International, Inc. (GII) — Pool Process	clay	5-10 feet	0.3-3.3 feet	5-20 volts 0.5-1.0 amperes	acid or alkali	230 feet by 10 feet Depth of 3.3 feet	arsenic, cadmium, chromium, copper, lead, nickel, zinc	2-18 months	<u>Before</u> Cd: 660 ppm Cu: 500-1,000 ppm Ni: 860 ppm Pb: 300-5,000 ppm Zn: 2,600 ppm <u>After</u> Cd: < 50 ppm Cu: < 250 ppm Ni: < < 80 ppm Pb: < 75 ppm Zn: < 300 ppm	\$300-\$500* per cubic yard *total cost

A1

Research: CADEX™ electrode system²

Developer(s): Electrokinetics, Inc. (EK)

Contact(s): Dr. Robert Gale or Elif Ozsu-Acar
Electrokinetics, Inc.
11552 Cedar Park Avenue
Baton Rouge, LA 70809
Phone: (504) 753-8004
Fax: (504) 753-0028

Research Description

The project investigated the feasibility of removing lead from the soils (approximately 5,400 mg/kg) in situ at Firing Range 24A located in Fort Polk, Louisiana (see Figure 2). Bullets from the firing operations disintegrated due to various environmental factors and resulted in the contamination of the soil. The site remediation project is being conducted for the U.S. Army Engineer Waterways Experiment Station (USAEWES), Vicksburg, Mississippi, and operated under the U.S. Environmental Protection Agency's (EPA) Superfund Innovative Technology Evaluation (SITE) Program. At the time of its initiation, this project represented the first comprehensive study in the United States of the electrokinetic separation technology applied to *in situ* remediation of heavy metals.

The principal compound for removal is lead which has accumulated at the site over a 30-year period. The remediation site size is 30 feet by 60 feet and the soils are to be remediated to a depth of 3 feet. The CADEX™ electrode system is being used to remediate the site. This electrode system controls the chemistry at the cathode and enhances the removal of metal species. The CADEX™ electrode

² Information provided was obtained from the following journals and reports:

Acar, Y.B. and Alshawabkeh, A.N., Principles of Electrokinetic Remediation, *Environmental Science and Technology* , Vol. 27, No. 13, pp. 2638-2647 (1993)

Acar, Y.B., Gale R., Marks R.E., and Ugaz, A., Feasibility of Removing Uranium, Thorium, and Radium from Kalonite by Electrochemical Soil Processing, *U.S. Environmental Protection Agency* , No. 009-292, Electrokinetics, Inc., LA (1992)

Electrokinetics, Inc., Technologies for Waste Management: Report on Project Descriptions

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007 , April 1995

system contains proprietary conditioning agents and a depolarizer that significantly reduces the input power cost and needs only minimum maintenance during processing.

Status

In 1995, pilot-scale studies with 1.5 ton samples of a soil retrieved from the Army firing range and contaminated with lead leached from bullets were conducted. As of June 1996, electrokinetic remediation at the demonstration site was operated on a remote basis from a central control house located at the site where DC input current, DC voltage, site resistivity, and pH can be measured. The demonstration site goal was to remove as much lead as possible from the soils between June and the end of 1996. For detail information on this project, please contact: Mr. Mark Bricka, Site Manager, Waterway Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180. Phone: (601) 634-3700.

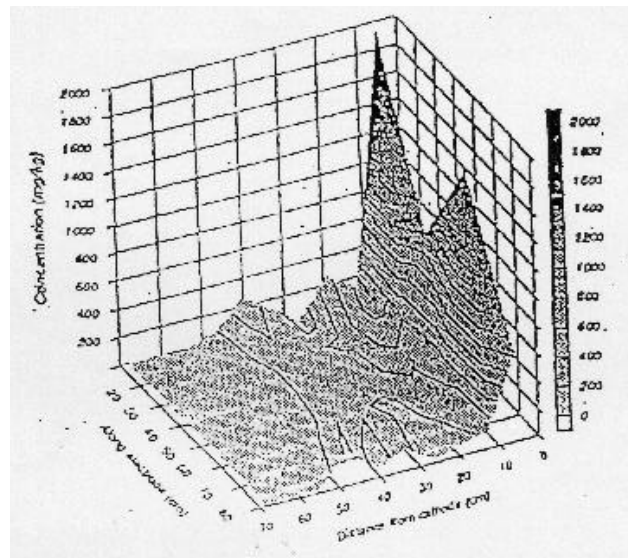


Figure 2
 Lead concentration profile after 123 days of processing kaolinite sand mixture spiked at 5,322 mg/kg. (Source: Electrokinetics, Inc., Technologies for Waste Management: Report on Project Descriptions)

A2

Research: Electrokinetic Enhancement³

Developer(s): Environmental & Technology Services (ETS)

Contact(s): Dr. Walter W. Loo
Environmental & Technology Services
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San Francisco, CA 94114
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Fax: (415) 861-3269

Research Description

Research and case closure was completed in 1991 at a site in Anaheim, California. The case involved remediation of 150,000 tons of soil contaminated with chlorinated solvents. The volatile organic compounds (VOCs) plume covered a 200 feet by 200 feet surface area. An electrokinetic electrode system involving electro-osmosis desorption of chlorinated VOCs from a 10-foot thick wet clay-composed layer was installed. Remediation of VOCs to less than 0.1 ppm was achieved. Remediation cost was at about \$17 per ton. The closure was approved by the Santa Ana Regional Water Quality Control Board and the Orange County Health Services in August 1991.

Another project conducted by ETS involved electrokinetic enhanced in-situ bioventing of gasoline and BTEX (benzene, ethylbenzene, toluene, xylene)-contamination in soil. The gasoline in soil was related to a 10,000-gallon underground storage tank spill in San Diego, California. The gasoline soil plume covered an area of about 2,400 square feet and to a depth of 30 feet with gasoline concentration ranging from 100 to 2,200 ppm. Direct current was applied through 56 electrodes installed in the upper clay layer to move the contaminants and water down 15 feet into dense cemented conglomerate sandstone where contaminants were removed by bioventing. Electrolysis of some water molecules, resulting from the electrical gradient, was thought to have produced hydroxyl ions that promoted oxidation of the contaminants. Total petroleum hydrocarbons (TPH) and BTEX were treated to non-detect in about 8 hours. The soil remediation effort was completed after about 90 days of treatment. The concentration of gasoline in soil after treatment was less than 40 ppm. The

³ Information provided was obtained from the following reports:

Loo, W.W. and Chilingar, G.V., Advances in the Electrokinetic Treatment of Hazardous Wastes in Soil and Groundwater, presented at *HAZMACON 97*, Santa Clara, California, pp. 1-15 (1997)

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, *EPA542-K-94-007*, April 1995

cost of treatment was about \$50 per ton for this advanced soil treatment process which provides a cost effective solution to this soil plume.

Another remediation effort in 1994 involved the removal of a 1,000-gallon underground storage tank located at a warehouse and distribution facility in Los Angeles (see Figure 3). The volume of the gasoline soil plume was estimated to be about 3,300 cubic yards and the TPH concentrations were as high as 23,000 ppm, with an average level of 3,000 ppm. The remedial system that was used included a heat enhanced bioventing system, an ultraviolet light disinfection system, granular activated carbon adsorption, and electrokinetic treatment which was designed to remediate the lower 5 feet, 35 to 40 feet below the surface grade, of low permeability clay-composed silts. The electrokinetic system was connected to direct current (DC) power supply. The system was operated at about 10 to 15 amperes of electricity flow to 'dry out' the clay-composed silts in the bottom 5 feet. After approximately 12 months, samples taken from the site indicated that the concentration of TPH as gasoline in soil after treatment was below 35 ppm. The effectiveness of the electrokinetics treatment of the clay-composed soil located at the 40-foot depth is given in Table 3.

Status

ETS is continuing to conduct research and remediation activities involving electrokinetic treatment of hazardous and toxic waste in soil and groundwater. Several state-of-the-art remedial technologies are being invented and implemented for use by Dr. Loo and ETS.

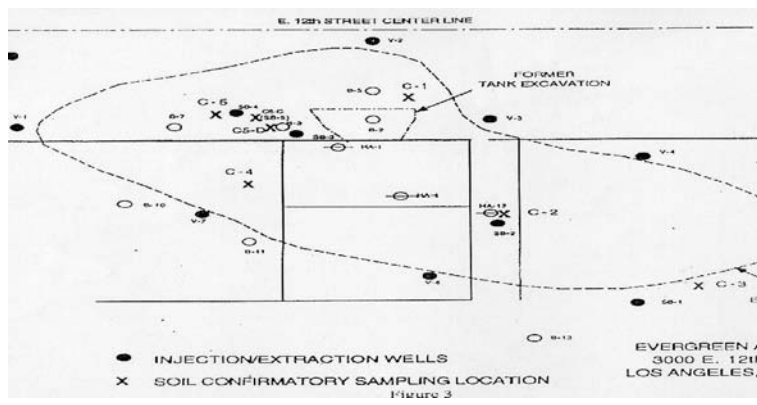


Figure 3
 Confirmatory sampling location (Source: Loo, W.W. and Chilingar, G.V., Advances in the Electrokinetic Treatment of Hazardous Waste in Soil and Groundwater, presented at HAZMACON 97, Santa Clara, California, pp. 1-15, 1997)

Table 3

Effectiveness of electrokinetic treatment of gasoline in clay-composed soil

(Source: Loo, W.W. and Chilingar, G.V., Advances in the Electrokinetic Treatment of Hazardous Waste in Soil and Groundwater, presented at *HAZMACON 97*, Santa Clara, California, pp. 1-15, 1997)

(All units are in mg/kg or ppm)

Before						After 12 months				
	TPH Gas	Benzene	Toluene	Ethylbenzene	Xylene	TPH Gas	Benzene	Toluene	Ethylbenzene	Xylene
C-1 Area	18	0.45	1.6	0.15	1.2	2.9	0.17	0.6	0.03	0.54
C-2 Area	1300	0.68	27	23	140	0.66	No data	0.18	0.06	No data
C-5 Area	87	0.28	2.7	1.4	8.7	1.7	0.07	0.43	0.04	0.51

A3

Research: Electrokinetic Remediation⁴

Developer(s): Geokinetics International, Inc. (GII)

Contact(s): Dr. Stephen R. Clarke
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E-mail: EDASteve@aol.com

Research Description

GII primarily uses an electrokinetic technology called the “Pool Process” (also called “closed loop process”) to remediate toxic heavy metals such as arsenic, chromium, nickel, copper, zinc, lead, and cadmium (see Figure 4). The major components of the Pool Process are as follows:

- ion-permeable electrolyte casings are placed in the contaminated media and connected to a centralized electrochemical ion-exchange (EIX) based electrolyte management system. Each casing has an electrode inside. Together, these form alternating rows of anodes and cathodes. Electrolyte is circulated in a closed loop between the electrode casings and the EIX units;
- electrolysis of water in the electrolyte results in the formation of H⁺ ions at the anodes and OH⁻ at the cathodes. These ions migrate through the casing into the soil generating a temporary and localized pH shift which desorbs contaminating ions;

⁴ Information provided was obtained from the Internet at the Geokinetics International, Inc. world wide web site at <http://www.geokinetics.com> and the following reports:

Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

- once desorbed, the contaminating ions migrate under the influence of the applied potential (electromigration) to their respective electrodes (anodes for anions, cathodes for cations). Here they pass through the electrode casing walls and are taken up by the circulating electrolytes. The pH at the anode and cathode is managed by the addition of acid or alkali as required;
- contamination is selectively recovered from the circulating electrolytes as they pass through the EIX units. Soluble but benign elements are returned to the soil to maintain soil properties;
- periodically the EIX units are regenerated by polarity reversal. This recovers the contaminants in a concentrated, pure and re-usable form.

Figure 5 shows some of the detail of the electrode wells. Figures 6, 7 and 8 show an example of an actual electrokinetic remediation of a lagoon of dredgings. GII's electrokinetic process can be operated in three separate ways:

- 1) *In situ remediation*: electrode wells are placed directly in the ground and contamination is recovered with the slightest disturbance to the site.
- 2) *Batch operation*: contaminated media is transported to a batch facility and treated ex situ. Batch times take between 1 to 5 days depending on electrode spacing and current loading.
- 3) *Electrokinetic Ring Fence (EKRF)*: this uses a chain of electrode pairs deployed in the ground to recover ionic contamination from groundwater as it flows past the electrodes. It is significantly more efficient than pump and treat and is sludge free.

The first ever commercial application of electrokinetics was conducted in a former paint factory, 'Oeverbosch' in Groningen, the Netherlands, by GII in 1987. The 400-cubic yard site was contaminated with 20,000 ppm of lead and 12,000 ppm of copper. A vertically installed array of alternating anodes and cathodes (each consisting of an electrode placed inside a semipermeable well casing) was spaced on 10-foot intervals. Anodes and cathodes were each connected to separate anolyte and catholyte management systems. Anolyte and catholyte pH was managed by the addition of acid or alkali as required. The recirculating electrolytes were periodically treated to remove collected contaminants and other ions. After 430 hours of operation, lead concentrations ranged from 90 to 700 ppm with an average reduction of 70 percent, while copper concentrations ranged from 15 to 250 ppm with an average reduction of 80 percent.

Another remediation project involving electrokinetics processing was conducted by GII during 1992. The project was performed at Woensdrecht on behalf of the Dutch ministry of defense. The work was undertaken at a former Dutch Royal Air Force base. The 3400-cubic yard site was contaminated with cadmium and other toxic heavy metals. Aircraft wash-down operations and plating shop activities were the main reasons for the contamination. The recovered material was placed in a temporary lagoon and treated in two large onsite batches. Large horizontal tubular cathodes and short vertical anodes were used. The cathodes were placed at 5-foot intervals at the bottom of the lagoon prior to it being filled with contaminated soil. The tubular anodes were placed at 5-foot intervals between the cathodes after the lagoon was filled. The electrokinetic process reduced cadmium concentrations from 7,300 ppm to 47 ppm in 580 days. All other toxic metal concentrations were also reduced significantly. This project is considered to be the largest electrokinetic project completed worldwide.

Status

GII continues to perform several remediation projects involving electrokinetics both in the United States and abroad. The commercial scale electrokinetic remediation technology used by GII is mainly used for the extraction of toxic metals and toxic anions from soil and groundwater. Table 4 summarizes GII's various completed and ongoing remediation projects.

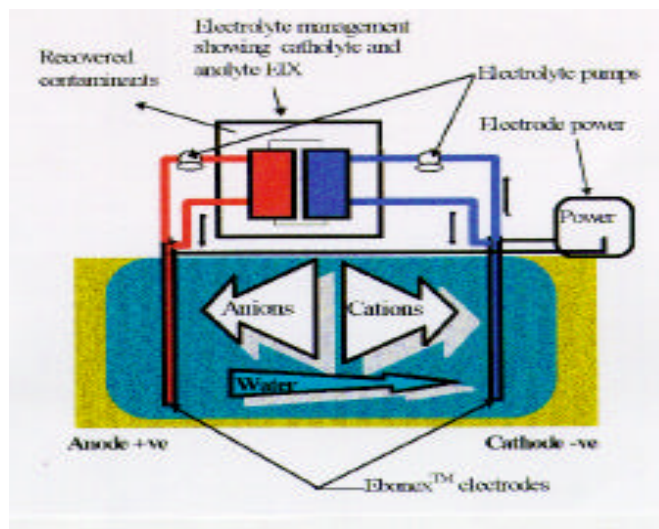


Figure 4
 Diagrammatic overview of the Pool Process (Source: Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)

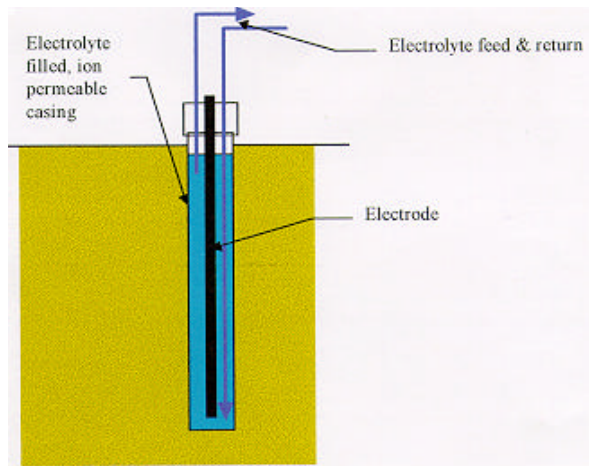


Figure 5

Detail of a general electrode well (Source: Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)



Figure 6

Lagoon based remediation of dredgings (Source: Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)



Figure 7
Electrodes in place before power is applied (Source: Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)



Figure 8
After remediation, electrodes removed (Source: Geokinetics, International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)

Table 4

Summary of Geokinetics International, Inc.'s various completed and ongoing remediation projects (Source: Geokinetics International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)

Year	Location	Client	Description	Cost
1997 - ongoing	California	Large International Chemicals Corporation	Pilot test of the recovery of Zn from 80,000 yd ³ chemical sludge ponds	Ongoing
1997 - ongoing	Virginia	Large US Engineering & Chemicals Corporation	Large pilot scale evaluation of Zn recovery from 200,000 yd ³ chemical sludge ponds	Ongoing
1997 - ongoing	Pearl Harbor - Oahu, HI	US Navy & EPA Office of Technology Development	In situ remediation of Pb from battery re-processing plant (1,500 yd ³)	Ongoing
1997 - ongoing	Alameda Naval Air Station	US Navy & EPA Office of Technology Development	Pilot scale (40 yd ³) recovery of Cr from former plating operations	Ongoing
1997	California	Large international water services company	Bench scale evaluation of Pb recovery from former battery plant	\$42,000
1996	California	EPA Region 6, Office of Emergency Response	Bench scale evaluation of Zn recovery from mine tailings	\$45,000
1996	California	Large US Industrial & Communications Company	Bench scale recovery of Cr from former plating shop	\$16,000
1996	California	EPRI & SoCal Eddison	Large bench scale study and conceptual design of Pb from battery manufacturing site	\$75,000
1992 - 1994	Temporary Landfill at the airbase of Woensdrecht	Ministry of Defence/DGWT	Form on site lagoon and in situ remediation of 3,400 yd ³ sludge contaminated with Cr, Ni, Cu, Zn and Cd	\$1,040,000

Table 4 (continued)

Summary of Geokinetics International, Inc.'s various completed and ongoing remediation projects (Source: Geokinetics International, Inc., Electrokinetic Remediation of Toxic Metals: Statement of Qualifications, June 1997)

Year	Location	Client	Description	Cost
1990 - 1992	Temporary Landfill "Vleddermond" at Stadskanaal	Municipality of Stadskanaal/Province of Groningen	Establish temporary landfill and in situ remediation of 2,500 yd ³ soil and sludges from gardens and canals at Stadskanaal contaminated with Cd	\$960,000
1989	Former wood impregnation plant "PERDOK" Loppersum	Kwint b.v./Municipality of Loppersum	In situ 300 yd ³ clay polluted with heavy metals Ar and Cu	\$160,000
1988	Galvanizing plant "Braat" at Deflt	Bammensgroep, Maarssen	In situ 300 yd ³ clay polluted with heavy metals Zn and Cd	\$160,000
1987	Former paint factory "Oeverbosch" at Groningen	Province of Groningen	In situ 400 yd ³ clay polluted with heavy metals Cu, Pb and Zn	\$120,000

A4

Research: Electrokinetic Remediation⁵

Developer(s): Isotron Corporation

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Research Description

Electrokinetics was used in situ in 1994 in the Old TNX Basin at the Savannah River Site in South Carolina to remediate mercuric nitrate contamination in unsaturated soil consisting primarily of sand and kaolinite. The ongoing project is supported by the U.S. Department of Energy's (DOE) Office of Technology Development. An ELECTROSORB™ process with a patented cylinder (see Figures 9 and 10) to control buffering conditions in situ and an iron exchange polymer matrix called ISOLOCK™ to trap metal ions were employed.

The electrodes are placed in boreholes in the soil and a direct current is applied (see Figure 11). Under the influence of the current, ions migrate through the pore water to an electrode, where they are trapped in the polymer matrix. If desired, the polymer can contain ion exchange resins or other sorbants that can trap and hold ions before they reach the electrode. When electric current is applied to the system, electrodes are monitored and periodically replaced with fresh electrode assemblies. This allows the used assemblies to be chemically treated and analyzed for the presence of mercury and other metals in the polymers and on the electrodes. The special features of this technology are

⁵ Information provided was obtained from the Internet at the Isotron Corporation world wide web site at <http://www.isotron.com> and the following report:

Isotron Corporation, Electrolytic Migration Technology For Mercury Decontamination of Old TNX Area, *Phase I Technical Report*, Subcontract No. AA89030P, July 1992

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

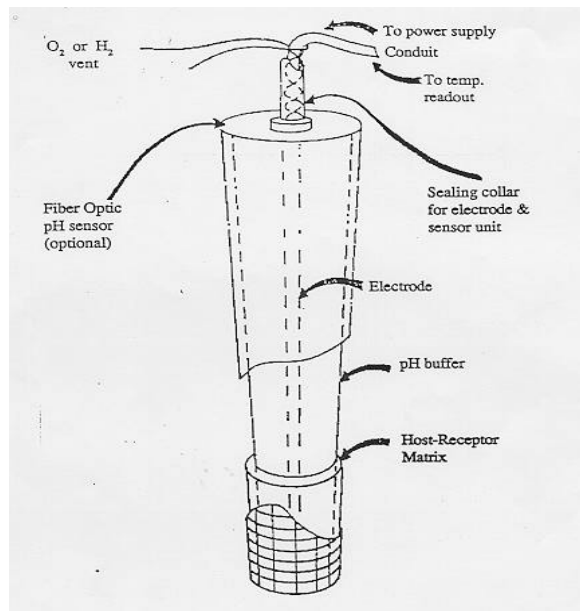


Figure 9
 ELECTROSORB™ Cell (Source: Isotron Corporation, Electrolytic Migration Technology For Mercury Decontamination of Old TNX Area, Phase 1 Technical Report, Subcontract No. AA89030P, July 1992)

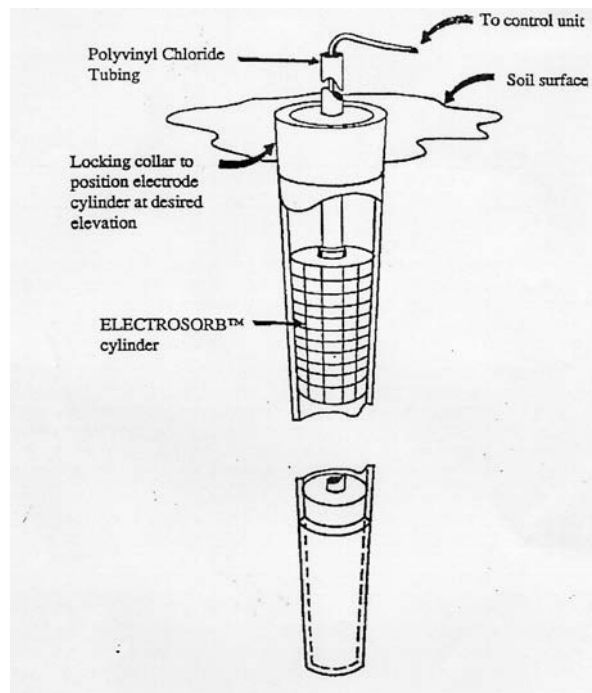


Figure 10
Installation of ELECTROSORB™ Cell (Source: Isotron Corporation, Electrolytic Migration Technology For Mercury Decontamination of Old TNX Area, Phase 1 Technical Report, Subcontract No. AA89030P, July 1992)

the polymer matrices that serve as ion traps. These matrices also serve as sources of chemicals that can regulate pH or that will enhance the efficiency of the process. Preliminary investigations indicated that mercury concentrations ranging from 10 to 20 ppm were found in the Basin.

Status

After the conclusion of the field demonstration at the Savannah River Site in 1995, the ELECTROSORB™ technology (see Figure 12) was also successfully used on a Unit 7 mine site in Uzbekistan to decontaminate a 10,000 meter area contaminated with gamma emitting radionuclides (uranium). The gamma range was reduced from 50-99 percent in some areas after application of the technology.

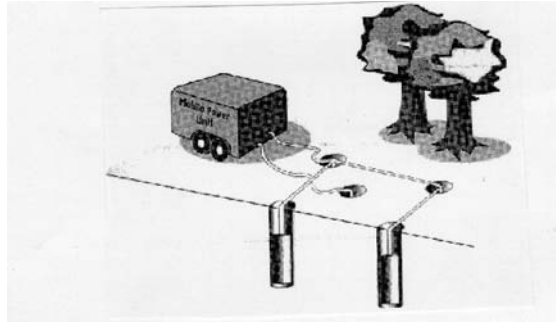


Figure 11
 Isotron Electrode Array at Old TNX Basin (Source: Isotron Corporation world wide web site at <http://www.isotron.com>)

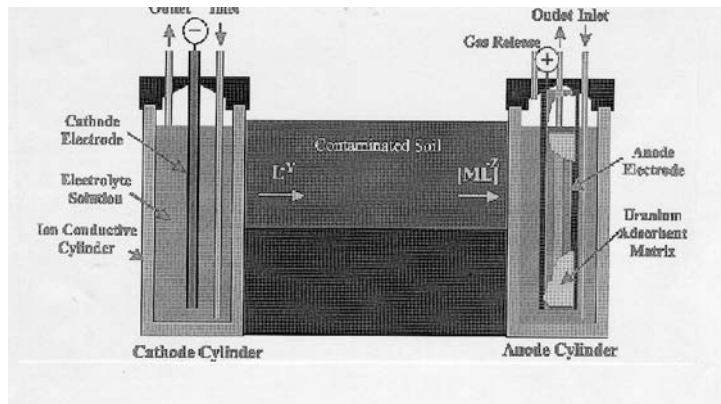


Figure 12
 Example of an application for uranium decontamination using ELECTROSORB™ cylinders
 (Source: Isotron Corporation world wide web site at <http://www.isotron.com>)

CATEGORY B

**Electrokinetic processes which are currently in the experimental testing stage
at bench, pilot or field scale**

Table 5
Category B Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels before and after remediation	Treatment cost
Consortium of Monsanto, DuPont and General Electric — Lasagna™ Process	clay-composed with gravel and sand layers	2-7 feet	15 feet	100-140 volts 40-45 amperes	not available	15 feet by 10 feet Depth of 15 feet	TCE	4-36 months	<u>Before</u> 1 ppb to 1760 ppm <u>After</u> < 1.5 ppm	\$40-\$90 per cubic yard
Electrokinetics, Inc. (EK) — Electro-Klean™ Soil Processing	saturated/unsaturated sands, silts, fine-grained clay, sediments	3 feet	3 feet	450-600 volts 15-20 amperes	acetic acid	Lead contaminated site: 10 feet by 34 feet Depth of 3 feet	uranium, thorium, radium, arsenic, BTEX compounds, cadmium, chromium, copper, lead, nickel, phenol, TCE, zinc	1-6 months	<u>Before</u> uranium: 1,000 pCi/g thorium: 50-300 pCi/g radium: 1,000 pCi/g lead: 2,000 ppm <u>After</u> uranium: 95% removal thorium, radium: not available lead: 25%-50% removal	\$50-\$150 per ton

Table 5 (continued)
Category B Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels before and after remediation	Treatment cost
Electro-Petroleum, Inc. and Lehigh University	kaolinite clay, sand	not available	not available	30 volts 1.5 amperes	ethylenedi-amine (EDA), distilled water	Laboratory soil sample tube 7.62 cm long and 3.55 cm deep	uranium, strontium, cesium, chromium, cobalt, cadmium, mercury, lead, nickel, zinc, hydrocarbons	24-170 hours	<u>Before</u> U: 10-100 ppm Sr, Cs: 1,000 ppm Cr: 3,000 ppm Hg: 5-130 ppm Ni: 1,000 ppm Pb: 15,000 ppm Zn: 22,500 ppm <u>After</u> U: 30%-80% removal Sr: 95%-100% removal Cs: 70%-90% removal Cr: 95% removal Hg: 60%-80% removal Ni: 94% removal Pb: 60%-85% removal Zn: 35%-65% removal	\$37.5 per cubic yard

Table 5 (continued)

Category B Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels before and after remediation	Treatment cost
Isotron Corporation — SEEC™ Pad Technology and ELECTROSORB™ Process	sand, kaolinite	4-5 feet	2 feet	90-100 volts 40-50 amperes	citrate and carbonate salts	8 feet by 9 feet Depth of 2 feet	uranium, mercury	20-40 days	<u>Before</u> uranium: 600 ppm <u>After</u> uranium: > 99% removal	\$95 per ton
Lynntech, Inc.	low permeability soils (clay)	not available	not available	not available	not available	not available	chromium, lead, chlorinated hydrocarbons	3-9 months	<u>Before</u> not available <u>After</u> lead: 65% removal	\$65-\$125 per cubic yard
Massachusetts Institute of Technology (MIT)	kaolinite	20 centimeters	1.5 centimeters	20 volts	acetic acid	Laboratory sample cylinder 200-mm long and 32-mm in diameter	zinc, phenol	9-60 days	<u>Before</u> 40% water + 500 mg/L zinc 60% kaolin clay phenol: 45-450 ppm <u>After</u> zinc: 98% removal phenol: 94% removal	\$20-\$30 per ton

Table 5 (continued)
Category B Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels before and after remediation	Treatment cost
Sandia National Laboratories (SNL)	unsaturated soils with 25% saturation	not available	15 feet	not available	sodium chloride	700 to 1,000 cubic feet (depth of 15 feet)	uranium, chromium	4-12 months	<u>Before</u> chromium: 25-10,000 ppm <u>After</u> chromium: 75%-90% removal	\$50-\$150 per ton
Texas A&M University	kaolinite, saturated silty clay	5 meters	5 meters	100 volts	citric acid, acetic acid, disodium ethylnedi-aminetetraacetate (EDTA)	50 meters by 100 meters Depth of 5 meters	copper, lead, organics	6 months	Pb: 5,000 ppm removal Cu: 10,000 ppm removal	\$39 per unit volume

B1

Research: Lasagna™ Process⁶

Developer(s): Consortium consisting of Monsanto, E.I. du Pont de Nemours & Co. (DuPont), and General Electric (GE)

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Research Description

In early 1994, EPA signed a Cooperative and Research and Development Agreement (CRADA) with a private research Consortium — consisting of Monsanto, DuPont and GE — to jointly develop an integrated, in situ remedial technology, referred to as the Lasagna™ process. The Consortium's activities are being facilitated by Clean Sites, Inc., under a Cooperative Agreement with EPA's Technology Innovation Office. The overall objective of the Consortium is to sufficiently develop the integrated in situ remediation technology so that it can be utilized for site remediation. Figure 13 shows the major contributions of the participating Consortium members.

The Lasagna™ process remediates soils and soil pore water contaminated with soluble organic compounds. Lasagna™ is especially suited to sites with low permeability soils where electro-osmosis can move water faster and more uniformly than hydraulic methods, with very low power consumption. The process uses electrokinetics to move contaminants in soil pore water into treatment zones where the contaminants can be captured or decomposed.

⁶ Information provided was obtained from the Internet at the Monsanto world wide web site at <http://www.monsanto.com> and the following report:

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

Highly permeable subsurface sorption zones will be created in vertical configuration by hydraulic fracturing or similar technology followed by the introduction of certain sorbants. The electrodes, placed vertically on either side of contaminant plume, will flush contaminants by electro-osmotic flow into sorption zones containing certain sorbants. (The electrodes may be constructed horizontally or vertically depending on the site and contaminant characteristics.) The layered configuration of the electrodes and degradation zones is shown in Figure 14. The contaminant targeted in this proposed program is trichloroethylene (TCE).

The major features of the technology are:

- electrodes energized by direct current, which causes water and soluble contaminants to move into or through the treatment layers and also heats the soil;
- treatment zones containing reagents that decompose the soluble organic contaminants or adsorb contaminants for immobilization or subsequent removal and disposal; and
- a water management system that recycles the water that accumulates at the cathode (high pH) back to the anode (low pH) for acid-base neutralization. Alternatively, electrode polarity can be reversed periodically to reverse electro-osmotic flow and neutralize pH.

The major limitations to the Lasagna™ process are the following:

- treatment chemistry and procedures need to be developed to ensure compatibility of the treatment processes for individual contaminants;
- problems in maintaining appropriate electrical contact to electrodes and trapping gases generated by electrolysis need to be resolved; and
- for field implementation, bioremediation in Lasagna™ treatment zones need to be further developed.

In early 1995, with significant funding by DOE, the work group initiated a field experiment at the DOE Paducah Gaseous Diffusion Plant (PGDP) in Kentucky, which has clay-composed soil contaminated with TCE, to test the vertical configuration of the Lasagna™ process. The PGDP site consists of a 4-foot layer of gravel and clay overlaying a 40-foot layer of sandy clay loam with interbedded sand layers. The clay soil had been contaminated with TCE at concentrations ranging

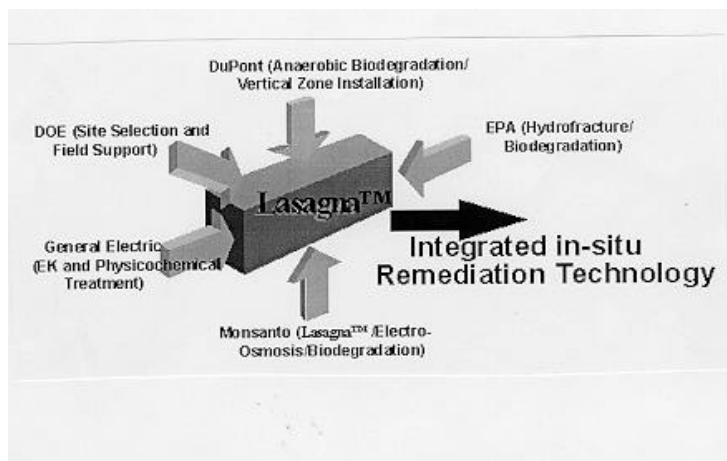


Figure 13
Major contributions of the participating Consortium members (Source: Monsanto world wide web site at <http://www.monsanto.com>)

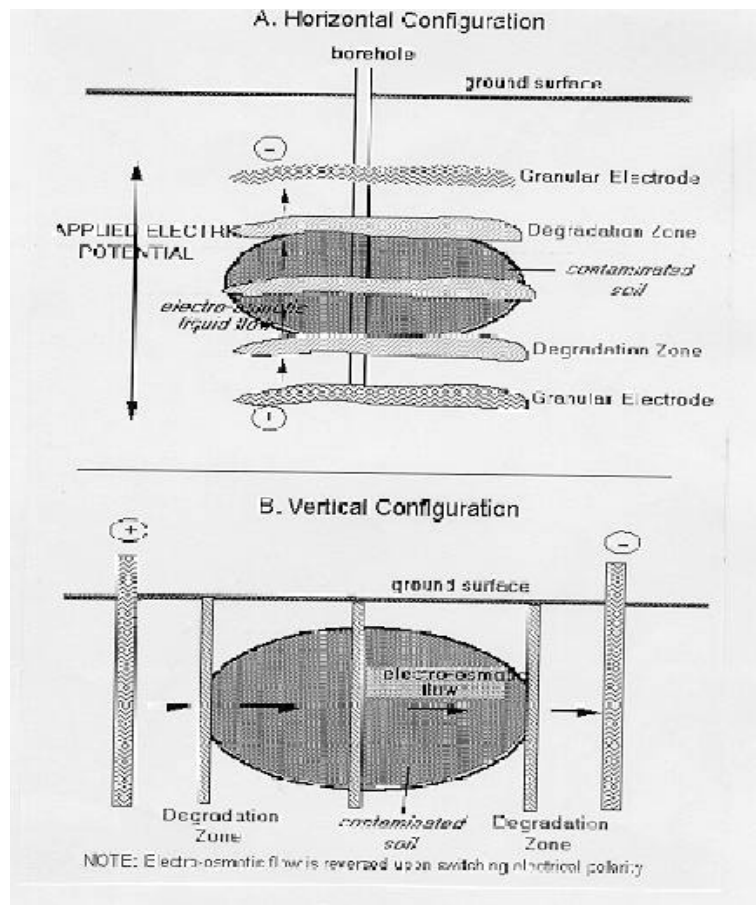


Figure 14
Layered horizontal and vertical configuration of the electrodes and degradation zones (Source: Monsanto world wide web site at <http://www.monsanto.com>)

from 1 ppb to 1,760 ppm. The average contamination at the PGDP site was 83.2 ppm. Due to low organic content, the soil adsorbed very little TCE.

Status

Installation procedures of important elements of the field experiments in the vertical configuration were conducted in the summer of 1994. CDM Federal Programs Corporation conducted preliminary field tests, and in November 1994 they installed the field experiment at the DOE PGDP site. The Phase I-Vertical field test, which operated for 120 days at the site, was successfully completed in May 1995. Soil samples taken throughout the test site before and after the test indicate a 98-percent removal of TCE, from a tight clay soil. A Phase II-Vertical field experiment was planned at the Paducah site for 1996. This phase is expected to consist of two stages. In the first stage (Phase IIa-Vertical), the Lasagna™ process will be used to treat 20 times more soil than Phase I. If successful, this will be followed by a full-scale first application demonstration encompassing the entire contaminated region (105 ft x 60 ft x 45-ft deep), with treatment to be completed in 12 to 24 months. In addition, Phase I-Horizontal field tests in TCE-contaminated soils using the Lasagna™ process, were to be conducted during the summer and fall of 1996 at sites in Ohio and Nebraska, where preliminary testing has already been conducted.

The technology implementation cost for Lasagna™ as conducted in the Phase I test (steel plate electrode with wick drains and carbon-filled treatment zone) is estimated at \$80-\$90 per cubic yard for remediation in 1 year, \$50-\$60 per cubic yard if 3 years are allowed for remediation. Comparable estimates for the Phase II mode of operation are \$60-\$70 per cubic yard (1 year) and \$40-\$50 per cubic yard (3 years). Deeper contamination, although involving more technically challenging enhancement, costs less because of the larger volumes remediated per electrode.

B2

Research: Electro-Klean™ Electrokinetic Soil Processing⁷

Developer(s): Electrokinetics, Inc. (EK)

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Research Description

Electro-Klean™ is a process that removes or captures heavy metals, radionuclides, and selected volatile organic pollutants from saturated or unsaturated sands, silts, fine-grained clays, and sediments. Electro-Klean™ can be applied in-situ or ex-situ, and uses direct currents with electrodes placed on each side of the contaminated soil mass. Conditioning fluids may be added or circulated at the electrodes to enhance the electrochemistry of the process. An acid front migrates towards the negative electrode (cathode) and contaminants are extracted through electroosmosis and electromigration (see Figure 15). The concurrent mobility of the ions and pore fluid decontaminates the soil mass. Contaminants are electroplated on the electrodes or separated in a post-treatment unit. Bench scale tests have removed arsenic, benzene, cadmium, chromium, copper, ethylbenzene, lead, nickel, phenol, trichloroethene, toluene, xylene, and zinc from soils. EPA has initiated the Volume

⁷ Information provided was obtained from the following journals and reports:

Acar, Y.B. and Alshwabkeh, A.N., Principles of Electrokinetic Remediation, *Environmental Science and Technology*, Vol. 27, No. 13, pp. 2638-2647 (1993)

Acar, Y.B., Gale R., Marks R.E., and Ugaz, A., Feasibility of Removing Uranium, Thorium, and Radium from Kalonite by Electrochemical Soil Processing, *U.S. Environmental Protection Agency*, No. 009-292, Electrokinetics, Inc., LA (1992)

Electrokinetics, Inc., Technologies for Waste Management: Report on Project Descriptions

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

Reduction and Chemical Extraction (VORCE) project to investigate technologies that can reduce the volume of soil contaminated with radioactivity at Superfund sites. The use of electrokinetics has been included for investigation as a potential VORCE technology.

There are however some limitations to the technology. Some of the major limitations to the technology are that: 1) it is less cost-effective in sands and gravels for removal of VOCs as these compounds are more easily removed by vacuum extraction, bioventing and soil washing techniques; and 2) complex mixtures of heavy metals, radionuclides and organic pollutants can affect the electrochemistry and result in loss of removal efficiency.

Bench scale studies under EPA's SITE Program also demonstrated the feasibility of removing uranium, thorium and radium from kaolinite. Uranium removal tests at 1,000 pCi/g of activity demonstrated that the process efficiently removed uranium from kaolinite. Removal efficiency decreased from the anode towards the cathode, due to increase in pH. A yellow uranium hydroxide precipitate was encountered in sections close to the cathode and on the cathode. Formation of this precipitate increases the resistivity, the voltage gradients and energy expenditure. Acetic acid introduction at the cathode successfully prevented the precipitation encountered close to the cathode and 95% of uranium removal was achieved. Thorium removal tests at 50-300 pCi/g of activity have demonstrated that thorium is only removed by migration from the leading anode sections of the cell. Complex species that can reduce the net ionic charge on the thorium species are necessary in order to efficiently remove thorium by electrokinetics. Radium tests at 1,000 pCi/g of activity have demonstrated minimal removal across the test cells. The only rational explanation is the extremely low solubility of the precipitated radium sulfate species. Similar to the tests results for thorium, complex species are necessary to remove radium.

Status

Theoretical and experimental modeling, bench scale, and pilot scale feasibility studies are routinely performed in EK laboratories for an assessment of the potential to extract hazardous metals, organics or radionuclides using in-situ electrokinetic remediation and/or in-situ electrokinetic bioremediation.

A pilot scale laboratory study investigating removal of 2,000 $\mu\text{g/g}$ lead loaded into kaolinite was completed in 1993. Removal efficiencies of 90 to 95 percent were obtained. The electrodes were placed 3 feet apart in a 2-ton kaolinite specimen for 4 months, at an energy cost of about \$15 per ton. The results of a second pilot-scale laboratory study using 5,000 $\mu\text{g/g}$ of lead absorbed on kaolinite showed similar efficiency results as the earlier study.

In 1994, EK developed a mathematical model for multicomponent contaminant transport of reactive species under an electric field. Three pilot scale tests were conducted using soil specimens weighing 1 ton in each test. The objective of these tests was to investigate the effect of up-scaling bench scale tests to pilot scale tests. These tests evaluated the feasibility and cost efficiency of electrokinetic soil remediation at dimensions representing field conditions, and also assessed the hypothesized principles of multicomponent contaminant transport under an electric field. Pilot scale tests demonstrated up to 98 percent lead removal from soils. Also in 1994, EK, in collaboration with a Norwegian firm, conducted bench scale tests on samples retrieved from a site in Heimdal, Norway, to assess the efficiency of removing chromium and to evaluate the efficiency of two different techniques proposed for enhancement. These tests were run for about 1200 to 1400 hours and, as a result, 68 percent of the initial chromium present in the soil was removed. A pilot scale testing study in collaboration with the Norwegian firm is currently in the planning stages.

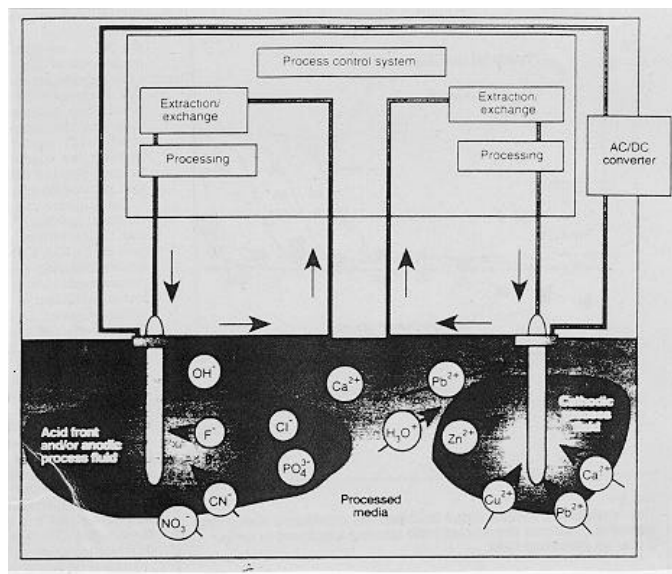


Figure 15

Metals removal at cathode (Source: Acar, Y.B. and Alshwabkeh, A.N., Principles of Electrokinetic Remediation, Environmental Science and Technology, Vol. 27, No. 13, pp. 2638-2647, 1993)

B3

Research: In Situ Electrokinetic Soil Processing⁸

Developer(s): Electro-Petroleum, Inc. and Lehigh University

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Research Description

Most of the research for the In Situ Electrokinetic Soil Processing has been conducted under two contracts through the Argonne and Sandia National Laboratories. Studies in the laboratory were conducted jointly by Electro-Petroleum, Inc. and Lehigh University. The research was composed of two phases of laboratory work.

In the first phase, short-term tests were carried out on the samples. The contaminant levels selected in the experiments were typical of levels to be found at various DOE sites. The laboratory experiments have shown mobilization of 11 heavy metals and 6 organic compounds in 5 soil matrices. The degree of success of decontamination seemed to be parameter specific and is more dependant on the type of contaminant to be removed than the type of medium being decontaminated. Researchers determined that this electrokinetic process can treat soils, sludges, and sediments

⁸ Information provided was obtained from the following journals and reports:

Wittle, J.K. and Pamukcu, S., Electrokinetic Treatment of Contaminated Soils, Sludges, and Lagoons. Final Report, DOE/CH-9206, U.S. Department of Energy, Argonne National Laboratory, (1993)

Wittle, J.K. and Pamukcu, S., Electrokinetically Enhanced In-situ Soil Decontamination, in Wise and Trantolo (eds.) *Remediation of Hazardous Waste Contaminated Soils, Chapter 13*, New York: Marcel Dekker, pp. 245-298 (1993)

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

contaminated with heavy metals (cadmium, mercury, lead, nickel, zinc), volatile and semi-VOCs, solvents, BTEX compounds, surrogate radionuclides (cobalt, cesium, strontium, uranium) and inorganic cyanides. It was determined, however, that the process works best on clay-composed soils with low hydraulic permeability. Electrokinetic permeabilities for aqueous systems in clays have been demonstrated to be up to one thousand times greater than normal hydraulic permeabilities, and some heavy metals have exhibited removal efficiencies of up to 100 percent.

The second phase of work involved development of a model of contaminant transport in soils. Testing of removal of soil contaminated with strontium and acetic acid was carried out. The model predicted a slower rate of removal of strontium and a faster rate of removal for acetic acid than what the laboratory tests demonstrated. In all the electrokinetics experiments, a constant 30-volts DC potential was applied across the electrodes. The actual voltage gradient in soil varied in time and space and also with type of soil contamination pair.

Status

The laboratory experiments demonstrated the capability to mobilize ionic and non-ionic contaminants through various types of soil. The experiments also indicated that electrokinetics process has the potential to solve soil remediation problems under a broad range of real site conditions. The process can work well together with a surfactant flush, pump and treat system. Although reductions of up to 100 percent have been demonstrated in the laboratory, field testing and treatability studies on site-specific soil samples using electrokinetics processes are still under development.

A cost evaluation based on laboratory results and previous in-field investigations provided the basis for estimating the treatment costs. For a 10,000-cubic yard site including equipment, power and post-waste treatment, the cost is on the order of \$37.5 per cubic yard.

B4

Research: Electrokinetic Enhancement⁹

Developer(s): Environmental & Technology Services (ETS)

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Research Description

Several bench scale and field demonstrations of electrokinetic treatment were conducted on selenium, boron, chlorinated solvents, and fuel hydrocarbons. A description of the various research activities is explained below.

In 1996 at the Panoche Water Drainage District (PWDD) in Firebaugh, California, ETS conducted an in-situ electrokinetic treatment project. The objectives of the in-situ treatment were to:

- reduce the dissolved selenium in the PWDD drainage runoff water;
- reduce the dissolved boron in the PWDD drainage water to the extent possible that the water can be recycled for crop irrigation water uses; and
- reduce the dissolved solids in the PWDD drainage runoff water to the extent possible that the water can be recycled for crop irrigation water uses.

⁹ Information provided was obtained from the following reports:

Loo, W.W. and Chilingar, G.V., Advances in the Electrokinetic Treatment of Hazardous Wastes in Soil and Groundwater, presented at *HAZMACON 97*, Santa Clara, California, pp. 1-15 (1997)

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, *EPA542-K-94-007*, April 1995

The in-situ electrokinetic treatment systems were installed and conducted at DP-25 site and Area 27 of PWDD as represented in Figures 16 and 17. ETS recommended that PWDD proceed with the design of a drainage water quality management program by installing a network of electrokinetic systems along the interceptor drain at DP-25.

Another research activity includes two case closures at a site located in Emeryville, California, with the biodegradation of chlorinated solvents (TOX). In 1989, ETS successfully demonstrated the field closure of the biodegradation of trichloroethene (TCE) and trichloroethane (TCA) together with toluene in soil through heat and nutrient enhancement by the growth of *Bacilli* and *Pseudomonas fluorescens*. In 1992 and 1993, a TOX contaminated aquifer at the site was remediated by electrokinetic enhanced in-situ passive cometabolic treatment.

Status

ETS is continuing to conduct research, field and remediation activities involving electrokinetic treatment of hazardous and toxic wastes in soil and groundwater. Several state-of-the-art remedial technologies are being invented and implemented for use by Dr. Loo and ETS.

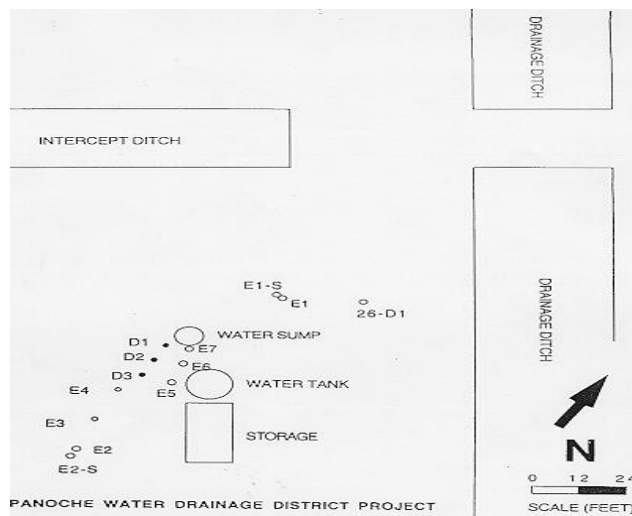


Figure 16
 Site map of DP-25 Sump Area (Source: Loo, W.W. and Chilingar, G.V., Advances in the Electrokinetic Treatment of Hazardous Wastes in Soil and Groundwater, presented at HAZMACON 97, Santa Clara, California, pp. 1-15, 1997)

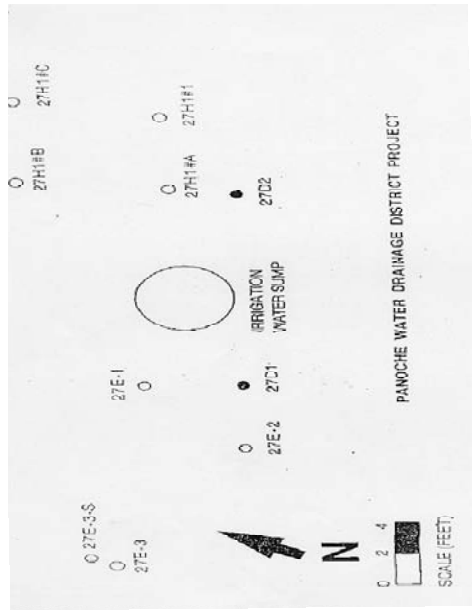


Figure 17

Site map of Area 27 (Source: Loo, W.W. and Chilingar, G.V., Advances in the Electrokinetic Treatment of Hazardous Waste and Groundwater, presented at *HAZMACON 97*, Santa Clara, California, pp. 1-15, 1997)

B5

Research: Electrokinetic Extraction¹⁰

Developer(s): Isotron Corporation

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Research Description

The effectiveness of electrokinetics to move and capture uranium and organic contaminants in soil was carried out in this demonstration project. The demonstration was supported by the U.S. DOE's Office of Technology and Development. Isotron's concrete decontamination technology applies an electric field to induce migration of ionic contaminants from within the porous concrete into the Isotron decontamination unit. The system utilizes the company's patented ELECTROSORB™ process and SEEC™ pad technology (see Figure 18). The electrolyte solution contains materials to promote formation of a soluble ionic complex of each specific contaminant present. The electrolyte solution is in contact with the concrete surface through the carpet-like SEEC™ pad, which partially removes contaminants from the electrolyte solution and limits the bulk flow of the electrolyte solution. All contaminants are collected in the aqueous electrolyte solution which flows into the separation module where the contaminants are removed. The contaminants are then collected in a disposable cylinder or sorbent material.

The SEEC™ pad technology was used on a concrete structure at the K-25 building site in Oak Ridge, Tennessee. The project combines the use of selective extractants (citrate and carbonate salts) to

¹⁰ Information provided was obtained from the Internet at the Isotron Corporation world wide web site at <http://www.isotron.com> and the following reports:

Isotron Corporation, Electrokinetic Extraction of Uranium From K-25 Soil, *Final Technical Brief*, November 1995

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, *EPA542-K-94-007*, April 1995

remove the uranium with electrokinetics to transport the contaminants to ion exchange media. The media surrounding the electrodes capture and concentrate the uranium for later recovery or disposal (see Figure 19). The electrokinetics demonstration process was carried out at the K-25 site over an area measuring 8 feet x 9 feet with an approximate volume of 144 cubic feet contaminated soil. The depth of the uranium contamination at this site was approximately 2 feet. An average uranium concentration of 600 ppm was estimated. The demonstration area was covered with 6 SEEC™ pads and the electrodes are buried at a depth of 2 feet with spacing 4.5 feet apart. A 40-ampere current is applied at a voltage gradient of 90 volts across the electrodes. The partial cost (not including labor and excavation cost) for the field demonstration was \$95 per ton of soil.

Status

Laboratory tests completed in 1994 using site soil showed that the process could move and capture 99 percent of the uranium. A final treatability test report and a site characterization report was issued in 1995 (see references). Isotron is continuing to use its patented electrokinetic technologies to remediate contaminated hazardous waste. Technological advances made by Russian scientists in this area of environmental remediation are being used as much as possible in conjunction with Isotron's own technology.

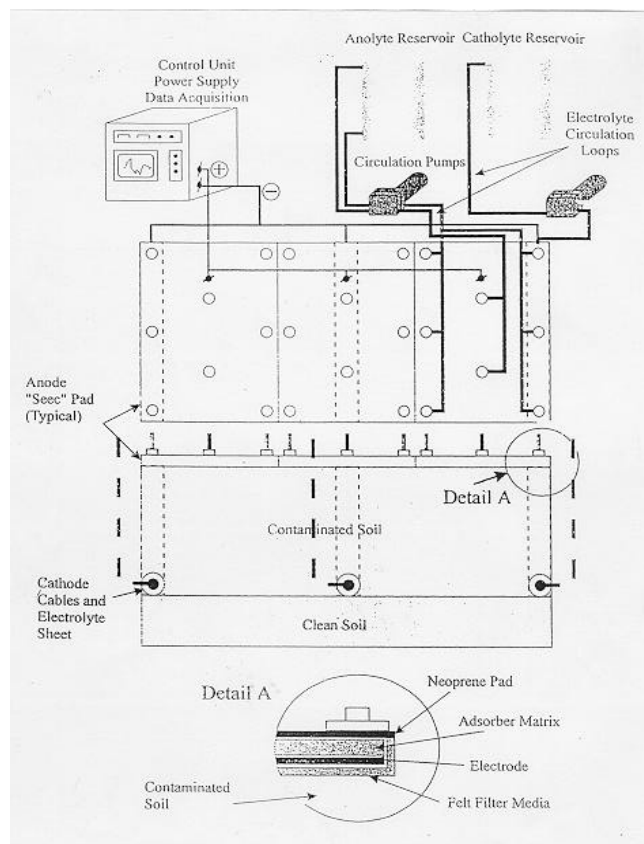


Figure 18
 General arrangement of a demonstration using SEEC™ Pad technology (Source: Isotron Corporation, Electrokinetic Extraction of Uranium From K-25 Soil, Final Technical Brief, November 1995)

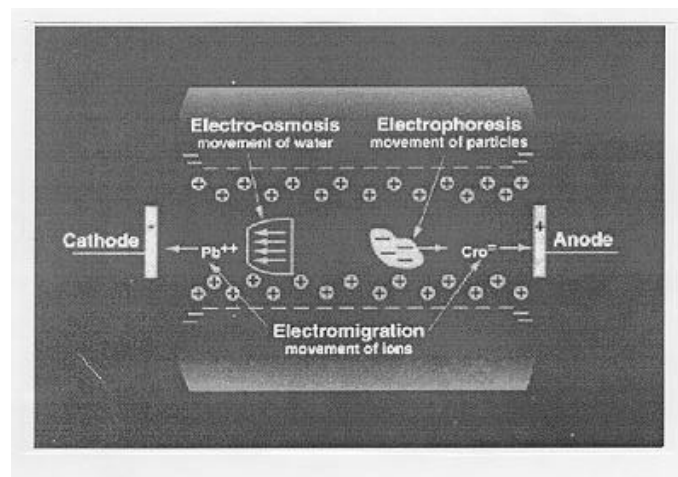


Figure 19

A general illustration of contaminant transport processes induced by applying direct current between buried electrodes (Source: Isotron Corporation world wide web site at <http://www.isotron.com>)

B6

Research: Electrokinetic Soil Processing¹¹

Developer(s): Lehigh University

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Research Description

The critical parameters of electroosmosis and flow enhancing ions have been investigated in a series of laboratory experiments. Laboratory tests on soil contents collected from a former manufactured gas plant (MGP) site indicate that electrokinetic processes can assist in the transport and removal of coal tar constituents from contaminated soils.

From 1992 to 1993, investigators conducted long-term electrokinetic tests on soil cores collected from a former MGP site. Some of the tests were enhanced by injecting solubilizing agents (surfactants) into the soil. Researchers subjected samples to varying levels of water flow, depending on the physical properties of the soil, for a period of 3 to 4 weeks. During each test, they monitored the systems for voltage, current, and in-flow and out-flow of liquid through the soil. After each test, they analyzed soil specimens for polynuclear aromatic hydrocarbon (PAH) concentration profiles and pH profiles to determine the extent of PAH transport and removal.

¹¹ Information provided was obtained from the following reports:

Pamukcu, S., Electrokinetic Removal of Coal Tar Constituents from Contaminated Soils, *Electric Power Research Institute Report*, EPRI-TR-103320, Palo Alto, CA, p 32 (1994)

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

The study demonstrated successful removal of 16 targeted PAH compounds from the soil (clay or granular) at a removal rate of 44 to 70 percent upon 2 to 9 pore-volumes of electro-osmotic water flow through the soil specimens. In general, the degree of success of decontamination by electrokinetic processes appeared to be parameter specific; more dependent on the type of the contaminant to be removed than the type of medium being contaminated. Electroosmosis appeared to be the dominant mechanism of transport when the contaminants present in the aqueous phase were nonpolar or nonionic, neutral micelles or surface-coated colloids.

Investigations of clay or clay mixtures and a known concentration of a selected heavy metal salt solution or an organic compound (such as sodium dodecylbenzene sulfonate) showed up to 99 percent heavy metal removal, and high removals of some organic compounds such as phenol, acetic acid, and O-nitrophenol. In addition, removal of radionuclides was also achieved. A cost evaluation based on laboratory results and previous in-field investigations provided the basis for estimating the treatment costs. For a 10,000 cubic yard site including equipment, power and post-waste treatment, the cost is on the order of \$37.5 per cubic yard.

Status

Further research and development of this method is being conducted to determine if the electrokinetics process can be used on a field scale to provide a reliable method for in-situ remediation of MGP sites.

B7

Research: Electrokinetic Remediation¹²

Developer(s): Lynntech, Inc.

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Research Description

Researchers at Lynntech have studied methods to combine electrokinetics and bioremediation, an effective low environmental impact treatment process, for in situ degradation of a wide range of organic pollutants. Bioremediation has two major disadvantages: 1) slow rate of action; and 2) its adverse effect on low permeability soil (such as clay). Electrokinetic process can overcome these disadvantages by:

- enabling movement and delivery of essential nutrients to the anaerobes; and
- uniform delivery of nutrients in low permeability soils

Although this method is in its early stage of development, there is an enormous commercial potential for this technology because of its low cost of implementation.

Lynntech has also successfully completed a 3-month field demonstration test for removal of heavy metals from soil at Radford Army Ammunition Plant in Radford, VA. During this test, more than 65 percent of lead contamination was removed. The method does not involve excavation or offsite transportation, does not create any environmental impact and is a favorable approach in terms of public perception.

¹² Information provided was obtained from the following report:

Hodko, D. and Rogers, T.D., Lynntech, Inc. Electrokinetics Technology Capabilities Brochure, August, 1997

The treatment costs, based on actual field experience range from \$65-\$125 per cubic yard of treated soil. The Lynntech field technology (see Figures 20 and 21) is fully automated and once installed, can be operated and monitored remotely, thus minimizing process and project cost.

Status

Lynntech is at present conducting a field demonstration in Florida at the Kennedy Space Center to practically apply the combinational bioremediation-electrokinetic process based on laboratory tests. This project is being conducted for the National Aeronautics and Space Administration (NASA) under the Small Business Innovative Research (SBIR) program. A summary of Lynntech's completed and ongoing electrokinetic projects is listed in Table 6.



Figure 20

Lynntech's Electrokinetic Field Technology (Source: Lynntech, Inc. capabilities brochure)



Figure 21

Lynntech's Electrokinetic Field Technology (Source: Lynntech, Inc. capabilities brochure)

Table 6
 Successfully completed or on-going electrokinetic remediation projects carried out by Lynntech since 1993 (Source: Lynntech, Inc. capabilities brochure)

Project Title	Client	Accomplishment
Pulsed DC Electric Fields for Heavy Metals Decontamination of Soil	DOD: \$50K 9/92 - 3/93	One of the first demonstrations of the value of non-uniform electric fields in electrokinetics
Pulsed DC Electric Fields for Heavy Metals Decontamination of Soil <i>- Field demonstrated in 1995</i>	DOD: \$683K 9/92 -12/95	Successful field implementation of electrokinetic for metal recovery. Significant developments made in process design and control
Dielectrophoresis: Application to Polluted Soil Remediation	NSF: \$65K 1/94 - 8/94	Implemented new electric field effects with unique applications to nonmetallic contaminants
In Situ Degradation of Dioxins by Chemical Oxidation	DOD (Air Force): \$58K 5/94 - 11/94	Laboratory demonstration of a combined electrokinetic/soil oxidation system
In Situ Degradation of Dioxins by Chemical Oxidation <i>- Field demonstrated in 1997</i>	DOD (Air Force): \$705K 5/95 - 5/97	At the time of its initiation, the first field scale implementation of electrokinetics for chemical oxidant delivery. Made substantial improvements in field hardware and installation procedures
Engineered Bioremediation of Contaminated Soil Through Enhancement of Microbial Populations	NASA: \$70K 11/94 - 5/95	A laboratory system demonstrating the use of electrokinetic soil processing to enhance bioremediation
Engineered Bioremediation of Contaminated Soil Through Enhancement of Microbial Populations <i>- 9-month field demonstration in progress at Kennedy Space Center</i>	NASA: \$539K 3/96 - 3/98	Field demonstration of electrokinetics to control soil redox chemistry to promote anaerobic biodegradation of chlorinated solvents. Advancements in electrode well designs made
New Electrochemical Process for In Situ Soil Decontamination	NSF: \$65K 1/95 - 6/95	Novel cathode designs were investigated as a unique method to control the redox chemistry surrounding the electrodes
A Micromodel Study of Residual Hydrocarbon Mass Transfer Rates in Porous Media	DOD (Air Force): \$80K 7/95 - 1/96	Development of a unique understanding of the effects of electrokinetics at the microscopic level

Table 6 (continued)

Successfully completed or on-going electrokinetic remediation projects carried out by Lynntech since 1993 (Source: Lynntech, Inc. capabilities brochure)

Project Title	Client	Accomplishment
Transport of Colloidal Size Particles Through Porous Media: A New Approach for Formation of Impermeable and Reactive Subsurface Barriers	NSF: \$70K <i>1/97 - 6/97</i>	The first laboratory demonstration of electrokinetic technology for in situ barrier emplacement
Soil Treatability Study Remedial Services: Camp Stanley Storage Activity Area <i>- Field demonstration in progress</i>	Parsons Engineering: \$73.5K <i>4/96 - 9/96</i>	An ongoing field demonstration of the use of non-uniform electric fields at a site contaminated with chromium
Electrokinetic Demonstration: NAWS Point Magu, CA <i>- 9-month field demonstration planned at 2 test sites in 1998</i>	LB&M Assoc., Inc.: \$756K <i>8/97 - 11/98</i>	Remediation of chromium in a tidal marsh area

B7

Research: Electroremediation¹³

Developer(s): Massachusetts Institute of Technology (MIT)

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Research Description

MIT researchers used laboratory experiments and mathematical modeling to study the changes in the flows of ions and pore liquid during the removal of contaminants from soils using electric fields. The flows are directly related to the removal of charged and uncharged contaminants by electromigration and electroosmosis, respectively. The laboratory experiments consist of purging a prepared kaolinite sample which is loaded with a known amount of phenol or acetic acid.

The process of electro-osmotic purging uses an electric field that is applied to soils which are saturated or partially saturated with contaminated water (see Figure 22). The applied electric field moves the water and dissolved contaminants to the electrode wells where they may be pumped to the

¹³ Information provided was obtained from the following journals and reports:

Jacobs, R.A. and Probst, R.F., Two-Dimensional Modeling of Electroremediation, *AICHE J.* 42, pp. 1685-1696 (1996)

Jacobs, R.A., Sengun, M.Z., Hicks, R.E., and Probst, R.F., Model and Experiments on Soil Remediation by Electric Fields, *J. Env. Sci & Health*, 29A, No.9 (1994)

Probst, R.F. and Hicks, R.E., Removal of Contaminants from Soils by Electric Fields, *Science* 260, pp. 498-503 (1993)

Probst, R.F. and Shapiro, A.P., Removal of Contaminants from Saturated Clay by Electroosmosis, *Env. Sci. & Technology* 27, pp. 283-291 (1993)

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, *EPA542-K-94-007*, April 1995

surface. A nontoxic purge solution that is drawn in at one of the electrodes is used to wash the soil and to prevent the formation of cracks by maintaining soil saturation. The solution may contain reagents to enhance the mobility of contaminants that are not originally present in the aqueous phase. A DC power connected to the carbon electrodes -- 1.5 centimeters deep and placed 20 centimeters apart -- was controlled to maintain a constant voltage of 20 volts across the clay. The process is shown to be very effective at removing organics such as phenol and acetic acid from clay, achieving at least 94 percent removal under certain conditions, and has also shown 98 percent removal of heavy metals such as zinc.

The factors which determine the success of the decontamination are the combined effects of electro-osmotic convection, ionic migration, chemical equilibria, and electrochemical reactions. These phenomena are analyzed in a model which compares favorably with experiments. The one-dimensional mathematical model takes into account the complex interaction of subsurface effects that occur simultaneously when a direct current is applied in soil. The model can also describe complexation, dissolution and precipitation reactions, surface complexation and sorption processes, and electrochemical reactions. Both the experiments and the mathematical model show the development of sharp fronts, some propagating with the electro-osmotic flow and others stationary at the electrodes. The pH of the purging solution is shown to have significant influence on the electro-osmotic velocity and can be selected to optimize the process.

Status

MIT has been conducting research on electroremediation for the past 10 years. This research, which is sponsored by DOE, is expected to improve the efficiency and reduce the cost of practical applications of the technology. It is expected that the model developed will provide an important guide to laboratory and pilot-scale treatability studies.

Recently, researchers at MIT have developed a two-dimensional model and numerical code for the simulation of contaminant removal from soils by electric fields. Like the one-dimensional model, this model also describes the coupled transport of mass and charge, and the chemical speciation of a multicomponent system subjected to an electric field. The two-dimensional model was developed to address the variation of the current density with the geometry of the electrode array. The computer code developed for the two-dimensional model, computes the time evolution of several state variables (including the spatial distributions of the electrostatic potential and pressure, the current density, and all species velocities and concentrations) in a multielectrode, multicomponent system of arbitrary shape subject to an electric field (see Figure 23). The results from this model can be applied to three-dimensional systems in which the distance between electrodes is small compared to their length, and there is no significant variation of the material properties with depth.

Laboratory experiments applying DC electric fields to soils containing aqueous solutions of soluble contaminants show potential for an effective in situ means for cleaning waste sites. Limited field tests and computer modeling support this projection, although the ability to make quantitative predictions of expected contaminant removal and costs at an actual hazardous waste site is at an early stage. Several development steps are needed to assess this method's potential: the results of well characterized field tests together with additional laboratory data, particularly on the removal of heavy metals and their interactions with different soils of varying degrees of saturation; reagents for enhancing the desorption and solubilization of both organic and inorganic contaminants; and improved predictive models that enable optimization of the process variables. MIT researchers are at present carrying out a field test in New Jersey on a chromate contaminated site under EPA auspices, but the test is essentially just starting and no results are available as yet.

Laboratory experiments on organics removal by electroosmosis purging at moderate voltages, so that heating losses are not excessive, show energy costs averaging about 20kWh per cubic meter of effluent. The estimated energy costs for contaminant removal by electric fields based on the experiments, could approximate \$20 to \$30 per ton.

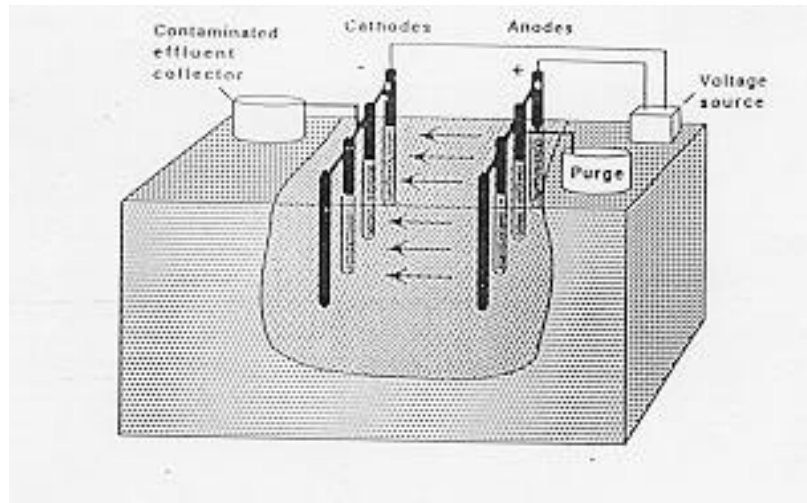


Figure 22

Schematic of a field installation for in situ remediation by electro-osmotic purging (Source: Probstein, R.F. and Shapiro, A.P., Removal of Contaminants from Saturated Clay by Electroosmosis, *Env. Sci. & Technology* 27, pp. 283-291, 1993)

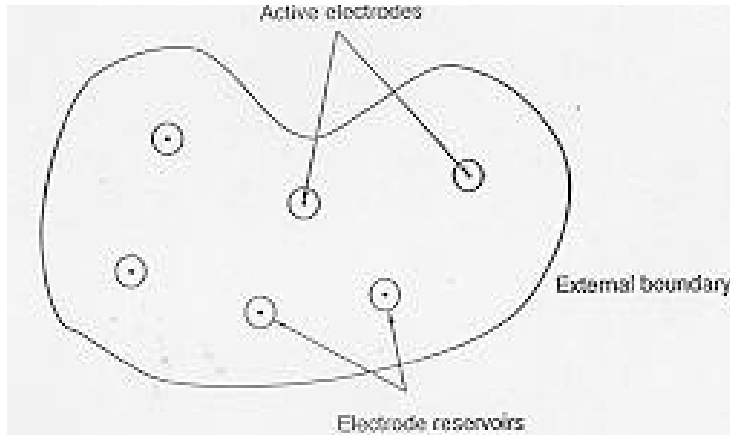


Figure 23

2-D multielectrode system (Source: Jacobs, R.A. and Probstein, R.F., Two-Dimensional Modeling of Electroremediation, *AIChE J.* 42, pp. 1685-1696, 1996)

B8

Research: In Situ Electrokinetic Extraction System¹⁴

Developer(s): Sandia National Laboratories (SNL)

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Research Description

The purpose of this research is to develop an in situ electrokinetic process for remediating unsaturated soils (as low as about 25 percent saturation) contaminated with anionic (negatively charged) heavy metals (such as chromium and radionuclides) without raising soil moisture content significantly. In sandy soils with approximately 40 to 60 percent moisture saturation, the bench scale electrokinetic process removed 75 to 90 percent chromium. Chromium contamination is of interest because it is one of the most significant contaminants in the SNL Chemical Waste Landfill (CWL) Unlined Chromic Acid Pit (UCAP) (see Figures 24 and 25). At the CWL, electrokinetics has been used to remove negatively charged chromium ions from the chromate plume in the vadose zone below the UCAP. Chromium contamination has been detected to a depth of 75 feet at the CWL.

Three to five electrode pairs, supplied with water and neutralization chemicals, were used to treat chromium-contaminated soil over a 120-day period. Between 25 and 120 kilograms of chromium was removed from 700 to 1,000 cubic feet of soil. Soluble chromium concentrations range from 25 (background) to 10,000 ppm with the upper limit at 15 feet below ground surface. Contaminants arriving at the electrode were removed using a vacuum system. To use the electrokinetic system, electrodes are installed in the ground in a square array and connected to a DC voltage power supply

¹⁴ Information provided was obtained from the Internet at the Sandia National Laboratory world wide web site at <http://www.sandia.gov> and the following report:

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

(see Figures 26 and 27). Each electrode assembly contains water, a pump, an electrode, and numerous sensors and controllers. The outer casings of the electrodes are made of porous ceramic which allows electrical current and contaminants to pass. A vacuum is applied to the casings which keeps the water inside the assembly from flowing out and saturating neighboring soils. The electrodes are placed in the predetermined treatment zone with the ceramic casing at the treatment depth of 15 feet below ground surface. When the DC power supply is applied to the soil between electrodes, water flows in the soil pores (usually towards the cathode). The SNL electrode design, however, allows water to enter the soil at the anode, supplying the pore water adjacent to the electrode casing but never saturating the soil. The ions are then pumped to the surface by circulating water within the ceramic casing. Electrode effluent containing chromate contamination is shown in Figure 28.

A major advantage of this particular electrokinetic system is that it operates in unsaturated soil for much longer periods of time than if simple electrodes were used. In addition, the process needs relatively limited amounts of energy compared to excavation: a 40K watt portable diesel generator can power the system. A major limitation to this process is that buried metal objects divert the current from the soil needing remediation. Another problem can arise if large amounts of nontargeted contaminants are present in the soil to be treated. Estimates for electrokinetic remediation range from \$50 to \$150 per ton. Processes involving excavation of soil cost \$200 to \$500 per ton.

Status

Research and demonstrations at SNL are supported by DOE. The technology was developed and tested at the bench and pilot scale in 1993. In 1994, a prototype electrode system was field-tested in the UCAP, inside the CWL, to characterize the process and to demonstrate in situ water control in unsaturated soil. Efforts are underway to extend the technology to treat cationic contaminants which adsorb strongly to soil or exist as solid precipitates. Organic complexants are electrokinetically injected into the soil at the cathode and form anionic complexes with certain contaminants which are attracted to and removed from the anodes. The SNL In Situ Electrokinetic Extraction System was also demonstrated at SNLs UCAP from May 15 to November 24, 1996, and evaluated under the EPA SITE Program. The target contaminant for the demonstration was hexavalent chromium in the form of chromate ions. SNL researchers indicate that this process can also be used for uranium removal at DOE's Hanford site. Commercial availability of the technology is expected in 1998.

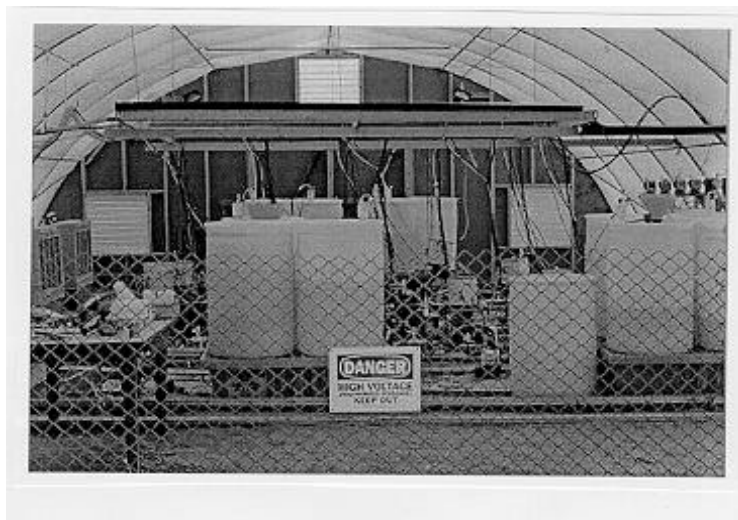


Figure 24
Electrokinetic demonstration for chromate removal at the Unlined Chromate Acid Pit (Sandia National Laboratories, Tech Area III, Chemical Waste Landfill) (Source: Sandia National Laboratory world wide web site at <http://www.sandia.gov>)

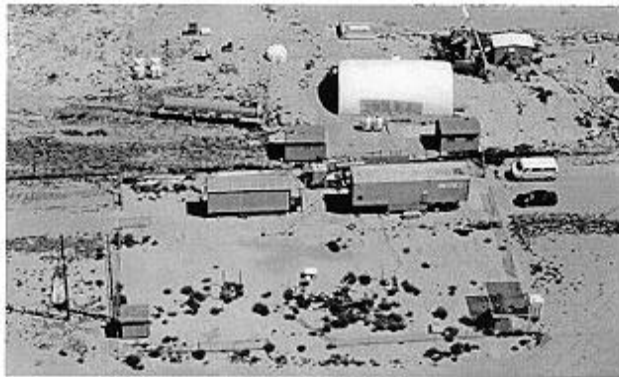


Figure 25

Aerial photo of electrokinetic site over the Unlined Chromic Acid Pit (Sandia National Laboratories, Tech Area III, Chemical Waste Landfill) (Source: Sandia National Laboratory world wide web site at <http://www.sandia.gov>)

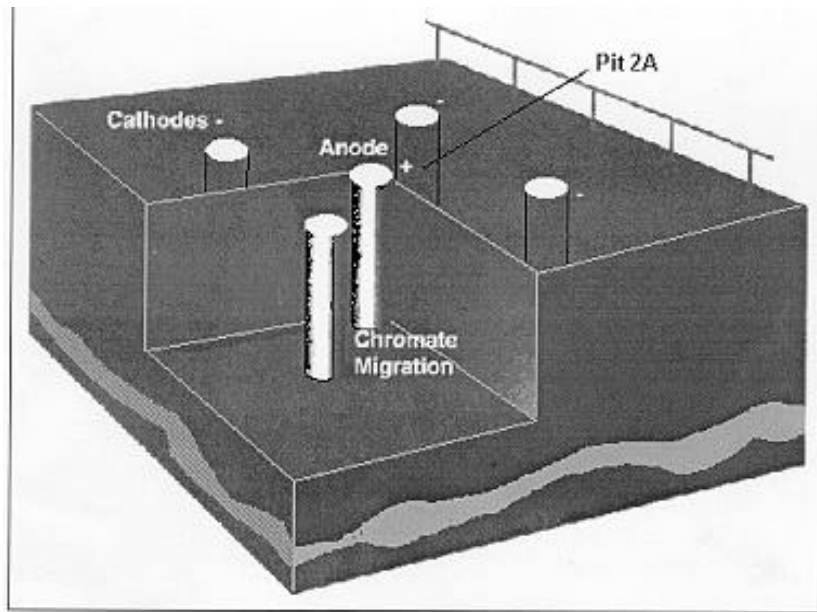


Figure 26
Electrode array configuration for electrokinetic remediation of the Unlined Chromic Acid Pit
(Source: Sandia National Laboratory world wide web site at <http://www.sandia.gov>)

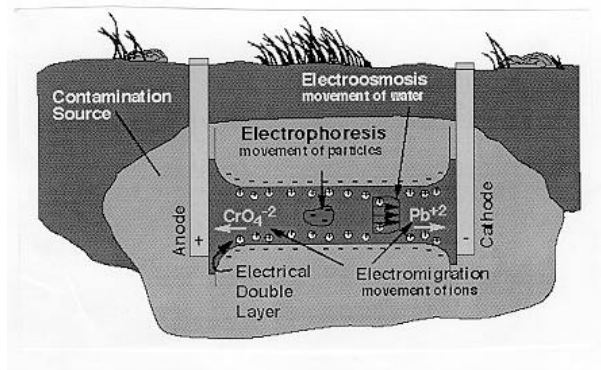


Figure 27
 Electrokinetic remediation schematic (Source: Sandia National Laboratory world wide web site at <http://www.sandia.gov>)

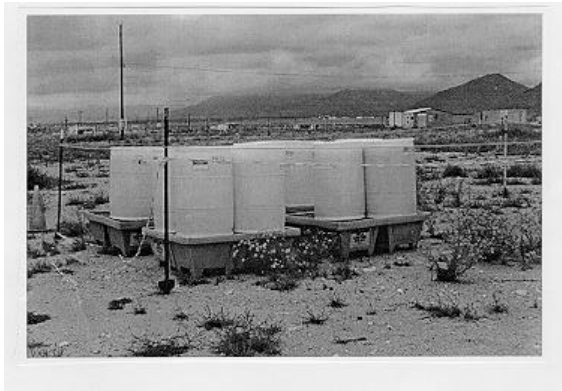


Figure 28
Electrode effluent containing chromate contamination (Sandia National Laboratories, Tech Area III, Chemical Waste Landfill) (Source: Sandia National Laboratory world wide web site at <http://www.sandia.gov>)

B9

Research: Electrokinetic Extraction¹⁵

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Research Description

Basic electrokinetic phenomena in clay and the fundamental contaminant removal mechanisms by electrokinetics was studied by researchers. The research was conducted for the U.S. Army Corps of Engineers (USACE) Waterways Experiment Station under the Installation Restoration Research Program. The research was funded in part with federal funds as part of the program of the Gulf Coast Hazardous Substance Research Center which is supported by the EPA, and in part with funds from the State of Texas as part of the program of the Texas Hazardous Waste Research Center.

A coupled flow theory for the transport of fluid, electricity, and chemical gradients to describe the contaminant transport during the electrokinetic extraction process was formulated. Electrochemical reactions associated with the processes and soil-contaminant interactions are also included. A numerical model was developed to simulate the contaminant transport, electrochemical reactions, and

¹⁵ Information provided was obtained from the following journals and reports:

Alshawabkeh, A.N. and Yueng, A.T., Practical Aspects of In-situ Electrokinetic Extraction, submitted to the *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management* of ASCE for review and possible publication on April 29, 1997

Datla, S. and Yueng, A.T., Subsurface Migration of Contaminants under the Coupled Influences of Hydraulic, Electrical, and Chemical Gradients, *Proceedings of the 8th International Conference of the International Association of Computer Methods and Advances in Geomechanics*, Morgantown, West Virginia, pp. 1042-1048 (1994)

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

soil-contaminant interactions during the extraction processes. Bench scale experiments on the cleanup of contaminants -- such as sodium chloride, lead nitrate, phenol, and acetic acid -- from Milwhite kaolinite (a commercial product from Patria Packaging, Inc., Valdosta, Georgia) were performed to evaluate the validity of the theory and numerical model. The results obtained from the extraction of lead from Milwhite kaolinite (using disodium ethylenediaminetetraacetate (EDTA) as an enhancement agent) show that the removal of contaminants started towards the end of the samples and slowly migrated inwards. Low pH conditions developed at the anode and high pH conditions developed at the cathode. The research shows that the validity of the theoretical model is supported by experimentally measured results, but there is need to develop guidelines and to optimize operation parameters for the electrokinetics process.

Status

In the laboratory experiments, an example of a contaminated area of 50 meters x 100 meters was considered. The depth of contamination was assumed to be 5 meters and the soil is saturated silty clay. Remediation time is assumed to be 6 months. The electrodes were placed 5.2 meters apart and the electric voltage across opposite electrodes was 100 volts. The total costs per unit volume based on these parameters was determined to be \$38.5. The viability of the research undertaken on electrokinetics extraction, an emerging in-situ technology, is being continued to be established by many bench-scale and large-scale experiments, and pilot-scale field investigations, but is not in use as a remediation tool. Some important practical aspects such as a cost analysis and design criteria need to be considered before the technology can be successfully implemented in the field.

CATEGORY C

Electrokinetic processes which are currently in the conceptual development stage

Table 7
Category C Summary Table

Name of developer(s)	Soil type(s) tested	Distance between electrodes	Depth the electrodes were placed in	Voltage and/or DC current level	Processing fluid(s)	Size of remediation area	Contaminant(s) treated	Time to complete cleanup	Contaminant concentration levels	Treatment cost
University of Massachusetts at Lowell	kaolinite and fine-grained soils	not available	not available	not available	natural and synthetic flushing solutions	not available	lead, benzene, toluene, m-xylene, TCE	not available	not available	not available
West Virginia University	fine-grained soil	not available	not available	not available	not available	not available	lead	not available	not available	not available

C1

Research: Electrokinetics¹⁶

Developer(s): University of Massachusetts at Lowell

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Research Description

Since 1992, researchers have been conducting laboratory studies on the effectiveness of electroosmosis for removing hydrocarbons and heavy metals from clay. Benzene, toluene, TCE and m-xylene — all of which have relatively high water solubilities — were more easily removed from fine-grained soils than hexane and isooctane and other compounds with low water solubilities and high distribution coefficients. Researchers also are studying the physical and chemical characteristics of electro-osmotic contaminant transport. The data are being used to gain insights into electro-osmotic organic contaminant displacement and how soil and pore water characteristics affect the process.

Status

In 1996, additional laboratory experiments for the use of electrokinetics in combination with natural and synthetic flushing solutions were studied to determine their efficiency in removing lead from clay. Natural flushing solutions were prepared by mixing water and clay in varying ratios by weight. An ideal ratio was determined through a comparison of lead removal efficiencies. The

¹⁶ Information provided was obtained from the following reports:

Bruell, C.J., Coletta, T.F., Inyang, H.I., and Ryan, D.K., Electrokinetics and Ionic Solutions to Remove Lead from Kaolin Clay, presented at the 3rd International Symposium on Environmental Geotechnology, June 10-12, 1996

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995

primary elemental constituents of the natural solution were then determined. A synthetic solution with varying concentrations of aluminum and calcium was made and compared to the natural solution for lead removal efficiency. The synthetic solutions of aluminum and calcium with the highest efficiency were then compared. In the final analysis, it was determined that the concentrations of the elemental constituents of the flushing solution complemented the electrokinetic removal of lead and Kaolinite clay.

C2

Research: In Situ Electrokinetics¹⁷

Developer(s): West Virginia University

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Research Description

Research on the use of electrokinetics to remediate fine-grained soil contaminated with lead was conducted. The research included an evaluation of the impact of initial conditions on the efficiency of electrokinetics to drive liquids and contaminants through soil samples. An electrokinetic soil reactor designed to mimic in situ electrokinetic flushing was applied to silt loam artificially contaminated with lead. Studies of the removal of lead from soils indicate that the efficiency of lead removal is related to the flow of the acid front generated by the positive electrode.

Status

The DOE National Research Center for Coal and Energy sponsored the laboratory studies between September 30, 1987, and June 30, 1993. Recent research on electrokinetics processing has not been undertaken by the university for the past few years.

¹⁷ Information provided was obtained from the following report:

U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, In Situ Remediation Technology: Electrokinetics, EPA542-K-94-007, April 1995