

Technology
Overview Report

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Electrokinetics

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FOREWORD

About GWRTAC

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) is a national environmental technology transfer center that provides information on the use of innovative technologies to clean-up contaminated groundwater.

Established in 1995, GWRTAC is operated by the National Environmental Technology Applications Center (NETAC) in association with the University of Pittsburgh's Environmental Engineering Program through a Cooperative Agreement with the U.S. Environmental Protection Agency's (EPA) Technology Innovation Office (TIO). NETAC is an operating unit of the Center for Hazardous Materials Research and focuses on accelerating the development and commercial use of new environmental technologies.

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About "O" Series Reports

This report is one of the GWRTAC "O" Series of reports developed by GWRTAC to provide a general overview and introduction to a groundwater remediation technology. These overview reports are intended to provide a basic orientation to the technology. They contain information gathered from a range of currently available sources, including project documents, reports, periodicals, Internet searches, and personal communication with involved parties. No attempts are made to independently confirm or peer review the resources used.

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ABSTRACT

This technology summary report is an overview of information collected by GWRTAC on electrokinetics as an *in situ* environmental remediation technology. Information provided includes an introduction to the general principles and techniques, a discussion of the general applicability of the technology, an overview of data related to its utilization, and reported advantages and limitations of the technology. References cited, and a bibliography compiled during preparation of this report containing additional information sources are also provided.

Electrokinetics is a developing technology that is intended to separate and extract heavy metals, radionuclides, and organic contaminants from saturated or unsaturated soils, sludges and sediments, and groundwater. The goal of electrokinetic remediation is to effect the migration of subsurface contaminants in an imposed electric field via electroosmosis, electromigration and/or electrophoresis. These phenomena occur when the soil is electrically charged with a low voltage current. The fundamental configuration for all three processes involves the application of an electrical potential between electrode pairs that have been implanted in the ground on each side of a contaminated soil mass.

Before electrokinetic remediation is undertaken at a site, tests must be conducted to determine if the site is amenable to the technology. This report discusses data which must be collected to evaluate the potential for successful implementation. Several applications of electrokinetic remediation technology are discussed which report that, when applied properly, this technique can be a cost effective method for meeting remedial objectives at sites contaminated with inorganic species. Finally, technology advantages and limitations are reviewed. An important advantage is the applicability of the technology in low permeability soils, as well as its potential applicability to a broad range of contaminants. Precipitation of metals close to the cathode has been the biggest impediment to the process.

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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 Introduction	1
2.0 Applicability	2
3.0 Methodology	3
4.0 Factors Affecting Electrokinetic Technology	4
4.1 General	4
4.2 Site Screening	4
5.0 Technology Advantages	6
6.0 Technology Limitations	7
7.0 Cost-Benefit Analysis	8
8.0 Technology Performance and Select Case Studies	9
8.1 Electro-Klean™ Electrical Separation	9
8.2 Electrokinetic Bioremediation	9
8.3 ElectroChemical GeoOxidation (ECGO)	10
8.4 Electrochemical Oxidative Remediation of Ground-water	11
8.5 Electrochemical Ion eXchange (EIX)	11
8.6 Electrosorb™	11
8.7 Lasagna™ Process	12
8.7.1 Lasagna™ Public-Private Partnership	12
8.7.2 Technology Description	12
8.7.3 Technology Status	13
8.7.4 Process Advantages	13
8.7.5 Costs	13
8.7.6 Cost Savings Versus Alternative Technologies	14
9.0 References Cited	15
10.0 Bibliography	17

1.0 INTRODUCTION

Electrokinetics is a developing technology that is intended to separate and extract heavy metals, radionuclides, and organic contaminants from saturated or unsaturated soils, sludges and sediments, and groundwater. In recent years there has been considerable interest in the application of electrokinetic processes, especially for the remediation of low permeability contaminated soils and groundwater. The demand to develop innovative, cost-effective *in situ* remediation technologies in waste management provided the impetus to exploit the conductive properties of soils, and using an electric field to remove chemical species from soils. The goal of electrokinetic remediation is to effect the migration of subsurface contaminants in an imposed electric field via electroosmosis, electromigration and/or electrophoresis. This technique is known as electrokinetic remediation, electroreclamation, electrochemical decontamination, electrorestoration or electrochemical soil processing.

Electroosmosis is the movement of soil moisture or groundwater from the anode to the cathode of an electrolytic cell. Electromigration is the transport of ions and ion complexes to the electrode of opposite charge. Electrophoresis is the transport of charged particles or colloids under the influence of an electric field; contaminants bound to mobile particulate matter can be transported in this manner. These three phenomena occur when the soil is electrically charged with a low voltage direct current. The fundamental configuration for all three processes involves the application of an electrical potential between electrode pairs that have been implanted in the ground on each side of a contaminated soil mass. The process may be enhanced through the use of surfactants or reagents to increase the contaminant removal rates at the electrodes. Upon their migration to the electrodes, the contaminants may be removed by electroplating, precipitation/co-precipitation, pumping near the electrode, or complexing with ion exchange resins (1, 2).

2.0 APPLICABILITY

In situ electrokinetic treatment has been developed largely to address contaminants present in low permeability soils. Although this application is relatively new, the oil industry has employed electrokinetics for enhanced recovery over the past several decades. The first successful demonstration of the use of electrokinetics for soil remediation was performed in the Netherlands in 1986 (3, 4).

Contaminants affected by electrokinetic processes include:

- Heavy metals (lead, mercury, cadmium, nickel, copper, zinc, chromium)
- Radioactive species (Cs_{137} , Sr_{90} , Co_{60} , Ur)
- Toxic anions (nitrates, sulfates)
- Dense non-aqueous phase liquids (DNAPLs)
- Cyanides
- Petroleum hydrocarbons (diesel fuel, gasoline, kerosene and lubricating oils)
- Explosives
- Mixed organic/ionic contaminants
- Halogenated hydrocarbons (TCE)
- Nonhalogenated organic pollutants (BTEX)
- Polynuclear aromatic hydrocarbons (PAH)

3.0 METHODOLOGY

Electrokinetic remediation techniques use low voltage DC on the order of mA/cm² of cross-sectional area between the electrodes or an electric potential difference on the order of a few volts per cm across electrodes placed in the ground in an open flow arrangement. The groundwater in the boreholes or an external supplied fluid is used as the conductive medium. Open flow arrangement at the electrodes allows ingress and egress of the processing fluid or of the pore fluid into and out of the porous medium. The low-level DC results in physico-chemical and hydrological changes in the soil mass leading to species transport in the porous media. The species input into the system at the electrodes (either by the electrolysis reactions or through the cycling processing fluid) and the species in the pore fluid will be transported across the porous media by conduction phenomena in soils under electric voltage gradient fields, towards respective electrodes depending on their charge. Non-ionic species will be transported along with the electroosmosis-induced water flow. This transport, coupled with sorption, precipitation and dissolution reactions, comprise the fundamental mechanisms affecting the electrokinetic remediation process. Extraction and removal are accomplished by several means including electrodeposition (electroplating at the electrode), precipitation or co-precipitation at the electrode, pumping of water near the electrode, or complexing with ion exchange resins (5). Adsorption into the electrode may also be feasible because some ionic species will change valence near the electrode (depending on the soil pH) making them more likely to adsorb (5, 6, 7).

There are several variations of the basic electrokinetic remediation process or implementing strategies:

- Electrokinetic bioremediation (or bioelectric remediation) for continuous treatment of groundwater or soil *in situ* utilizes either electroosmosis or electrochemical migration to initiate or enhance *in situ* bioremediation (8).
- Electrokinetically-deployed oxidation (9, 10)
- Electrokinetically-deployed fixation (3, 4)
- Electroheated extraction (3)
- Periodically reversing the polarity of the field is intended to repeatedly pass contaminants through a degradation zone, while limiting the development of high or low pH conditions in the vicinities of electrodes and reducing fouling of electrodes by precipitation. This approach of *in situ* remediation is the essence of the “Lasagna™” process, which will be discussed in detail later in this report.
- Surfactants and complexing agents can be used to increase solubility and assist in the movement of the contaminants.
- Reagents, such as metal catalysts (iron particles, etc.) may be introduced at the electrodes to enhance contaminant removal rates.

4.0 FACTORS AFFECTING ELECTROKINETIC TECHNOLOGY

4.1 GENERAL

Electromigration rates in the subsurface depend upon grain size, ionic mobility, contamination concentration, total ionic concentration, and significantly upon the soil pore water current density. The process efficiency is not as dependent on the fluid permeability of soil as it is on the pore water electrical conductivity and path length through the soil, both of which are a function of the soil moisture content (2, 11).

The direction and quantity of the contaminant movement is influenced by the contaminant concentration (anions versus cations), soil type and structure, interfacial chemistry, and current density of the soil pore water. Electrokinetic remediation is possible in saturated and unsaturated soils. Experimental results indicate that there is a minimum moisture content at which electromigration can take place, which is related to, and can be estimated from, the residual moisture content of a soil, also called “immobile water.” The soil moisture content must be high enough to allow electromigration, but for optimum results, should likely be less than saturation, to avoid the competing effects of tortuosity and pore water content. The direction and rate of movement of an ionic species will depend on its charge, both in magnitude and polarity, as well as the magnitude of the electroosmosis-induced flow velocity. When electroosmosis processes are operative, non-ionic species will be transported along with the induced water flow (2, 11).

The efficiency of extraction relies upon several factors such as the type of species, their solubility in the specific soil, their electrical charge, their concentration relative to other species, their location and form in the soil, and availability of organic matter in the soil (5, 12).

Electrokinetics is applicable in zones of low hydraulic conductivity, particularly with a high clay content. The technology is most efficient when the Cation Exchange Capacity (CEC) and the salinity are low.

During electrokinetic treatment, electrolysis results in the formation of H^+ at the anode and OH^- at the cathode. H^+ and OH^- migrate toward one another by electrokinetic processes. As these two fronts meet, a rapid transition from low to high pH occurs, creating a region of minimum solubility of metals. These sharp discontinuities in pH induced within the soil mass by electrokinetics could result in a deposition front where minerals are precipitated in soil pores, markedly reducing permeability and inhibiting recovery. This can be prevented by flushing the cathode with water or a dilute acid to arrest the migration of the OH^- front into the soil (1).

4.2 SITE SCREENING

Before electrokinetic remediation is undertaken at a site, a number of field and laboratory screening tests must be conducted to determine if the site is amenable to the technology, including the following (11):

- **Field electrical conductivity surveys** The natural spatial conductivity variance should be delineated because buried metallic or insulating material can induce variability in the

electrical conductivity of the soil and, therefore, the voltage gradient. In addition, it is important to assess if there are deposits that exhibit very high electrical conductivity levels, where the technique may be inefficient.

- ***The pH and electrical conductivity of the pore water*** The pore water pH and conductance should be determined because the pH has an effect on the valence, solubility, and sorption of contaminant ions. The electrical conductivity of the pore water is an integral factor in determining the efficiency of the electrokinetic process.
- ***Chemical analysis of pore water*** The pore water should be analyzed for major dissolved anions and cations, as well as for the predicted concentration of contaminants.
- ***Chemical analysis of soil*** The buffering capacity and geochemistry (CEC, salinity, etc.) of the soil should be determined.

5.0 TECHNOLOGY ADVANTAGES

Electrokinetics may be utilized for site remediation under conditions which normally limit *in situ* approaches, such as in the case of the following;

- Recovery of ionic contaminants by conventional means is complicated due to soil being a powerful ion exchange medium. Ionic contaminants are absorbed in soil particles, and are often not available for removal by the simple flushing action of groundwater. A pH shift must be applied to desorb and mobilize the contaminants. However, flushing with strong acids usually destroys the basic soil structure, and may thus be self-limiting. Electrokinetics may be applied to mobilize contaminants without such concern, because acids are not pumped directly into the soil. Electrolysis of water in the circulating electrolyte produces the H^+ ions at the anodes and the OH^- ions at the cathodes. These ions migrate through the soil, generating a localized pH shift which desorbs contaminating ions (4, 6) .
- Fine-grained sediments or low permeability soils present the greatest obstacle to *in situ* remediation at many contaminated sites. In clay and tight soils, hydraulic flow through fine pores is extremely limited, making these soils non-responsive to traditional soil flushing. Accessibility of the contaminants and delivery of treatment reagents have posed problems, rendering traditional technologies, such as vapor extraction and pump-and-treat, rather ineffective when applied to the low permeability soils present at many sites. Electrokinetics is an effective method of inducing movement of water, ions and colloids through fine-grained sediments (7).
- There currently are no other viable *in situ* methods for remediating heavy metals contamination from unsaturated soils. Excavating and processing, or disposal at a licensed landfill, will not always be feasible and will always be expensive (13). If the total area of metals contamination is relatively small (1 acre or 0.4 hectares) and highly concentrated, the application of a conventional technology like excavation or solidification might prove to be more economically feasible. But as excavation does not work well adjacent to buildings, small areas with high concentrations located in close proximity to structures may be more receptive to electrokinetics.

When cost-effectiveness and technical feasibility of other remedial options prohibit their use, electrokinetic remediation may offer an alternative at sites contaminated with inorganic species.

6.0 TECHNOLOGY LIMITATIONS

Based on the results of laboratory tests and field applications, electrokinetics has been shown to be a promising method of recovering ionic and water-soluble contaminants. However, the process has associated limitations, such as (7, 11, 14):

- The electrokinetic process is limited by the solubility of the contaminant and the desorption of contaminants from the soil matrix. Heavy metals in their metallic state have not been successfully dissolved and separated from soil samples. The process is also not efficient when the target ion concentration is low and non-target ion concentration is high.
- Acidic conditions and electrolytic decay can corrode some anode materials.
- Conventional electrokinetic remediation requires contaminants to migrate from their initial location to an electrode. In some cases, the migration path could be long or there could be stagnant zones between wells where the rate of migration is particularly slow, both of which result in incomplete remediation of the contaminated zone. Moreover, sharply convergent electrical fields can result in heating and potential losses in the vicinities of electrodes. A pH-related deposition can cause contaminants to be removed from solution prior to arrival at the ground surface or point of removal.
- Electrolysis reactions in the vicinity of the electrodes may cause changes in ambient pH that may change the solubility and speciation of the contaminants.
- Heterogeneties or subsurface anomalies at sites, such as building foundations, rubble, large quantities of iron or iron oxides, large rocks or gravel, or submerged cover materials such as seashells, can reduce removal efficiencies. Immobilization of metal ions by undesirable chemical reaction with naturally occurring and co-disposed chemicals can also occur.
- The presence of buried metallic conductors or insulators in the soil and reduction/oxidation and pH changes induced by the process electrode reactions can reduce the effectiveness of the process.
- Precipitation of species close to the cathode has been an impediment to the process. Heavy metals can prematurely precipitate close to the cathode at their hydroxide solubility value if the chemistry of the electrolyte at the electrodes is not altered or controlled (unenhanced electrokinetic remediation). Currently, studies conducted by Electrokinetics Inc. and the U.S. Army Waterways Experiment Station are underway to overcome the problem of precipitation close to the cathode, and the feasibility of employing different techniques to enhance the process are being evaluated. An objective of the studies is to promote transport of the positively charged species into the catholyte where they could be removed by electrodeposition, membrane separation, or ion exchange.

7.0 COST - BENEFIT ANALYSIS

The cost of electrokinetic remediation is dependent on specific chemical and hydraulic properties present at the site. Ongoing pilot-scale field studies indicate that the energy consumption in extracting heavy metals from soil may be approximately 500 kW-hr/m³ or more at an electrode spacing of 1.0-1.5 meters (0.30-0.45 feet). The direct cost would be approximately \$25/m³ (\$20/yd³) or \$0.05/kW-hr at this level of energy consumption. The energy consumption rate can be significantly lowered if cathodic polarization techniques are used, because no low conductivity zone would be formed around the cathode compartment (15). The total power consumed is directly proportional to the time required for migration to achieve the clean up level desired. A typical migration rate of dissolved constituents in soil pore water would be 2.5 cm (1 inch) per day. For an electrode spacing of 2 to 3 meters (0.6 to 0.9 feet), the corresponding time frame would approximate 100 days (11).

Estimated price ranges per unit of waste treated by various vendors include:

- DuPont R&D: \$85 per m³ (\$65 per yd³)
- Electrokinetics, Inc: \$25 to \$130 per m³ (\$20 to \$100 per yd³)
- Geokinetics International: \$80 to \$300 per m³ (\$60 to \$225 per yd³)

The price estimates above do not include indirect costs associated with remediation, such as permits and treatment of residues.

Factors which have a significant effect on unit price are:

- Initial and target contaminant concentrations
- Concentration of non-target ions, or conductivity of pore water
- Soil characteristics and moisture content
- Depth of contamination
- Residual waste processing
- Site preparation requirements
- Electricity and labor costs

8.0 TECHNOLOGY PERFORMANCES AND CASE STUDIES

Due to the specialized nature of electrokinetic remediation, as well as its innovative status, relatively few commercial vendors apply the technology. Therefore, in this section of the report, several trademarked or patented commercial electrokinetic processes are described, as well as additional extended uses of electrokinetics, such as electrokinetic bioremediation and oxidation, and electro-heating to enhance technologies such as vapor extraction, and others. This information is provided for informational purposes only.

For more case studies consult:

- “Projects using Electrokinetics in Groundwater Remediation” at <http://www.gwrtac.org/html/electro.html>
- “In situ Remediation Technology: Electrokinetics,” EPA542-K-94-007, available in PDF format at http://www.gwrtac.org/html/tech_status.html#ELECTRO

8.1 ELECTRO-KLEAN™ ELECTRICAL SEPARATION

Electro-Klean™ is a process available through Electrokinetics, Incorporated of Baton Rouge, Louisiana. The process removes or captures heavy metals, radionuclides, and selected volatile organic contaminants from saturated and unsaturated sands, silts, fine-grained clays, and sediments. It can be applied *in situ* or *ex situ*. Electrodes are placed on each side of the contaminated soil mass, and direct current is applied. Conditioning fluids such as suitable acids may be added or circulated at the electrodes to enhance the process electrochemistry. The concurrent mobility of the ions and pore fluid decontaminates the soil mass, as the contaminants migrate to the electrodes. Contaminants are separated on the electrodes or separated in a post-treatment unit (8).

Electro-Klean extracts heavy metals, radionuclides, and other inorganic contaminants, and can reduce their concentration to below their solubility limit. Treatment efficiency depends on the specific chemicals, their concentration, and the buffering capacity of the soil. The technique proved 85 to 95% efficient for removing phenol at concentrations of 500 ppm. In addition, the removal efficiency for lead, chromium, cadmium, and uranium at levels up to 2,000 mg/kg, ranged between 75 and 95%.

8.2 ELECTROKINETIC BIOREMEDIATION

Electrokinetic bioremediation technology is designed to activate dormant microbial populations by use of selected nutrients to promote growth, reproduction, and metabolism of the microorganisms capable of transforming organic contaminants. The bioelectric technology directs the nutrients to the organic pollutant. Normally there is no requirement to add microorganisms (8).

The economics of this process are favorable because external microbial populations are not required, and nutrients can be uniformly dispersed over the contaminated volume of soil or directed at a specific location, thus reducing nutrient costs. This process may be extremely valuable because it avoids the problems associated with transport of microorganisms through fine-grained soils.

Electrokinetic bioremediation (or bioelectric remediation) technology for continuous treatment of groundwater or soil *in situ* utilizes either electroosmosis or electrochemical migration to initiate or enhance *in situ* bioremediation.

Electroosmosis is the dominant process where a direct current can produce an accelerated flow of groundwater in the soil strata. Electroosmosis flow develops more easily in sands, sandy silts or sandy clays. Biological growth factors, including microbial populations, surfactants, and inorganic and organic nutrients, can be moved and often directed into the soil/groundwater matrix. Electroosmosis in this case can be used to accelerate the natural groundwater movement and increase the efficiency of the biodegradation process by the addition of the biological agent into the coarse soils. The flow in coarse-grained soils, however, will tend to follow natural fissures or high permeability lenses and not be uniform throughout the bed. Thus the possibility exists that organic pollutants present in lower permeability areas may not be remediated.

Electrochemical or ion migration is the dominant process in stiff silty clays and mixed clays. Under these conditions, electroosmosis has limited or no effect on groundwater movement. With electrochemical migration, the electrical field will move uniformly through the soil and ions will readily pass through the small pores in the clay. Natural biological populations tend to exist around organic pollutant spills in soils. Complex organic compounds, however, are not prime energy sources for microbial populations and biodegradation will not flourish until sufficient food, nutrients, and electron acceptors are available to initiate growth and reduce the organic pollutant concentration. The electrical field in this case spreads charged soluble inorganic and some simple organic nutrients uniformly through the site and directs these nutrients to the spatial locations where the food source (e.g., hydrocarbon pollutant) is located.

Limitations of the process include the following:

- The concentration of the organic pollutant may be above the toxic threshold limit of the microbial population.
- The bioremediation of mixed organic pollutants may produce by-products which are toxic to the microorganisms, thereby inhibiting the biodegradation process.

8.3 ELECTROCHEMICAL GEOOXIDATION (ECGO)

ElectroChemical GeoOxidation (ECGO) is a patented *in situ* technology available from ManTech International Corporation (a license of Geotechnologies of Germany) that remediates soil and water contaminated with organic and inorganic compounds. The ECGO *in situ* process works by applying an electrical current to probes driven into the ground. The process utilizes induced electric currents to create oxidation-reduction reactions which lead to the mineralization of organic constituents (or the immobilization of inorganic constituents) present in a volume of soil and groundwater between the electrode locations (9).

ECGO relies on the induced polarization of naturally occurring conducting surfaces in soil and rock particles. These conducting surfaces are composed of elements such as iron, magnesium, titanium and elemental carbon. Heavy metal impurities that are also naturally-occurring further contribute to the process by acting as catalysts for the redox reactions.

Depending on the site conditions, accessibility, and targeted constituents, the ECGO process may take 60 to 120 days.

8.4 ELECTROCHEMICAL OXIDATIVE REMEDIATION OF GROUNDWATER

Under contract from the Air Force Armstrong Laboratory at Tyndall Air Force Base, SRI International, a non-profit organization with its headquarter in Silicon Valley, California, is developing an innovative technology for groundwater remediation that uses a permeable electrochemical oxidation reactor (PEOR) that is part of an engineered system placed within an aquifer. A stand-alone wall system comprised of porous carbon electrodes and an iron-based catalyst is being designed for installation in the path of a contaminant plume. Utilizing the natural hydraulic gradient, groundwater flows into the permeable wall, where the electrodes are used to generate hydrogen peroxide, which decomposes to hydroxyl radicals in a reaction catalyzed by the iron-based catalyst. The hydroxyl radicals oxidize the organic contaminants *in situ*, and purified water flows out of the wall into the aquifer. The technology is suited for active pumping or passive groundwater flow. It combines the advantages of an advanced oxidation process with the ability of electrochemical methods to generate oxidants *in situ* at a controllable rate (10).

8.5 ELECTROCHEMICAL ION EXCHANGE (EIX)

Geokinetics International Incorporated, (GII), a joint venture of five separate companies, uses a combination of electrokinetics and above ground Electrochemical Ion eXchangers (EIX's) to remove ionic contamination from environmental media (16).

A series of electrodes are placed in porous casings which are supplied with circulating electrolytes. Ionic contamination is captured in these electrolytes and pumped to the surface where the recovered solution is passed through the electrochemical ion exchanger which selectively recovers the contaminants allowing the reuse of some of the contaminants.

Because cleaning effluents containing low levels of contamination can be difficult and expensive, EIX can isolate and recover heavy metals, halides, and certain organic species. Typically, inflow concentrations of target species in the range 10 to 500 ppm can be reduced to less than 1 ppm.

Decontamination costs are expected to be in the range of \$200 to \$325 per cubic meter (\$150 to \$250 per cubic yard).

8.6 ELECTROSORB™

The Electrosorb™ technology of Isotron Corporation (New Orleans, Louisiana) uses cylindrical electrode assemblies where the electrode is coated with Isotron's Isolock™ polymer material. The polymer is impregnated with pH-regulating chemicals to prevent fluctuations in pH. The electrodes are placed in boreholes in the soil and a direct current is applied. 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 also contain ion exchange resins or other sorbents that can trap and hold ions before they reach the electrode. The electrode assemblies and equipment needed for the operation are all commercially available (17, 18).

8.7 LASAGNA™ PROCESS

8.7.1 Lasagna™ Public-Private Partnership

In early 1994, the U.S. Environmental Protection Agency (EPA) signed a Cooperative Research and Development Agreement with a private consortium, consisting of Monsanto, DuPont, and General Electric to jointly develop an integrated *in situ* remedial technology. In early 1995, with significant funding by the Department of Energy (DOE), the work group initiated a field experiment.

General roles of partnership members are (19):

- DuPont: Anaerobic biodegradation and vertical zone installation;
- General Electric: Electrokinetic and physiochemical treatment;
- Monsanto: Lasagna™, electroosmosis, biodegradation;
- DOE: Site selection and field support; and,
- EPA: Hydrofracturing, biodegradation.

8.7.2 Technology Description

The Lasagna™ process, so named because of its treatment layers, combines electroosmosis with treatment zones that are installed directly in the contaminated soils to form an integrated *in situ* remedial process. Electroosmosis is well known for its effectiveness in moving water uniformly through low-permeability soils at very low power consumption. Electrokinetics is used to move contaminants in soil pore water into vertically or horizontally oriented treatment zones where the contaminants can be captured or decomposed. Conceptually, the Lasagna™ process would be used to treat inorganic and organic contaminants, as well as mixed wastes.

Major features of the technology are (20):

- Electrodes energized by direct current cause water and soluble contaminants to move into or through treatment layers, and heat the soil;
- Treatment zones contain reagents that decompose the soluble organic contaminants or absorb contaminants for immobilization or subsequent removal or disposal;
- A water management system 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 periodically reversed to reverse electro-osmotic flow and neutralize pH.

The orientation of the electrodes and the treatment zones depends on the site/contaminant characteristics. In general, a vertical configuration is probably applicable to shallow contamination (within 15 meters [50 feet] of the ground surface), whereas a horizontal configuration, using hydraulic fracturing or related methods, is capable of treating much deeper contamination (12).

8.7.3 Technology Status

Phase I - Vertical Field Test at the DOE Paducah Gaseous Diffusion Plant (PGDP) in Kentucky, focused on *in situ* TCE (trichloroethylene) remediation. The test operated for 120 days and was completed in May 1995. The zone to be remediated measured 4.5 meters wide by 3 meters across and 4.5 meters deep (15 ft by 10 ft by 15 ft deep). The average contamination was 83.2 ppm, and the highest TCE concentrations (200 to 300 ppm) were found 3.5 to 4.5 meters (12 to 18 feet) below surface.

About 4% of the total TCE was lost through evaporation. Soil samples taken throughout the test site before and after the test indicate a 98% removal of TCE from a tight clay soil (hydraulic conductivity $<10^{-7}$ cm/sec), with some samples showing greater than 99% removal. TCE soil levels were reduced from the 100 to 500 ppm range to an average concentration of 1 ppm.

DNAPL (dense non-aqueous phase liquid) locations were cleaned to 1 ppm levels except for a 4.5 meter deep sample that was reduced to 17.4 ppm. Because treatment zones were only 4.5 meters deep, diffusion from untreated deep zones may have contributed to the 17.4 ppm result.

Phase II - Vertical Field Test, also conducted at the DOE PGDP, will modify the Phase I configuration by using zero-valent iron in the treatment zones to chemically reduce TCE to non-toxic end products. The zone being remediated measures 6 meters wide by 9 meters across and 13.5 meters deep (20 ft by 30 ft by 45 ft deep). This is approximately 20 times more soil (1,360 tonnes, or 1,500 tons) than was treated in Phase I. Phase II is to help resolve scale-up questions, substantiate technology cost estimates, and evaluate the performance of zero-valent iron in the treatment zones. The test is scheduled to be complete on August 4, 1997.

Various treatment processes are currently being investigated in the laboratory to address other types of contaminants, such as heavy metals and mixed wastes (20).

8.7.4 Process Advantages

- Effective in low permeability soils (hydraulic conductivity $<10^{-5}$ cm/s)
- Contaminants can be destroyed underground
- Silent operation
- Rapid installation, low profile
- Relatively short treatment duration (19)

8.7.5 Costs

Direct treatment costs for a 0.4 hectare (one-acre) site similar to that used in the Phase I test are estimated at \$105-\$120/m³ (\$80-\$90/yd³) for remediation in one year and at \$65-\$80/m³ (\$50-\$60/yd³) of soil if the remediation could occur over a period of three years. Comparable estimates for the Phase II mode of operation are \$80-\$90/m³ (\$60-\$70/yd³) for one year, and \$50-\$65 (\$40-\$50/yd³) for three years. Deeper contamination, although involving more technically challenging emplacement, costs less because of the larger area of influence per electrode (21).

8.7.6 Cost Savings Versus Alternative Technologies

DuPont has benchmarked a number of *in situ* technologies over the last three years. These include:

- *In situ* treatment zones using iron filling for dehalogenation of chlorinated solvents
- Pump and treat of contaminated groundwater
- *In situ* aerobic biological dechlorination
- Surfactant flushing

Costs for these technologies, some of which require more than 30 years to remediate a site, are between \$35 and \$100/m³ (\$25-\$75/yd³). Lasagna™ is within the range of these competing technologies with an implementation cost (over three years) of about \$65/m³ (\$50/yd³), using the method proposed for Phase II.

Use of treatment zones for *in situ* destruction of contaminants gives Lasagna™ a competitive advantage over other electrokinetic methods that extract contaminants for aboveground treatment or disposal. Because treatment zones eliminate the need for aboveground waste handling, and are presumably cheaper to make and install than electrodes, their use imparts cost advantages.

Typical costs for full-scale installation to treat a zone measuring 0.4 hectares, 13.5 meters deep (one acre, 45 feet deep):

	Soil Excavation	Lasagna
Capital (\$K)		3,750 ²
O&M (\$K)	10,600 ¹	900 ³
Post-treatment sampling		360 ⁴
Total cost (\$K)	10,600	5,010
Cost per ton	\$107	\$51

¹ Cost estimate includes excavation, transportation and landfilling fees. Example assumes 30% of soil is disposed in a hazardous landfill and 70% in sanitary landfill.

² Capital includes installation, materials, rectifiers and other fixed costs.

³ Operation is assumed to last one year. Costs include electricity and labor.

⁴ Sampling costs are assumed to be an average of \$6.50 per cubic meter (\$5 per cubic yard).

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