United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/540/R-98/XXX
December 1998

Sandia National Laboratories In Situ Electrokinetic Extraction Technology

Innovative Technology Evaluation Report

SITE
SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

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National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

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Foreword

The U. S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and groundwater; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

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E. Timothy Oppelt, Director

National Risk Management Research Laboratory

Abstract

This report evaluates an in situ electrokinetic extraction system's ability to remove hexavalent chromium in the form of chromate ions from soil under unsaturated conditions. Specifically, this report discusses performance and economic data from a Superfund Innovative Technology Evaluation (SITE) demonstration of an In Situ Electrokinetic Extraction (ISEE) system developed by Sandia National Laboratories (SNL).

The ISEE system demonstrated combines electrokinetic and lysimeter technologies. The lysimeter technology hydraulically and electrically creates a continuum between fluid in the anode casings (anolyte) and soil pore water, thereby enabling extraction of the chromate ions in the anolyte while the anolyte is held in the electrode casing through application of a vacuum. This feature allowed removal of chromate from unsaturated soil during the demonstration without significantly altering the soil moisture content.

The ISEE system developed by SNL was demonstrated at the U.S. Department of Energy SNL Chemical Waste Landfill (CWL) site's Unlined Chromic Acid Pit (UCAP) in Albuquerque, New Mexico, from May 15 to November 24, 1996. The system was housed in two buildings: a control trailer and a temporary structure. The electrode system of the ISEE system consisted of an anode row oriented east to west and four rows of cathodes parallel to the anode row, two rows to the north and two rows to the south of the anode row. The entire system was operated for a total of 2,727 hours during 13 tests performed in six phases. The first 12 tests were performed to determine the preferred operating conditions for Test 13, which consisted of system performance testing under SNL's preferred operating conditions for the SITE demonstration.

Approximately 520 grams (g) of hexavalent chromium was removed during the demonstration. Overall hexavalent chromium removal rates varied from 0.074 gram per hour (g/hour) during Test 1 to 0.338 g/hour during Test 5. Overall hexavalent chromium removal efficiencies varied from 0.0359 gram per kilowatt-hour (g/kW-h) during Test 7 to 0.136 g/kW-h during Test 13. More than 50 percent of the postdemonstration soil samples exceeded the toxicity characteristic leaching procedure (TCLP) limit of 5 milligrams per liter (mg/L) for total chromium. The soil TCLP leachate concentrations that were above the TCLP limit ranged from 6 to 67 mg/L. Downtime during system operation ranged from 0 percent during Test 11 to 66 percent during Test 1. Over the entire demonstration, the ISEE system was on line 64 percent of the time.

Economic data indicate that the costs for treating 16 cubic yards (yd^3) of hexavalent chromium-contaminated soil with the ISEE system configuration used during Test 13 are about $1,400 per yd^3 for 200 g of hexavalent chromium removed.

The ISEE technology developed by SNL is applicable for treating unsaturated soil contaminated with hexavalent chromium. According to SNL, this technology can be modified to treat saturated contaminated soil and to remove contaminants dissolved in pore water other than chromate. A full-scale, commercial system has not yet been developed. SNL maintains that a full-scale system would be significantly be improved over the system tested during the demonstration. Therefore, further performance and cost analyses should be performed on a full-scale system.

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Acronyms, Abbreviations, and Symbols

AAA	Abbreviated analytical approach
AEA	Atomic Energy Act
amp	Ampere
ARAR	Applicable or relevant and appropriate requirement
bgs	Below ground surface
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CFR	Code of Federal Regulations
CWL	Chemical waste landfill
DC	Direct current
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
g	Gram
g/hour	Gram per hour
g/kW-h	Gram per kilowatt-hour
ICP	Inductively coupled plasma
ISEE	In situ electrokinetic extraction
ITER	Innovative technology evaluation report
kW	Kilowatt
kW-h	Kilowatt-hour
LDR	Land Disposal Restriction
L/min	Liter per minute
mg/kg	Milligram per kilogram
mg/L	Milligram per liter
m/s	Meter per second
m^2/V-s	Square meter per volt-second
N-s/m^2	Newton-second per square meter
N/V^2	Newton per square volt
NCP	National Oil and Hazardous Substances Contingency Plan
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory

Acronyms, Abbreviations, and Symbols (continued)

NSPS	New Source Performance Standard
O&M	Operation and maintenance
ORD	Office of Research and Development
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PCB	Polychlorinated biphenyl
PPE	Personal protective equipment
ppm	Part per million
psi	Pound per square inch
PVC	Polyvinyl chloride
QA	Quality assurance
QC	Quality control
QAPP	Quality assurance project plan
Quanterra	Quanterra Environmental Services, Inc.
RCRA	Resource Conservation and Recovery Act of 1976
SAP	Sampling and analysis plan
SITE	Superfund Innovative Technology Evaluation
SNL	Sandia National Laboratories
TCLP	Toxicity characteristic leaching procedure
TER	Technology evaluation report
TSCA	Toxic Substances Control Act
UCAP	Unlined chromic acid pit
V	Volt
V/m	Volt per meter
VOC	Volatile organic compound
yd^3	Cubic yard
µg/L	Microgram per liter
>	Greater than
<	Less than

Conversion Factors

	To Convert From	*To*	*Multiply By*
Length	inch	centimeter	2.54
	foot	meter	0.305
	mile	kilometer	1.61
Area:	square foot	square meter	0.0929
	acre	square meter	4,047
Volume:	gallon	liter	3.78
	cubic foot	cubic meter	0.0283
Mass:	pound	kilogram	0.454
Energy:	kilowatt-hour	megajoule	3.60
Power:	kilowatt	horsepower	1.34
Temperature:	(°Fahrenheit - 32)	°Celsius	0.556

Acknowledgments

This report was prepared under the direction and coordination of Mr. Randy Parker, U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program project manager of the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. Contributors and reviewers for this report were Sam Hayes and Ed Barth of EPA NRMRL, Cincinnati, Ohio; and Dr. Eric Lindgren of Sandia National Laboratories, Albuquerque, New Mexico. This report was prepared for EPA's SITE program by Dr. Kirankumar Topudurti, Ms. Cristina Radu, Mr. Shin Ahn, and Ms. Linda Hunter of Tetra Tech EM Inc.

Executive Summary

The electrokinetic extraction technology is a treatment process that facilitates the in situ extraction of metals from unsaturated and saturated soil. The In Situ Electrokinetic Extraction (ISEE) system developed by Sandia National Laboratories (SNL) focused on the remediation of hexavalent chromium-contaminated soil under unsaturated conditions (optimal moisture content in the range 10 to 12 percent by weight, representing approximately 25 percent saturation). The SNL ISEE system was accepted into the Superfund Innovative Technology Evaluation (SITE) Demonstration program in Summer 1994 and was demonstrated at the U.S. Department of Energy (DOE) SNL Chemical Waste Landfill (CWL) site's Unlined Chromic Acid Pit (UCAP) in Albuquerque, New Mexico, from May 15 to November 24, 1996. This demonstration was funded by DOE's Office of Science and Technology through the Subsurface Contamination Focus Area. The ISEE system was independently evaluated under the SITE program.

The purpose of this innovative technology evaluation report (ITER) is to present information that will assist Superfund decision-makers in evaluating the ISEE system developed by SNL for application to a particular hazardous waste site cleanup. The report provides an introduction to the SITE program and ISEE system technology (Section 1), analyzes the technology's effectiveness and applications (Section 2), analyzes the economics of using the ISEE system to treat soil contaminated with hexavalent chromium in the form of chromate (Section 3), summarizes the technology's status (Section 4), and presents a list of references used to prepare the ITER (Section 5). Vendor's claims for the ISEE system are presented in the appendix.

This executive summary briefly describes the ISEE technology and system, provides an overview of the SITE demonstration of the technology, summarizes the SITE demonstration results, discusses the economics of using the ISEE system to treat soil contaminated with hexavalent chromium in the form of chromate, and discusses the Superfund feasibility evaluation criteria for the ISEE system.

Technology and System Description

The ISEE system developed by SNL applied electrokinetic technology to unsaturated soil to remove hexavalent chromium. The application of current to the soil-water system results in the following: (1) ionic species in the soil pore water migrate to the oppositely charged electrode (a phenomenon called electromigration), (2) charged particles in the soil pore water migrate to the oppositely charged electrode (a phenomenon called electrophoresis), (3) bulk water moves toward the cathode (a phenomenon called electroosmosis), and (4) electrolysis reactions occur at the electrodes. The combination of these phenomena results in the movement of ionic contaminants toward the electrodes. The direction and rate of movement will depend on the charge of the ions (both in terms of magnitude and polarity), the degree to which the ions adsorb to the soil particles, and the magnitude of the electroosmosis flow velocity.

The ISEE system used for the SITE demonstration was housed in two buildings: a control trailer and a temporary structure. The ISEE system used for the demonstration consisted of anodes, cathodes, and cold fingers cathodes that made up the electrode system. The electrode system consisted of an anode row oriented east to west and four rows of cathodes parallel to the anode row, two rows north and two rows south of the anode row. Two types of cathodes were used during the SITE demonstration: cathodes similar to the anodes, which will be referred to as "cathodes," and simple design cathodes, which will be referred to as "cold finger cathodes." The treatment zone was determined by the active portion of these electrodes and extended from 8 to 14 feet below ground surface (bgs).

The operation of the ISEE system was regulated by a water control system, a vacuum control system, a power supply system, a monitoring system, and ancillary equipment.

The anodes and cathodes used at UCAP were designed to combine electrokinetic and lysimeter technologies. This combination was necessary to allow the operation of the system under unsaturated soil conditions. Lysimeter technology hydraulically and electrically creates a continuum between the anolyte and the pore water, thereby enabling the extraction of the chromate ions in the anolyte while the anolyte is held in the electrode casings through the application of a vacuum. This feature allowed the removal of chromate from unsaturated soil during the demonstration without significantly altering the soil moisture content.

The ISEE technology developed by SNL is applicable for treating unsaturated soil contaminated with hexavalent chromium. According to SNL, this technology can be modified to treat saturated contaminated soil and to remove contaminants dissolved in pore water besides chromate. Because other anions will compete with the targeted contaminant ions to be removed, it is necessary to determine the electrical conductivity of soil pore water and the target ion concentration to determine the applicability of the ISEE technology.

Overview of the SNL ISEE System SITE Demonstration

The ISEE system SITE demonstration took place at the UCAP, which is part of the CWL site located within Technical Area III at SNL. The UCAP is a rectangular pit measuring about 15 by 45 feet and is 10 feet deep. The areal extent and depth of the area targeted by the demonstration was selected based on the highest results of water soluble chromium concentrations from sampling performed during previous investigations. During the demonstration, the system was operated for a period of 2,727 hours between May 15 and November 24, 1996.

The primary objective of the technology demonstration was to estimate the amount of hexavalent chromium removed from soil by the ISEE system because the ISEE system is primarily designed to remove hexavalent chromium. To accomplish this objective, SNL collected and analyzed anolyte samples for hexavalent chromium at its field laboratory throughout the demonstration period. An independent check of field analytical data was provided by EPA through split sample analysis at an off-site laboratory. Field analytical data were subsequently deemed adequate to estimate the amount of hexavalent chromium removed from soil by the ISEE system. Predemonstration and postdemonstration soil samples collected by EPA were analyzed for hexavalent chromium to verify the hexavalent chromium removal estimate based on anolyte sample analyses.

The secondary objectives of the technology demonstration were to determine whether treated soil meets the toxicity characteristic leaching procedure (TCLP) regulatory criterion for total chromium and to evaluate the ISEE system's ability to remove trivalent chromium from site soil.

To conduct the demonstration, SNL was required to meet the conditions of the New Mexico Environmental Department's Resource Conservation and Recovery Act (RCRA) Research, Development, and Demonstration permit for the ISEE system. Predemonstration testing results indicated that some of the soil in the demonstration area is hazardous (EPA waste code D007) because chromium concentrations exceeded the TCLP criterion for chromium. Therefore, the permit required that SNL perform postdemonstration TCLP testing to determine the impact of the ISEE system on soil known to be contaminated. SNL therefore collected a large number of treated soil samples for total chromium analysis after extraction using TCLP.

Because incidental removal of trivalent chromium will likely be accomplished by the ISEE system, evaluation of trivalent chromium removal was a secondary project objective of this project. To accomplish this objective, the predemonstration and postdemonstration soil samples collected for hexavalent chromium analysis were also analyzed for total chromium so that the trivalent chromium concentrations could be calculated as the difference between the total and hexavalent chromium concentrations.

During the SITE demonstration, 13 tests were performed during six phases. The test areas ranged from 36 to 72 square feet, and contaminated soil from 8 to 14 feet bgs was treated. The first 12 tests were conducted so that SNL could determine the preferred operating conditions for Test 13 and to facilitate the migration of hexavalent chromium toward the central portion of the test area. Test 13 consisted of system performance testing under SNL's preferred operating conditions for the SITE demonstration.

Three sampling events occurred during the ISEE system SITE demonstration: one of predemonstration soil, one of anolyte (electrolyte from the anodes), and one of postdemonstration soil. SNL collected predemonstration soil samples from various depth in boreholes within and near the test areas using a 1-inch-diameter by 24-inch-long Geoprobe® Large Bore Sampler. SNL extracted a portion of each sample with water and analyzed the extract for chromium. Additional sample portions were sent to an off-site laboratory in order to have these soil samples extracted using TCLP and the extracts analyzed for total chromium. EPA used SNL's archived soil samples to determine total and hexavalent chromium concentrations in the predemonstration soil.

During operation of the ISEE system, SNL collected anolyte samples daily and analyzed them for hexavalent chromium to determine removal rates. To verify these results, EPA obtained anolyte samples from all four operating anodes daily for 8 days. These samples were all sent to Quanterra for analysis for hexavalent chromium. The relative percent differences between the SNL and Quanterra results varied from 0 to 20 percent indicating that SNL's field hexavalent chromium analyses were acceptable.

After the demonstration, EPA collected soil samples using the Geoprobe® from locations near (within 1 foot laterally and 2 inches vertically) the predemonstration sampling locations and sent these samples to an off-site laboratory for the same sort of preparation and analyses for hexavalent chromium and total chromium conducted during predemonstration sampling. SNL collected a separate series of Geoprobe® samples and sent them to an off-site laboratory for TCLP extraction and total chromium analysis.

SITE Demonstration Results

Key findings of the ISEE system SITE demonstration are listed below.

- Approximately 520 grams (g) of hexavalent chromium were removed during the entire demonstration. Overall hexavalent chromium removal rates varied from 0.074 gram per hour (g/hour) during Test 1 to 0.338 g/hour during Test 5. Overall hexavalent chromium removal efficiencies varied from 0.0359 gram per kilowatt-hour (g/kW-h) during Test 7 to 0.136 g/kW-h during Test 13.

- The total mass of hexavalent chromium extracted by the ISEE system should have been verified by calculating the difference between hexavalent chromium mass in treated soil before and after the demonstration. However, soil results for hexavalent chromium exhibited a high spatial variability resulting from (1) the nonhomogeneous distribution of chromate concentrations in soil before the demonstration and (2) the fact that the demonstration was terminated before chromate removal was completed. In addition, limited data appear to indicate that contaminants had likely migrated from areas outside of and near the treatment area. Thus, a determination of the mass of hexavalent chromium removed based on soil sampling results was not possible.

- Of the 43 predemonstration soil samples analyzed by TCLP, 18 exceeded the TCLP limit of 5 milligrams per liter (mg/L) of total chromium at concentrations ranging from 5.6 to 103 mg/L, with a median concentration of 15.4 mg/L. Postdemonstration results indicate that 18 out of 35 soil samples exceeded the TCLP regulatory criterion for chromium at concentrations ranging from 6 to 67 mg/L, with a median concentration of 20.4 mg/L.

- Trivalent chromium concentrations were to be determined by calculating the difference between total and hexavalent chromium concentrations. In general, the ratio of trivalent chromium to total chromium ranged from 7.6 to 94.9 percent in the predemonstration samples and from 27.6 to 99.6 percent in the postdemonstration samples. This large variability precluded the calculation of trivalent chromium concentrations as originally intended because it would have further increased the data variability. Therefore, no conclusion was drawn regarding the ISEE system's ability to remove trivalent chromium.

- The entire system was operated for a total of 2,727 hours during 13 tests performed in six phases. The first 12 tests were performed to determine the preferred operating conditions for Test 13. Test 13 consisted of system performance testing under SNL's preferred operating conditions for the SITE demonstration.

Economics

Based on information provided by SNL and the results and experiences gained from the SITE demonstration, an economic analysis was performed to examine 12 separate cost categories for using the ISEE technology to remediate hexavalent chromium-contaminated, unsaturated soils. According to SNL, a full-scale commercial system design would significantly differ from the system operated during the demonstration. In addition, the developer has not completed a full-scale design of a commercial ISEE system. Therefore, it is not possible to prepare a cost estimate for a full-scale ISEE system. Because SNL states that the full-scale treatment system design will be significantly improved based on the performance of the system used during the demonstration, the treatment cost of a full-scale system will also differ from the treatment cost of the system operated during the demonstration. When the technology is ready for commercialization, further economic analysis should be performed.

Treatment costs were determined for the ISEE system configuration used during Test 13 (SNL's preferred operating conditions) to treat 16 cubic yards (yd^3) of soil and remove 200 g of hexavalent chromium (the approximate mass of hexavalent chromium removed during Test 13). Because the treatment volume is only 16 yd^3 and the ISEE system configuration used during Test 13 is currently at the pilot-scale level, the cost per yd^3 of treated soil is very high; the estimated treatment costs are about $1,400 per yd^3 for 200 g of hexavalent chromium removed. If SNL is able to further optimize the ISEE system configuration so that hexavalent chromium removal rate increases from that calculated for Test 13, treatment time and costs will be lower. As mentioned above, costs from economic analysis of a full-scale ISEE system would be more indicative of costs of a commercial-scale ISEE system.

Superfund Feasibility Evaluation Criteria for the ISEE System

Table ES-1 briefly discusses the Superfund feasibility evaluation criteria for the ISEE system to assist Superfund decision-makers considering the technology for remediation of contaminated groundwater or soil at hazardous waste sites.

Table ES-1. Superfund Feasibility Evaluation Criteria for the ISEE Technology

Criterion	Discussion
Overall Protection of Human Health and the Environment	• The ISEE technology is expected to protect human health by lowering the concentration of hexavalent chromium in soil under unsaturated conditions. According to the developer, the technology can also treat soil contaminated with other heavy metals under both saturated and unsaturated conditions, but this capability was not evaluated during the SITE demonstration. • Overall reduction of human health risk should be evaluated on a site-specific basis because VOCs could be stripped from soil during treatment and increase VOC soil vapor concentrations and VOC migration in the soil. Also, the system effluent (anolyte) contains hexavalent chromium and therefore needs to be characterized and handled and disposed of as hazardous waste. • The technology protects the environment by curtailing migration of hexavalent chromium in soil. • Protection of the environment at and beyond the point of anolyte extraction depends on how the anolyte is handled and disposed of. Protection of the environment also depends on the extent of VOC emissions.
Compliance with Applicable or Relevant and Appropriate Requirements (ARAR)	• According to the developer, the technology has the potential to comply with existing federal, state, and local ARARs (for example, TCLP limits) for several inorganic contaminants (for example, chromium). However, about 51 percent of the postdemonstration samples did not meet the chromium TCLP limit of 5 mg/L.
Long-Term Effectiveness and Permanence	• Human health risk can be reduced to acceptable levels by treating soil to a 1×10^{-6} excess lifetime cancer risk level. The time needed to achieve cleanup goals depends primarily on contaminated soil characteristics. • The treatment achieved is permanent because contaminants are contained in the anolyte, which is extracted from the soil for disposal. • Periodic review of treatment system performance is needed because application of the technology to contaminated soil at hazardous waste sites is new.
Reduction of Toxicity, Mobility, or Volume Through Treatment	• The technology reduces the volume and mobility of contaminants in soil because contaminants are contained in the anolyte, which is extracted from the soil for disposal. • The technology can effectively control soil contaminant migration because contaminants are contained in the anolyte, which is extracted from the soil for disposal.
Short-Term Effectiveness	• About 51 percent of postdemonstration samples did not meet the chromium TCLP limit of 5 mg/L. This failure may be because the developer did not have the state permit required to carry out the demonstration for a longer period of time.
Implementability	• The technology is still in the development stage. No commercial system is currently available from SN. • State and local permits must be obtained to operate the ISEE system.

Table ES-1. Superfund Feasibility Evaluation Criteria for the ISEE Technology (continued)

Criterion	Discussion
Cost	• Treatment costs vary significantly depending on the size of the treatment system used, contaminant characteristics and concentrations, cleanup goals, the volume of contaminated soil to be treated, and the length of treatment. Economic data indicate that soil remediation costs are very high, perhaps because the system demonstrated at UCAP was not of commercial scale and requires significant improvements.
State Acceptance	• This criterion is generally addressed in the record of decision. State acceptance of the technology will likely depend on (1) expected residual contaminant in soil, (2) how the analyte is handled and disposed of, and (3) the steps taken to reduce the potential for VOC migration.
Community Acceptance	• This criterion is generally addressed in the record of decision after community responses have been received during the public comment period. Because communities are not expected to be exposed to harmful levels of fugitive emissions, the level of community acceptance of the technology is expected to be moderate.

Section 1
Introduction

This section briefly describes the Superfund Innovative Technology Evaluation (SITE) program and SITE reports; states the purpose and organization of this innovative technology evaluation report (ITER); provides background information on the demonstration of the Sandia National Laboratories (SNL) In Situ Electrokinetic Extraction (ISEE) system under the SITE program; describes the ISEE technology; identifies wastes to which this technology can be applied; and provides a list of key contacts for information about the system and SITE demonstration.

1.1 Brief Description of SITE Program and Reports

This section provides information about the purpose, history, and goals of the SITE program and about reports that document SITE demonstration results.

1.1.1 Purpose, History, and Goals of the SITE Program

The primary purpose of the SITE program is to advance the development and demonstration, and thereby establish the commercial availability, of innovative treatment technologies applicable to Superfund and other hazardous waste sites. The SITE program was established by the U.S. Environmental Protection Agency (EPA) Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA), which recognized the need for an alternative or innovative treatment technology research and demonstration program. The SITE program is administered by ORD's National Risk Management Research Laboratory (NRMRL). The overall goal of the SITE program is to research, evaluate, test, develop, and demonstrate alternative or innovative treatment technologies that can be used in response actions to achieve long-term protection of human health and welfare and the environment.

This ITER was prepared under the SITE Demonstration program. The objective of the Demonstration program is to provide reliable performance and cost data on innovative technologies so that potential users can assess a given technology's suitability for specific site cleanups. To produce useful and reliable data, demonstrations are conducted at actual hazardous waste sites or under conditions that closely simulate actual waste site conditions.

Data collected during the demonstration are used to assess the performance of the technology, the potential need for pretreatment and post-treatment processing of the treated waste, the types of wastes and media that can be treated by the technology, potential treatment system operating problems, and approximate capital and operating costs. Demonstration data can also provide insight into a technology's long-term operation and maintenance (O&M) costs and long-term application risks.

Under each SITE demonstration, a technology's performance in treating an individual waste at a particular site is evaluated. Successful demonstration of a technology at one site does not ensure its success at other sites. Data obtained from the demonstration may require extrapolation to estimate a range of operating conditions over which the technology performs satisfactorily. Also, any extrapolation of demonstration data should be based on other information about the technology, such as case study information.

Implementation of the SITE program is a significant, ongoing effort involving ORD, OSWER, various EPA regions, and private business concerns, including technology developers and parties responsible for site

remediation. The technology selection process and the Demonstration program together provide a means to perform objective and carefully controlled testing of field-ready technologies. Innovative technologies chosen for a SITE demonstration must be pilot- or full-scale applications and must offer some advantage over existing technologies. Mobile technologies are of particular interest.

1.1.2 Documentation of SITE Demonstration Results

The results of each SITE demonstration are usually reported in four documents: the demonstration bulletin, technology capsule, technology evaluation report (TER), and ITER.

The demonstration bulletin provides a two-page description of the technology and project history, notification that the demonstration was completed, and highlights of the demonstration results. The technology capsule provides a brief description of the project and an overview of the demonstration results and conclusions.

The purpose of the Technology Evaluation Report (TER) is to consolidate all information and records acquired during the demonstration. It contains both a narrative portion and tables that summarize data. The narrative portion discusses predemonstration, demonstration, and postdemonstration activities, any deviations from the sampling and analysis plan (SAP) during these activities, and the impact of such deviations, if applicable. The tables summarize quality assurance and quality control (QA/QC) data and data quality objectives. The TER is not formally published by EPA. Instead, a copy is retained by the EPA project manager as a reference for responding to public inquiries and for recordkeeping purposes. The purpose and organization of the ITER are discussed below.

1.2 Purpose and Organization of the ITER

Information presented in the ITER is intended to assist Superfund decision-makers in evaluating specific technologies for a particular cleanup situation. Such evaluations typically involve the nine remedial technology feasibility evaluation criteria, which are listed in Table 1-1 along with the sections of the ITER where information related to each criterion is discussed. The ITER represents a critical step in the development and commercialization of a treatment technology. The report discusses the effectiveness and applicability of the ISEE system and

Table 1-1. Correlation Between Superfund Feasibility Evaluation Criteria and ITER Sections

Evaluation Criterion[a]	ITER Section
Overall protection of human health and the environment	2.2.1 through 2.2.3
Compliance with ARARs[b]	2.2.2 and 2.7
Long-term effectiveness and permanence	1.4 and 2.2.1
Reduction of toxicity, mobility, or volume through treatment	2.2.1 and 2.2.2
Short term effectiveness	2.2.1 through 2.2.3
Implementability	1.4, 2.2, 2.3, and 2.4
Cost	3.0
State acceptance	2.8
Community acceptance	2.8

Note

[a] Source: EPA 1988
[b] ARAR = Applicable or relevant and appropriate requirement

analyzes costs associated with its application. The system's effectiveness is evaluated based on data collected during the SITE demonstration and from other case studies. The applicability of the system is discussed in terms of waste and site characteristics that could affect technology performance, material handling requirements, technology limitations, and other factors.

This ITER consists of five sections, including this introduction. These sections and their contents are summarized below.

- Section 1, Introduction, presents a brief description of the SITE program and reports, the purpose and organization of the ITER, background information about the ISEE system demonstration under the SITE program, a technology description, applicable wastes that can be treated, and key contacts for information about the ISEE system and SITE demonstration.

- Section 2, Technology Effectiveness and Application Analysis, presents an overview of the SNL ISEE system SITE demonstration, SITE demonstration results, factors affecting ISEE system performance, site characteristics and support requirements, material handling requirements, technology limitations, potential regulatory requirements, and state and community acceptance.

- Section 3, Economic Analysis, discusses estimated costs, issues and assumptions, and the basis for the economic analysis.

- Section 4, Technology Status, discusses the developmental status of the ISEE system.

- Section 5, References, lists references used to prepare this ITER.

In addition to these sections, this ITER has an appendix, Vendor's Claims for the Technology.

1.3 Background Information on the Demonstration of the SNL ISEE System Under the SITE Program

The SNL ISEE system was accepted into the SITE Demonstration program in Summer 1994. The ISEE system was demonstrated at the U.S. Department of Energy (DOE) SNL Chemical Waste Landfill (CWL) site's Unlined Chromic Acid Pit (UCAP) in Albuquerque, New Mexico, from May 15 to November 24, 1996. This demonstration was funded by DOE's Office of Science and Technology through the Subsurface Contamination Focus Area. The ISEE system was independently evaluated under the SITE program.

1.4 Technology Description

This section describes the ISEE process chemistry, ISEE treatment system, and innovative features of the technology.

1.4.1 Process Chemistry

The ISEE technology is a treatment process that facilitates the in situ extraction of metals from unsaturated and saturated soil. The electrokinetic removal system developed by SNL focused on the remediation of hexavalent chromium-contaminated soil under unsaturated conditions (moisture content as low as 7 percent by weight, representing approximately 25 percent saturation in laboratory studies) (Lindgren and others 1991).

The application of electrokinetics to various types of unsaturated soils, including clays and sands, has been studied by numerous investigators. Electrokinetic systems apply low-level direct current (DC) on the order of milliamperes per square centimeter between electrodes, thus establishing an electrical potential on the order of volts per centimeter across the electrodes. Electrokinetic systems are effective as long as the pore water in the soil can maintain the electrical potential between the electrodes (Lindgren and others 1991).

The application of the current to the soil-water system under saturated or unsaturated conditions results in the following: (1) ionic species in the soil pore water migrate to the oppositely charged electrode (a phenomenon called electromigration), (2) charged particles in the soil pore water migrate to the oppositely charged electrode (a phenomenon called electrophoresis), (3) bulk water moves toward the cathode (a phenomenon called electroosmosis), and (4) electrolysis reactions occur at the electrodes (Hunter 1981). Figure 1-1 is a diagram of these phenomena. The combination of these phenomena results in the movement of ionic contaminants toward the electrodes. The direction and rate of movement will depend on the charge of the ions (both in terms of magnitude and polarity), the degree to which the ions

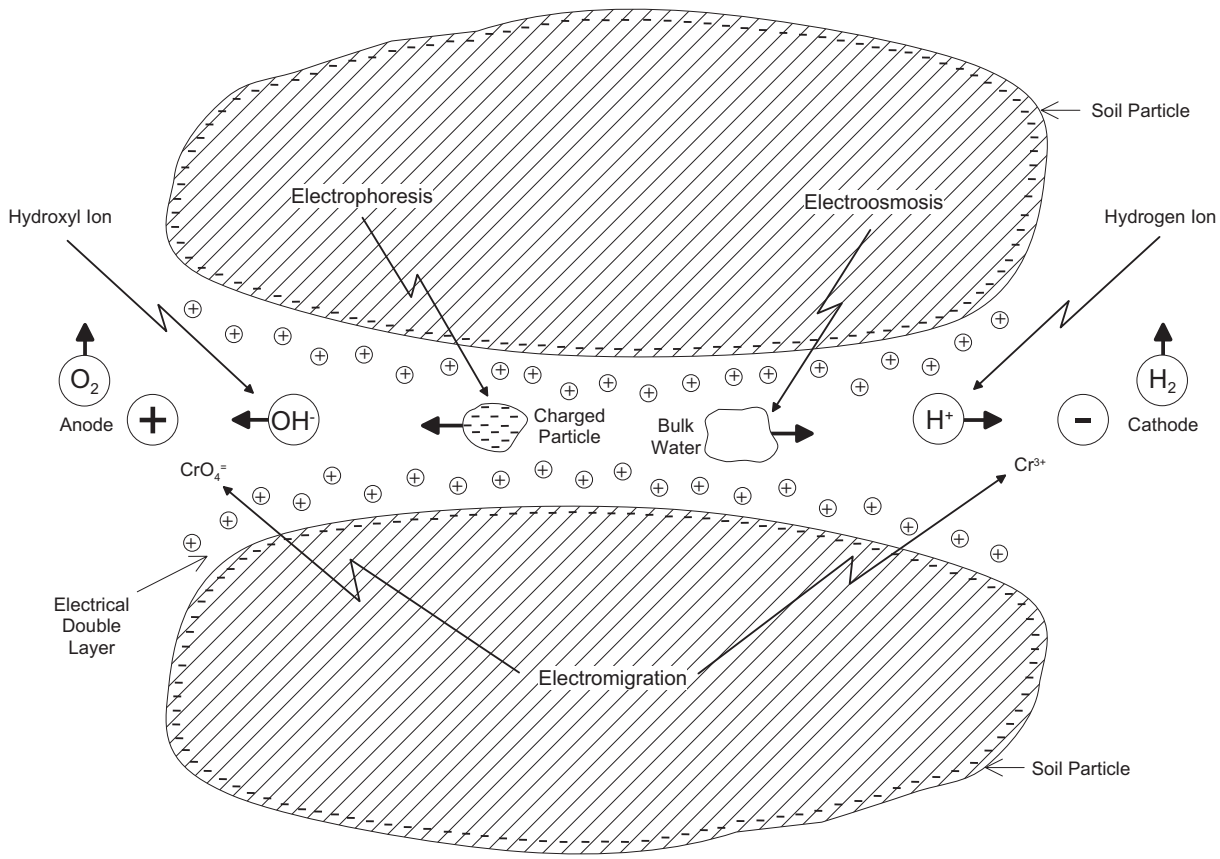


Figure 1-1. Electrokinetic phenomena in a soil pore.

adsorb to the soil particles, and the magnitude of the electroosmosis flow velocity. Contaminants arriving at the electrodes can be removed by extracting the pore water near the electrodes, electroplating or adsorbing contaminants onto the electrodes, precipitating and coprecipitating contaminants at the electrodes, or complexing the contaminants with ion-exchange resins (Mattson and Lindgren 1993).

The two most important transport mechanisms in electrokinetic remediation are electromigration and electroosmosis. Previous testing does not prove that electrophoresis is an efficient transport mechanism because the flow of colloid particles requires large pore spaces and the colloid particles are likely to become mechanically lodged in the pore space and taken out of suspension. On the other hand, electromigration and electroosmosis follow the potential gradient and are independent of pore size. Electromigration and electroosmosis are briefly discussed below.

1.4.1.1 Electromigration

Electromigration represents the transport of ionic species in pore fluid across the soil mass under the influence of an electric field. These ionic species may include anions such as CrO_4^-, $HAsO_4^-$, SeO_4^-, and carbonate complexes of uranium and cations such as Cr^{3+}, Na^+, Fe^{2+}, and Fe^{3+}.

The electromigration velocity of an ion in a dilute solution is a function of the electrical ionic mobility of a species (the ionic transport rate under the voltage gradient). A tortuosity term can be incorporated into the general ionic transport equation to account for the nonlinear path of ion travel in a soil matrix (Shapiro 1990). Equation 1-1 presents a modified version of the general ionic transport equation, which is specific for movement under a voltage gradient.

$$v_{em} = \frac{\mu}{\tau^2}\frac{dV}{dx} \qquad (1\text{-}1)$$

where:

v_{em}	=	electromigration velocity (meter per second [m/s])
μ	=	electric ionic mobility (square meter per volt-second [m^2 /V-s])
τ	=	tortuosity (dimensionless)
dV/dx	=	voltage gradient (volt per meter [V/m])

1.4.1.2 Electroosmosis

Most clay minerals have a negatively charged surface mainly resulting from imperfections in the mineral lattices developing during formation. The excess negative charge on the soil surface results in the attraction and cluster of excess cations to this surface, and the neutrality of charge in the pore water is maintained by the respective anionic or cationic concentrations of species away from the soil surface. When an electric field is established across the soil mass, soil pore water cations close to the soil surface move toward the cathode. The movement of these cations and any water molecules closely associated with these species will result in pore water flow in the same direction. This pore water flow is due to the voltage gradient and is called electroosmosis. Generally, a wider zone of excess cations, also known as the diffuse electrical double layer, results in more electroosmotic flow. The double layer is defined by the zeta potential, which is the electrostatic potential on an imaginary surface near the soil particles. This surface is defined by zero shear, meaning that water particles on this surface are stationary. The zeta potential depends on the magnitude of the charge density on the soil surface, ionic strength of the pore water, valence of the cation, pH, and permittivity (the ratio of electric flux density produced by an electric field in water to that produced in vacuum by the same field) of the pore water.

To account for the tortuosity of ion transport in the soil pore, the Helmholtz-Smoluchowski equation (Hunter 1981), which describes the transport of water in an electrical field, can be extended to porous media as presented in Equation 1-2.

$$v_{eo} = \frac{\epsilon \zeta}{\nu \tau^2} \frac{dV}{dx} \qquad (1\text{-}2)$$

where:

v_{eo}	=	electroosmotic velocity (m/s)
ϵ	=	fluid permittivity (Newton-per square volt [N/V^2])
ζ	=	zeta potential (V)
ν	=	fluid viscosity (Newton-second per square meter [$N\text{-}s/m^2$])
τ	=	tortuosity (dimensionless)
dV/dx	=	voltage gradient (V/m)

In general, electromigration is the dominant transport mechanism for ions in typical soils. As shown in Figure 1-1, the charge of the ion determines the electromigration direction in an electric field, either toward the cathode if the ion is positively charged or toward the anode if the ion is negatively charged. However, because of a negative zeta potential (the electrostatic potential on an imaginary surface near the soil particles) of soil particles, surrounding water has a net positive charge; therefore, the electroosmosis or bulk water flow is toward the cathode. Therefore, when a contaminant is anionic, electromigration of the contaminant ion is counter to the direction of the electroosmotic water flux. For a cationic contaminant, electromigration and electroosmotic transport are in the same direction.

By applying electric current to soil, electrolysis of pore water occurs, producing an acid (H^+) at the anode and a base (OH^-) at the cathode, which could significantly affects the chemistry of the soil system during treatment. If no pH conditioning is used at the electrodes, soil could have a net acidic characteristic at steady state conditions because the hydrogen ion has double the mobility of the hydroxyl ions.

A secondary effect of current application to soil during remediation is an increase in temperature because some of the electrical energy will be transformed into thermal energy. This heating may affect the remediation process, depending on whether the electrokinetic system is operated under constant current or constant voltage conditions. Under constant current conditions, an increase in pore water temperature will not affect the velocity of electromigration; however, electroosmotic velocity will decrease by 0.4 percent per degree Celsius. Under constant voltage conditions, each degree increase in temperature will increase the electromigration velocity by 3.4 percent and the electroosmotic velocity by 2.1 percent, and the increase in temperature will decrease the viscosity of water, thereby also increasing the electroosmotic velocity. The increase in transport mechanism velocity with elevated temperatures results in reduction of the time required for remediation (Mattson and Lindgren 1994; EPA 1997). System operation under constant voltage conditions is therefore preferred.

Methodologies are not well established for evaluating a site for electrokinetic remediation or for predicting the associated cleanup level, remediation time, and cost. The design problem can be addressed in two stages. First, an estimate of the total amount of electric current required must be made. This estimate will depend not only on the contaminant mass to be removed but also on the efficiency of current usage (in grams of chromium removed per ampere-hour) or the transference number, which itself depends primarily on the chemical nature of the contamination. Second, a determination must be made of how the current will be applied over a given time period (which will determine the grams of chromium removed per kilowatt-hour). This determination requires additional physical information about the site, such as the contaminant plume geometry, soil resistivity, and expected temperature changes. This information, coupled with the electrode layout, determines the voltage and electrical power requirements.

1.4.2 SNL ISEE System

The ISEE system developed by SNL applies electrokinetic technology to unsaturated soil. The SITE demonstration of the system took place at the UCAP in Technical Area III at SNL and targeted the removal of chromate ($CrO_4^{=}$) from an area of chromium-contaminated soil that underlies the pit. The UCAP measures about 15 by 45 feet and is 10 feet deep (SNL 1994).

The ISEE system used for the demonstration was housed in two buildings: a control trailer and a temporary structure. The control trailer contained the control panels, the power supply, and the data logging system. The temporary structure protected electrokinetic technology equipment and personnel and maintained the operational exclusion zone required during ISEE system operation.

The ISEE system used for the demonstration shown in Figure 1-2 consisted of anodes, cathodes, and cold finger cathodes that made up the electrode system. Because cathodes were used only during the first phase of the demonstration, they are not shown in Figure 1-2. The operation of the ISEE system was regulated by four units: a water control system, a vacuum control system, a power supply system, a monitoring system, and ancillary equipment. Each of these systems is discussed in detail below.

1.4.2.1 Electrode System

Figure 1-3 shows the electrode layout of the ISEE system used during the SITE demonstration. The system consisted of an anode row oriented east to west and four rows of cathodes parallel to the anode row, two rows north and two rows south of the anode row. Two types of cathodes were used during the SITE demonstration: cathodes similar to the anodes, which will be referred to as "cathodes," and simple design cathodes, which will be referred to as "cold finger cathodes" (identified as "CF" if they are standalone or "CFC" if they are adjacent to cathode casings). The treatment zone was determined by the active portion of these electrodes and extended from 8 to 14 feet below ground surface (bgs). The electrode system's anodes and cathodes and cold finger cathodes are discussed below.

Anodes and Cathodes

The anodes (A1 through A5) and cathodes (C6 through C10) used at UCAP were designed to combine electrokinetic and lysimeter technologies. This combination was necessary to allow the operation of the system under unsaturated soil conditions. Lysimeter technology hydraulically and electrically creates a continuum between the anolyte and the pore water, thereby enabling the extraction of the chromate ions in the anolyte while the anolyte is held under tension in the electrode casings through the application of a vacuum.

Anodes and cathodes were installed in 6-inch-diameter boreholes (see Figure 1-4C). Boreholes were generally drilled to 20 feet bgs. An approximately 4-inch-thick dry bentonite plug was installed on top of the borehole sluff, and cuttings were added to bring the borehole bottom to 15 feet bgs. The bottom of the borehole was sealed with bentonite. The electrodes were lowered in the borehole and suspended from the ground surface. A watery slurry of clean native soil was added to the borehole until at least 6 inches above the top of the ceramic part of the electrode casing. The annular space above was filled with native soil cuttings to 1 foot bgs. Finally, a bentonite plug was installed to approximately 2 inches bgs and covered to the ground surface with native soil. After installation was complete, a vacuum was applied to each electrode to remove excess water from the slurry.

The anodes and cathodes consisted of two main components: the electrode casing and the internal

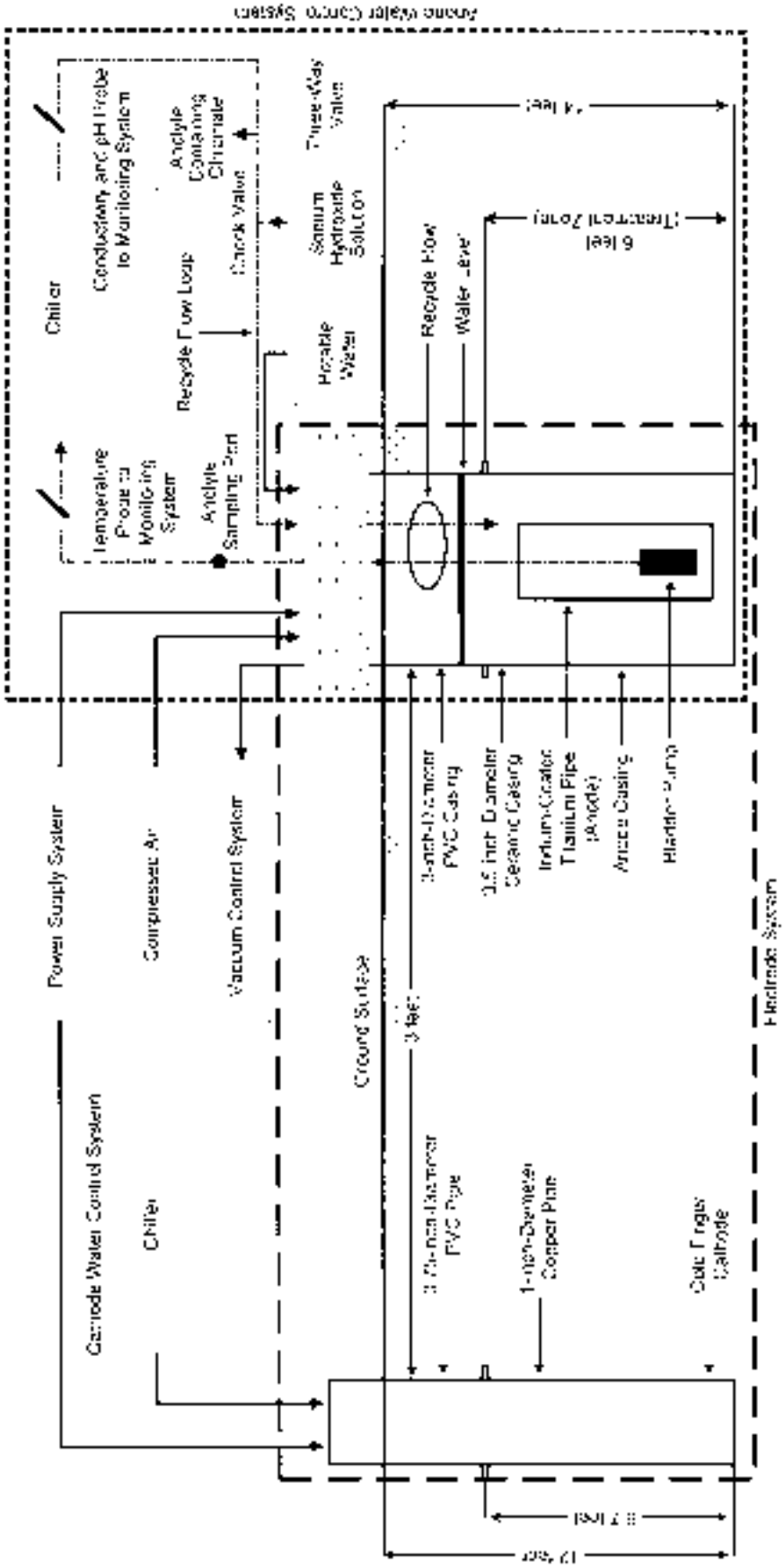


Figure 1-2. ISEE system schematic diagram.

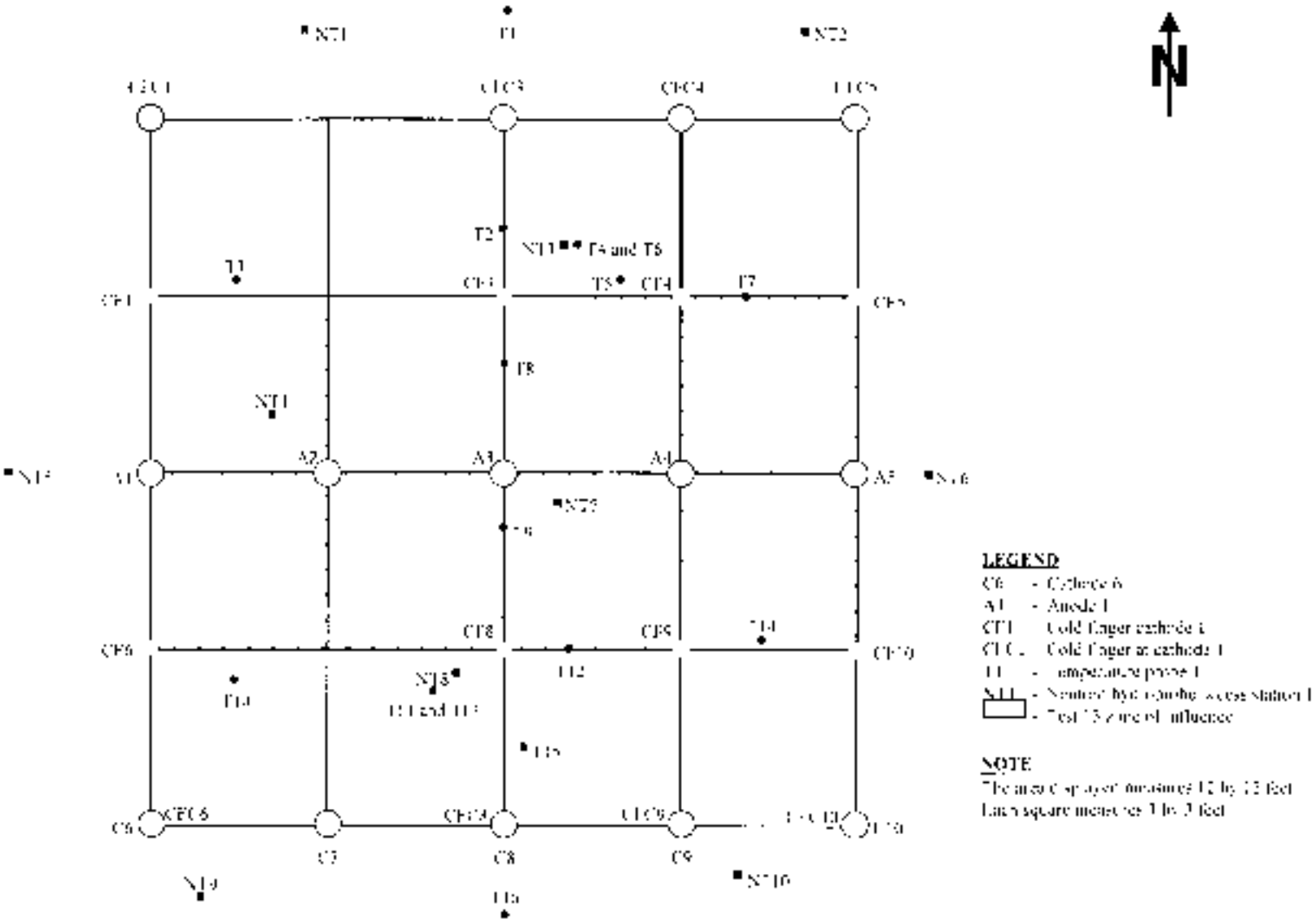


Figure 1-3. ISEE system electrode layout.

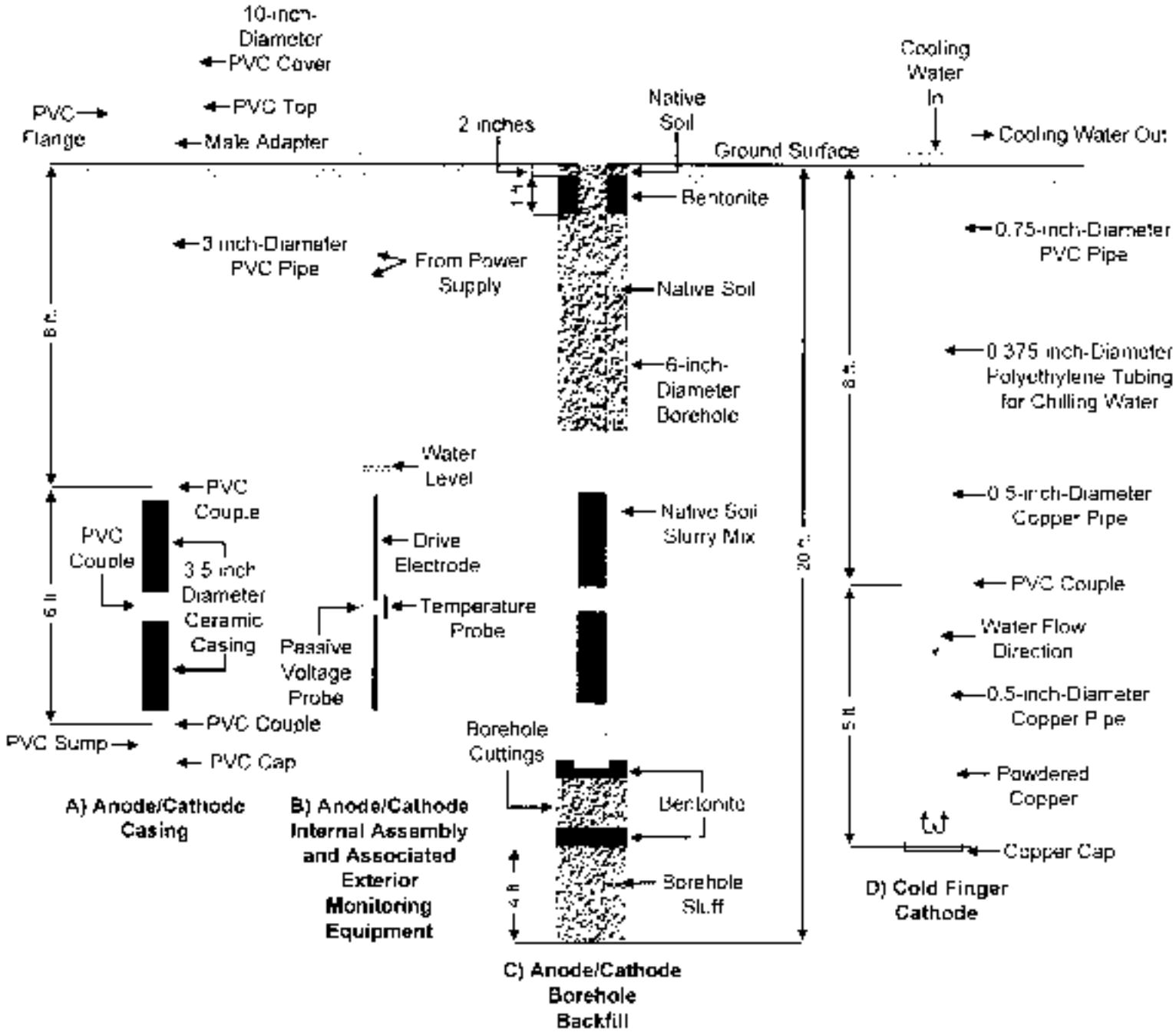


Figure 1-4. Anode/cathode and cold finger cathode construction cross sections.

assembly. Figure 1-4A illustrates the electrode casing assembly. The electrode casing consisted of two parts: the bottom 6 feet (located from 8 to 14 feet bgs) was constructed of a porous ceramic material, and the top part (extending from the ground surface to 8 feet bgs) was constructed of 3-inch-diameter polyvinyl chloride (PVC) pipe. The top part of the electrode casing was impermeable and nonconductive. The ceramic material had a pore size of 3 microns, resulting in bubbling pressures of 19 to 28 pounds per square inch (psi). High bubbling pressure material was an important factor in the construction of the electrodes. Depending on the magnitude of the vacuum applied to the electrode casing and the pore water tension in soil immediately adjacent to the electrode casing, the pore water could enter the electrode casing or water present in the casing could be transferred to the soil. This innovative feature of the electrodes was derived from lysimeter technology. The design overcame the difficulty of soil drying near the anodes, thus allowing operation of the electrokinetic process in unsaturated soil for much longer periods than if simple electrodes were implanted in direct contact with the soil. Soil drying occurs when electric current is applied to soil between the electrodes, thus causing water flow by electroosmosis, usually to the cathode. The SNL ISEE system design allowed soil moisture to be replenished through the electrode casing.

The ceramic of the anode casings was treated with a surfactant to alter the negative zeta potential of the ceramic, thereby preventing electroosmotic movement of water out of the anodes. After the surface was washed with a 0.1-molar solution of hydrochloric acid, a 0.01-molar solution of hexadecyltrimethylammonium bromide was purged through the ceramic to form a layer that changed the effective charge of the surface from negative to positive.

The internal assembly of the anodes and cathodes consisted of a drive electrode (see Figure 1-4B) constructed of iridium-coated titanium for the anodes and of copper for the cathodes. The drive electrodes were connected to the power supply system by insulated wire rated for 600 V DC. Control and monitoring systems also located inside the electrode casing discussed in the following sections.

Cold Finger Cathodes

The purpose of the cold finger cathodes was twofold: (1) to function as active bare electrodes to increase the voltage gradient and (2) to function as heat exchangers in case soil temperatures become excessive. As shown in Figure 1-3, 16 cold finger cathodes were used during the SITE demonstration of the ISEE system (cold fingers CFC2, CF2, CF7, and CFC7 were not energized during the demonstration and do not appear in this figure).

Originally, cold finger cathodes CF1 through CF10 were constructed of 5-foot-long, 0.75-inch-diameter copper piping. The bottom of the pipe was capped with a copper cap, and the top end was fitted into a 0.75-inch-diameter, schedule 40 PVC pipe extending to the ground surface. An insulated copper wire was soldered to the pipe and was brought to the ground surface. After September 24, 1996, to prepare for the final demonstration test, cold finger cathodes CF1, CF3 through CF6 and CF8 through CF10 were refurbished. The refurbished design (see Figure 1-4D) consisted of 0.5-inch-diameter copper pipe extending to the ground surface. This pipe was enclosed by the 0.75-inch-diameter PVC piping described above and filled with powdered copper. Inside of the 0.5-inch-diameter copper piping, a 0.375-inch-diameter polyethylene tubing was used to recycle cold water to maintain the cold finger cathode at a low temperature.

All cold finger cathodes were installed in holes drilled using the Geoprobe® rig. The diameter of the holes was 1.5 inches, and the depth of installation ranged from 12.5 to 13.6 feet bgs. These holes were filled with soil slurry to above the metallic part of the electrode. The cold finger cathodes were installed immediately after soil slurry was poured into the holes, and remaining space in the hole was backfilled with native materials. The top of the hole was plugged with bentonite.

The construction of cold finger cathodes CFC1 through CFC5 was simple. These cathodes were 6.67 feet long and constructed of 1-inch-diameter copper pipe. The conductive part of the electrode was connected to the bottom of 0.75-inch-diameter PVC piping extending to the ground surface.

1.4.2.2 Water Control System

Anode and cathode casings were filled with water to about 6 inches above the fitting between the ceramic material and the PVC pipe. The water control system consisted of the water circulation system and the pH control system, which are described below.

Water Circulation System

The purposes of the water circulation system were to (1) monitor the chemical condition of water in the electrode casings, (2) cool water in the electrode casings, (3) provide means to sample and remove water from the casings, (4) provide means to regulate water pH, (5) mix anolyte in the electrode casings, and (6) add potable water (influent) to the anode and cathode casings to compensate for the extraction of effluent.

The water circulation system was powered by bladder pumps located in each electrode casing (see Figure 1-2). The screen portion of the pump was located in the electrode casing sump. Because the bladder pumps operated in a subatmospheric pressure environment because of vacuum applied to the head space of the electrode, a liquid ring vacuum pump and an air compressor were used to activate the pumps. The recirculation flow rate was about 4 liters per minute (L/min).

Anode and cathode effluent was collected in 55-gallon, closed-top polypropylene drums. Catholyte was extracted only from the cathodes and not from the cold finger cathodes. At 30-minute intervals, the effluent controller in the control trailer sent a signal to the air-operated, three-way-solenoid valve, and recycle flow was redirected to the drums instead being returned to the electrode casings. The three-way valve was deactivated after a preset amount of water measured by the effluent sensor was extracted from the system. Under normal operating conditions, the amount of water extracted from the system varied from 0.1 to 0.5 liter per 30 minutes.

The water level in the electrode casings was maintained within a 6-inch interval above the PVC couple joining the ceramic and PVC casing sections using reed-type float switches.

pH Control System

The pH of water in the ISEE system had to be maintained to ensure proper system operation. High pH values could result in the precipitation of metals and hinder contaminant transport and removal. To minimize these effects, the required pH range for the anolyte was 5.5 to 11, with an ideal pH of 8.8. The pH range for the catholyte was 3 to 11, with an ideal pH of 5.5.

The pH of pore water in the treatment area was likely to be influenced by the hydrogen and hydroxyl ions produced at the electrodes from electrolysis. Consequently, the pH of the recycled water was closely monitored and controlled for each electrode using sensors, transmitters, and controllers. The pH controller regulated the operation of a chemical feed pump located on top of a 55-gallon polyethylene drum containing buffer fluid. A 10 percent sodium hydroxide solution was used to control the anolyte pH, and a 20 percent acetic acid solution was used to control catholyte pH.

1.4.2.3 Vacuum Control System

As stated earlier in this section, the SNL ISEE system uses lysimeter technology to control the amount of water delivered to the unsaturated zone. An air compressor provided the compressed air necessary for the operation of the vacuum pumps (see Figure 1-2). Compressed air was driven through a series of venturis within the vacuum pumps, causing additional air to be drawn through the venturi system. An added feature of the system was the ability to purge hydrogen gas produced by electrolysis from electrode casing headspace thus eliminating the danger of explosion.

Vacuum in the cathode casings was created by three vacuum ejector pumps installed in parallel. Vacuum in the anode casings was created using four vacuum ejector pumps installed in parallel. Rather than directly regulating the vacuum applied to the electrodes, vacuum regulators allowed air to enter the electrodes and dilute oxygen and hydrogen gases in the electrode headspace. The regulators were generally maintained at a vacuum of 14 inches of mercury for both the anodes and cathodes.

The minimum air purge necessary to maintain hydrogen at the lower explosive limit in the anode casings was estimated to be 3.3 L/min. The system alarm was set to 3.5 L/min for added safety, and the purge rate was set for 8 L/min to ensure that the hydrogen level was maintained well below the explosive limit. Air was also purged through the cathode casings at 2 L/min to dilute oxygen produced by electrolysis.

1.4.2.4 Power Supply System

The ISEE system electrodes were energized using four 10 kilowatt (kW) power supply units. Each unit was capable

of a maximum output of 16 amperes (amp) at 600 V DC. Each unit was operated independently under constant voltage conditions.

The power units were located in the control trailer, and electric current was delivered to the electrodes by underground cables protected by 3-inch-diameter electrical conduits. Both parallel- and independent-type connections were equipped with a main manual disconnector that cut off power while the system was not in operation. The current delivered to each electrode was limited to 15 amps by an in-line fuse and was monitored using an isolated current transmitter by measuring the voltage drop across a 20 amp per 100 millivolt shunt. Transmitter output was processed to determine the current, which was displayed on a control panel and recorded by a data logger.

1.4.2.5 Monitoring System

The operating parameters of the ISEE system were displayed on the control panel and recorded by a data logger. Table 1-2 summarizes monitoring system parameters. The parameters monitored were measured at 1-minute intervals, averaged and were recorded over 60-minute intervals. The monitoring system could shut down the ISEE system and send a problem-specific coded message by cellular telephone to two operators if any monitored parameters were out of preset tolerance limits.

In addition, when the system was energized, access to the exclusion zone was not permitted. Thus, entrance to the temporary structure was monitored using a simple switch to ensure that the entry door to the temporary structure was closed. Also, effluent barrels and their secondary containment were equipped with overflow switches that could signal system shutdown.

The shutdown system could cut off the power to the electrodes, close influent water valves, de-energize influent and effluent solenoids, and discontinue the pumping of pH control solutions. Depending on the type of alarm that triggered the shutdown, recycle of electrode water through the recycle board could also be terminated.

Table 1-2. Monitoring System Parameters

Parameter Measured	Support System	Automatic Shutdown Limit
Air purge rate	Vacuum control system	Below 3.5 L/min for cathodes only
Vacuum level	Vacuum control system	Below 1.47 psi
Electrode casing water level	Water control system	More than 6 inches above or below the water level control floats
Recycle flow	Water control system	No recycle flow
Influent and effluent rates	Water control system	None
Conductivity	Water control system	None
Recycle flow temperature	Water control system	Above 50 °C
pH	Water control system	For cathodes less than 3 and greater than 11, and for anodes less than 5.5 and greater than 11
Soil temperature	Ancillary equipment	Above 50 °C
Voltage in soil	Ancillary equipment	Step potential of 10 V

1.4.2.6 Ancillary Equipment

To monitor and control the operation of the ISEE system, SNL installed ancillary equipment that provided information on the state of system operation or that provided access to the treated media to influence local soil conditions (such as devices that altered soil moisture content). Ancillary equipment included soil moisture content control devices, neutron hydroprobe and radio imaging probe tubes, temperature probes, and passive voltage probes. This equipment is discussed below.

Soil Moisture Content Control Devices

Unsaturated soil conditions were maintained at the demonstration site throughout the operation of the ISEE system. Soil moisture control infiltration wells were installed to add water to the soil, if desired. Infiltration wells increased soil moisture content. Fourteen wells were used prior to the operation of the system under SNL's preferred operating conditions to add moisture to soil. These wells were constructed of 0.5-inch-diameter PVC piping 11 to 13 feet long. Approximately 20 slots were made in the bottom 9 to 12 inches of the PVC pipe, and the bottom of the pipe was sealed with a PVC plug. These wells were installed in 1.5-inch-diameter boreholes drilled using the Geoprobe® rig. The annular space was filled with 10/20 silica sand in the area of the screen interval and with dry, granular bentonite above this interval.

Neutron Hydroprobe and Radio Imaging Probe Tubes

Neutron hydroprobe measurements of soil moisture content were taken on a weekly basis using 10 access tubes (see Figure 1-3). Most of the tubes were installed to 39 to 41 feet bgs, and one tube was installed to 31 feet bgs. The tubes were installed in 7-inch-diameter boreholes drilled using a hollow stem auger. The annular space was filled using drill cuttings, and the holes were plugged at the top with dry bentonite. The tubes were constructed of 2.5-inch-diameter, threaded PVC piping. The diameter was selected to allow access of radio imaging probes used to determine vertical conductivity profiles of soil beneath the UCAP.

Temperature Probes

A total of 32 temperature probes were installed at the demonstration site (see Figure 1-2). The temperature probes were located generally at 11 feet bgs in the treatment zone. Sixteen of the probes (not shown in Figure 1-3) were installed on electrode casings at the PVC couple between the two ceramic pieces that make up the electrode casings and 16 were installed between the electrodes as shown in Figure 1-3.

Passive Voltage Probes

Passive voltage probes were used to generate data needed to prepare electrical potential maps of the demonstration site. Twenty passive voltage probes were located on the electrode casings, and another 12 were installed throughout the demonstration site. These probes consisted of 50-mesh stainless steel screen squares with an area of about 2 square inches attached to insulated wires that reached the ground surface. The pieces of mesh were attached to 0.75-inch-diameter PVC pipe at a depth of about 10 feet bgs. Probes were installed using the Geoprobe® rig.

1.4.3 Innovative Features of the Technology

Metals-contaminated soil can be treated either in situ or ex situ. Common methods for treating soil in situ include stabilization/solidification and vitrification. Promising results were obtained during testing of other innovative treatment technologies such as soil flushing. The most common ex situ treatment technology is soil washing.

Treatment of soil in situ using electrical separation/ electrokinetic removal under saturated soil conditions has been tested by several vendors. However, the ISEE system designed by SNL focuses on the remediation of unsaturated soil instead of saturated soil.

The innovative feature of the ISEE system is that lysimeter technology is used in the construction of the anodes and cathodes to hydraulically and electrically create a continuum between the electrolyte and the pore water. The electrode fluid is held inside the electrode by an applied vacuum, keeping the fluid from saturating soil. This feature allowed the removal of chromate from unsaturated soil during the demonstration without significantly altering the soil moisture content. The vacuum control system maintains the vacuum in the anode electrode, which creates the pressure gradient between the anode's porous ceramic casing and the surrounding soil necessary to hydraulically control water movement between the anode casing and the soil.

The ISEE system developed by SNL presents the advantage that the structure, volume, and makeup of treated soils are not significantly affected by the application of the technology as is the case with remediation by stabilization/solidification, vitrification, or chemical treatment. The moisture content of the soil is maintained at levels below saturation, which is not the case with soil flushing or chemical treatment because these technologies use water as the transport medium for treatment additives. Table 1-3 compares several in situ treatment options for soil contaminated with heavy metals.

1.5 Applicable Wastes

The ISEE technology developed by SNL is applicable for treating unsaturated soil contaminated with hexavalent chromium. According to SNL, this technology can be modified to treat saturated contaminated soil and to remove contaminants dissolved in pore water besides chromate. Because other anions will compete with the targeted contaminant ions to be removed, it is necessary to determine the electrical conductivity of soil pore water and the target ion concentration to determine the applicability of the ISEE technology.

1.6 Key Contacts

Additional information about the ISEE system and the SITE program can be obtained from the following sources:

SNL ISEE System
Dr. Eric R. Lindgren
Sandia National Laboratories
Dept. 6621, MS 0719
P.O. Box 5800
Albuquerque, NM 87185-0719
Telephone No.: (505) 844-3820
Fax No.: (505) 844-0543
E-mail Address: erlindg@sandia.gov

The SITE Program
Mr. Randy Parker
Office of Research and Development
U.S. Environmental Protection Agency
26 West Martin Luther King Drive
Cincinnati, OH 45268
Telephone No.: (513) 569-7271
Fax No.: (513) 569-7571
E-mail address: parker.randy@epamail.epa.gov

Information on the SITE program is available through the following on-line information clearinghouse: the Vendor Information System for Innovative Treatment Technologies (VISITT) (Hotline: 800-245-4505) database contains information on 154 technologies offered by 97 developers.

Technical reports may be obtained by contacting U. S. EPA/NCEPI, P. O. Box 42419, Cincinnati, Ohio 45242-2419, or by calling 800-490-9198.

Table 1-3. Comparison of In Situ Treatment Technologies for Metals-Contaminated Soil

Technology	Advantage	Disadvantage
SNL In Situ Electrokinetic Extraction System	Maintain unsaturated soil conditions; soil makeup not significantly affected	Currently tested for the removal of chromate from unsaturated soil only; requires disposal of liquid waste containing hexavalent chromium as hazardous waste; volatile organic compounds (VOC) may be stripped from soil and increase soil vapor concentrations and contaminant migration; relatively high cost; no commercial-scale system available
Stabilization/Solidification	Applicable to wide range of soils because of flexibility in design of appropriate additives and use of a large variety of mixing techniques; some organic compounds can be incorporated in the solidified matrix; relatively low cost	Long-term reliability not well known; considerably increases volume of waste; leachate from curing process may need to be collected and disposed of as hazardous waste
Vitrification	Applicable to complex wastes (combination of metals and organics, including mixed wastes); also applicable to nonhomogeneous soils containing buried containers (however, under some conditions, metal objects could short-circuit the current path); relatively moderate cost	High soil moisture content limits applicability; off-gases (VOCs, combustion gases, and steam) need to be collected; presence of buried materials could start underground fire; soil characteristics dramatically changed by application of the technology; decrease in volume of soil
Soil Flushing	Applicable to soils containing organic and inorganic wastes; relatively low cost	Not applicable to soil with low permeability; migration of contaminants to deeper zones possible from increased mobility if no controls exist (for example, a clay layer); soil moisture content increases; requires treatment of water recovered after flushing

Section 2
Technology Effectiveness and Application Analysis

This section addresses the effectiveness and applicability of the ISEE system designed by SNL for treating unsaturated soil contaminated with hexavalent chromium in the form of chromate. Vendor claims regarding the effectiveness and applicability of the ISEE system are included in the appendix. The evaluation of the ISEE system's effectiveness and potential applicability is based mainly on the demonstration results presented in this section. This section provides an overview of the ISEE system SITE demonstration and discusses SITE demonstration results, factors affecting performance, site characteristics and support requirements, material handling requirements, technology limitations, potential regulatory requirements, and state and community acceptance.

2.1 Overview of ISEE System SITE Demonstration

The ISEE system SITE demonstration took place at the UCAP, which is part of the CWL site located within Technical Area III at SNL. The UCAP is a rectangular pit measuring about 15 by 45 feet and is 10 feet deep. The areal extent and depth of the area targeted by the demonstration was selected based on the highest results of water soluble chromium concentrations from sampling performed during previous investigations (SNL 1994). During the demonstration, the system was operated for a period of 2,727 hours between May 15 and November 24, 1997. The area of the demonstration ranged from 36 to 72 square feet and targeted contaminated soil located between 8 and 14 feet bgs. The configuration of ISEE system electrodes is presented in Figure 1-3.

The CWL site was used by SNL for chemical disposal from 1962 to 1985. During this time, chemicals were separated by type and disposed of in separate trenches. Over 4,290 gallons of chromic sulfuric acid solution was disposed in the UCAP (SNL 1997). During predemonstration sampling activities, a few soil samples exhibited high moisture content and pieces of glass plastic were present in the samples, suggesting that the Geoprobe® sampler penetrated chemical disposal containers that have maintained their integrity.

Project objectives, the SITE demonstration approach, and sampling and analytical procedures are discussed below.

2.1.1 Project Objectives

Project objectives were developed based on EPA's understanding of the SNL ISEE technology, SITE demonstration program goals, and input from the technology developer and the State of New Mexico. The SITE demonstration had one primary objective and two secondary objectives. The primary objective was considered critical for the technology evaluation. Secondary objectives involved collection of additional data that were useful but not critical to the technology evaluation. The primary objective of the technology demonstration was to estimate the amount of hexavalent chromium removed from soil by the ISEE system because the ISEE system is primarily designed to remove hexavalent chromium. To accomplish this objective, SNL collected and analyzed anolyte samples for hexavalent chromium at its field laboratory throughout the demonstration period. An independent check of field analytical data was provided by EPA through split sample analysis at an off-site laboratory. Field analytical data were subsequently deemed adequate to estimate the amount of hexavalent chromium removed from soil by the ISEE system. Predemonstration and postdemonstration soil samples collected by EPA were analyzed for hexavalent chromium to verify the hexavalent chromium removal estimate based on anolyte sample analysis.

The secondary objectives of the technology demonstration were to determine whether treated soil meets the toxicity characteristic leaching procedure (TCLP) regulatory criterion for chromium and to evaluate the ISEE system's ability to remove trivalent chromium from site soil.

To conduct the demonstration, SNL was required to meet the conditions of the New Mexico Environmental Department's Resource Conservation and Recovery Act (RCRA) Research, Development, and Demonstration permit for the ISEE system. Predemonstration testing results indicated that some of the soil in the demonstration area is hazardous (EPA waste code D007) because chromium concentrations exceeded the TCLP criterion for chromium. Therefore, the permit required that SNL perform postdemonstration TCLP testing to determine the impact of the ISEE system on soil known to be contaminated. SNL therefore collected a large number of treated soil samples for total chromium analysis after extraction using TCLP.

Because incidental removal of trivalent chromium will likely be accomplished by the ISEE system, evaluation of trivalent chromium removal was a secondary project objective of this project. To accomplish this objective, the predemonstration and postdemonstration soil samples collected for hexavalent chromium analysis were also analyzed for total chromium so that the trivalent chromium concentrations could be calculated as the difference between the total and hexavalent chromium concentrations.

2.1.2 Demonstration Approach

The ISEE system SITE demonstration system operation and test plan is detailed in SNL's demonstration plan (SNL 1997). This section summarizes SNL's demonstration plan. During the SITE demonstration, 13 tests were performed during six phases. The test areas ranged from 36 to 72 square feet, and contaminated soil from 8 to 14 feet bgs was treated. The first 12 tests were conducted so that SNL could determine the preferred operating conditions for Test 13 and to facilitate the migration of hexavalent chromium toward the central portion of the test area. Test 13 consisted of system performance testing under SNL's preferred operating conditions for the SITE demonstration. Table 2-1 summarizes key conditions during the 13 tests.

During Phase 1, six tests were conducted in the southern half of the test grid between the anode row and C6 through C10. During these tests, SNL identified inefficient electrodes (A2 and C7) and adjusted the electrical current, electrical power level, and anolyte extraction rate.

During Phase 2, three tests were conducted in the northern half of the test grid between the anode row and CFC1 through CFC5. During these tests, SNL used the less expensive cold finger cathodes; adjusted the electrical current, electrical power level, and anolyte extraction rate; and operated the infiltration wells to facilitate hexavalent chromium migration toward the middle portion of the test grid.

During Phase 3, one test was conducted in the southern portion of the northern half of the test grid between the anode row and CF1 through CF5. SNL set the operating conditions for this test based on results from Phases 1 and 2.

During Phase 4, one test was conducted in the southern half of the test grid between the anode row and CFC6 through CFC10. This test was intended to be a replicate of Test 6 during Phase 1 and was conducted to fill information gaps identified for Test 6.

During Phase 5, one test was conducted in the northern portion of the southern half of the test grid between the anode row and CF6 through CF10. SNL set the operating conditions for this test based on results from Phases 1, 2, and 3.

During Phase 6, one definitive test was conducted in the middle portion of the test grid between CF1 through CF5 and CF6 through CF10. SNL set the operating conditions for this test based on results from Phases 1, 2, 3, and 5. SNL identified Phase 6 (Test 13) conditions as the ISEE system's preferred operating conditions. Operating conditions during Test 13 are summarized in Table 2-2. SNL operated the ISEE system at the preferred conditions to evaluate system performance and treatment costs.

2.1.3 Sampling and Analytical Procedures

Three sampling events occurred during the ISEE system SITE demonstration: predemonstration soil sampling, anolyte (electrolyte from the anodes) sampling during the

Table 2-1. Test Matrix for SNL ISEE System Demonstration

Phase	Test Area	Test No	Anodes Used	Cathodes Used	Average Current[a] (amp)	Average Power[a] (kW)	Average Anolyte Extraction Rate[a] (L/hour)	Test Duration (hour)
1	Southern Half Anode Row and C6 through C10	1	A1, A2, A3, A4, and A5	C6, C7, C8, C9, and C10	19.45±1.68	1.301±0.11	0.440±0.075	106
		2	A1, A3, A4, and A5	C6, C7, C8, C9, C10	21.38±2.07	1.581±0.16	0.870±0.542	368
		3	A1, A3, A4, and A5	C6, C8, C9, and C10	20.38±1.41	1.77±0.15	0.879±0.633	263
		4	A1, A3, A4, and A5	C6, C8, C9, and C10	34.25±5.58	4.55±0.54	2.026±0.904	244
		5	A1, A3, A4, and A5	C6, C8, C9, and C10	42.15±2.20	5.75±0.30	3.54	34
		6	A1, A3, A4, and A5	C6, C8, C9, and C10	41.37±2.55	4.55±0.31	3.557±0.924	181
2	Northern Half Anode Row and CFC1 through CFC5	7	A1, A3, A4, and A5	CFC1, CFC3, CFC4, and CFC5	29.27±3.48	4.14±0.56	3.404±0.283	75
		8	A1, A3, A4, and A5	CFC1, CFC3, CFC4, and CFC5	20.94±2.10	1.90±0.21	0.376±0.103	89
		9	A1, A3, A4, and A5	CFC1, CFC3, CFC4, and CFC5	20.79±1.21	1.87±0.11	0.723±0.554	333
3	Southern Portion of Northern Half Anode Row and CF1 through CF5	10	A1, A3, A4, and A5	CF1, CF3, CF4, and CF5	30.31±3.78	2.70±0.36	0.510±0.046	176
4	Southern Half Anode Row and CFC6 through CFC10	11	A1, A3, A4, and A5	CFC6, C8, CFC9, and CFC10	33.49±1.87	2.33±0.15	0.60	20
5	Northern Portion of Southern Half Anode Row and CF6 through CF10	12	A1, A3, A4, and A5	CF6, CF8, CF9, and CF10	29.31±3.94	2.06±0.29	0.848±0.693	111
6	Middle Portion (CF1 through CF5 and CF6 through CF10)	13	A1, A3, A4, and A5	CF1, CF2 through CF5, and CF8 through CF10	25.92±4.71	2.10±0.31	0.062±0.294	737

Notes:

amp = Ampere
kW = Kilowatt
L/hour = Liter per hour
[a] Average ± standard deviation of hourly readings for all anodes used in the test
[b] Average ± standard deviation of daily readings for all anodes used in the test; only average presented when fewer than three values available

Table 2-2. SNL ISEE System Preferred Operating Conditions

Parameter	Operating Conditions			
	A1	A3	A4	A5
Average Current (A)	9.9	7.6	8.2	10.3
Average Power (kW)	0.40	0.50	0.54	0.67
Average Effluent Extraction Rate (L/hour)	0.25	0.25	0.20	0.22

demonstration, and postdemonstration soil sampling. From December 1995 through February 1996, SNL collected predemonstration soil samples from various depth in boreholes within and near the test areas using a 1-inch-diameter by 24-inch-long Geoprobe® Large Bore Sampler. SNL extracted a portion of each sample with water and analyzed the extract for chromium. Additional sample portions were sent to the Quanterra Environmental Services, Inc. (Quanterra), laboratory in Arvada, Colorado. Quanterra extracted these soil samples by TCLP, SW-846 Method 1311, and analyzed the extracts for total chromium by inductively coupled plasma (ICP) analysis using SW-846 Method 6010A. TCLP extract results are included in Appendix A of the TER.

In July 1996, EPA selected certain of these soil samples for Quanterra analysis to provide information on the concentrations of total chromium and of hexavalent chromium throughout the test area. More samples from more contaminated areas as determined by SNL's TCLP results were selected because these areas are of major concern. To maximize extraction of hexavalent chromium, Quanterra dried these soil samples and ground them in a ceramic-lined ring and puck mill until the samples could pass through a No. 42 mesh sieve. A preliminary study found that use of an ordinary steel ring mill to grind samples resulted in unacceptable contamination of the samples with chromium derived from mill material. "Grinder blanks," clean sand subjected to the pretreatment and analysis, and "sand blanks," sand sent directly for analysis, were analyzed to monitor for such problems.

Quanterra prepared portions of the sieved soil samples by acid digestion using SW-846 Method 3050A and analyzed them for total chromium using SW-846 Method 6010A. Quanterra also prepared other portions of the sieved soil samples by alkaline digestion using SW-846 Method 3060A. These alkaline-digested samples were analyzed for hexavalent chromium by colorimetry using SW-846 Method 7196A. These analyses were accompanied by analysis of the usual QC samples (method blanks, matrix spikes, blank spikes, duplicates, and so on) to ensure that results were acceptable for use in meeting project objectives. The results of these QC analyses are included in Appendix B of the TER.

During operation of the ISEE system, SNL collected anolyte samples daily and analyzed them for hexavalent chromium to determine removal. To verify these results, EPA obtained anolyte samples from all four operating anodes daily for 8 days. These samples were all sent to Quanterra for analysis for hexavalent chromium by SW-846 Method 7196A. The relative percent differences between the SNL and Quanterra results varied from 0 to 20 percent

After the demonstration, EPA collected soil samples using the Geoprobe® from locations near (within 1 foot laterally and 2 inches vertically) from the sampling locations and sent these samples to Quanterra for the same sort of preparation and analyses for hexavalent chromium and total chromium conducted during predemonstration sampling. SNL collected a separate series of Geoprobe® samples and sent them to Quanterra for TCLP extraction and chromium analysis. All Quanterra and corresponding SNL results are included in Appendix A of the TER.

2.2 SITE Demonstration Results

This section summarizes ISEE system SITE demonstration results and discusses its effectiveness in removing chromate from contaminated soil. This section is organized according to the project objectives stated in Section 2.1.1. Estimated treatment costs are discussed in Section 3.0.

2.2.1 Removal of Hexavalent Chromium from Site Soil

The primary objective of the ISEE system SITE demonstration was to estimate the amount of hexavalent chromium removed from soil by the system. The mass of hexavalent chromium removed was to be determined from the amount of hexavalent chromium in the anolyte. In general, SNL performed daily sampling and analysis of the anolyte throughout the demonstration. For each test, SNL anolyte results were used to determine the total amount of hexavalent chromium removed and the system's overall removal rate and removal efficiency. These results are summarized in Table 2-3.

As mentioned before, 13 tests were performed in six phases during the demonstration. The first 12 tests, performed between May 15 and October 18, 1996, were used by SNL to determine the system's preferred operating conditions. Test 13 was performed between October 21 and November 24, 1996, to determine system performance and operating costs.

Approximately 520 grams (g) of hexavalent chromium were removed during the entire demonstration. Overall hexavalent chromium removal rates varied from 0.074 gram per hour (g/hour) during Test 1 to 0.338 g/hour during Test 5. Overall hexavalent chromium removal efficiencies varied from 0.0359 gram per kilowatt-hour (g/kW-h) during Test 7 to 0.136 g/kW-h during Test 13. Downtime during system operation ranged from 0 percent during Test 11 to 66 percent during Test 1.

Test 13 results showed increased efficiency of hexavalent chromium removal compared to previous test results. The system configuration during Test 13 was representative of the configuration of a full-scale remediation system, with cold finger cathodes placed symmetrically outward from a central anode row. Consequently, a more detailed analysis was performed for Test 13 to determine the hexavalent chromium removal efficiency and rate of each electrode in addition to overall system performance. The data set used for this analysis was culled from Test 13 data to eliminate data points not representative of the system performance. For example, data points not representative of steady-state operation of the system, such as during the pumping out of electrode effluent, were eliminated, as were data points measured within 6 hours or less because the system was shut off for some reason and had to be restarted after servicing. The hexavalent chromium removal efficiency of each electrode is shown in Figure 2-1, and the hexavalent chromium removal rate of each electrode is shown in Figure 2-2.

After data outliers were eliminated, the average hexavalent chromium removal efficiency for anode 4 was approximately 0.189 g/kW-h, which is considerably higher than the average removal efficiencies for the other three anodes (anodes 1, 3, and 5), which ranged from about 0.087 to about 0.111 g/kW-h. Hexavalent chromium removal rates were low for anodes 1 and 3 (0.040 and 0.057 g/hour, respectively) and higher for anodes 4 and 5 (0.110 and 0.079 g/hour respectively).

Verification of the total mass of hexavalent chromium extracted by the ISEE system was supposed to be provided by the difference between average hexavalent chromium concentrations in soil before and after the demonstration. Figure 2-3 presents the spatial distribution of hexavalent chromium concentrations at the 2-foot depth intervals characterized by the samples collected before and after the demonstration. These results can be summarized as follows:

- Predemonstration samples contained hexavalent chromium concentrations ranging from below the detection limit of 0.4 milligram per kilogram (mg/kg) to 6,890 mg/kg.
- Postdemonstration samples contained hexavalent chromium concentrations from below the detection limit of 0.4 mg/kg to 4,730 mg/kg.
- Of the 48 locations sampled both before and after the demonstration, 21 locations contained postdemonstration hexavalent chromium concentrations that exceeded predemonstration concentrations.

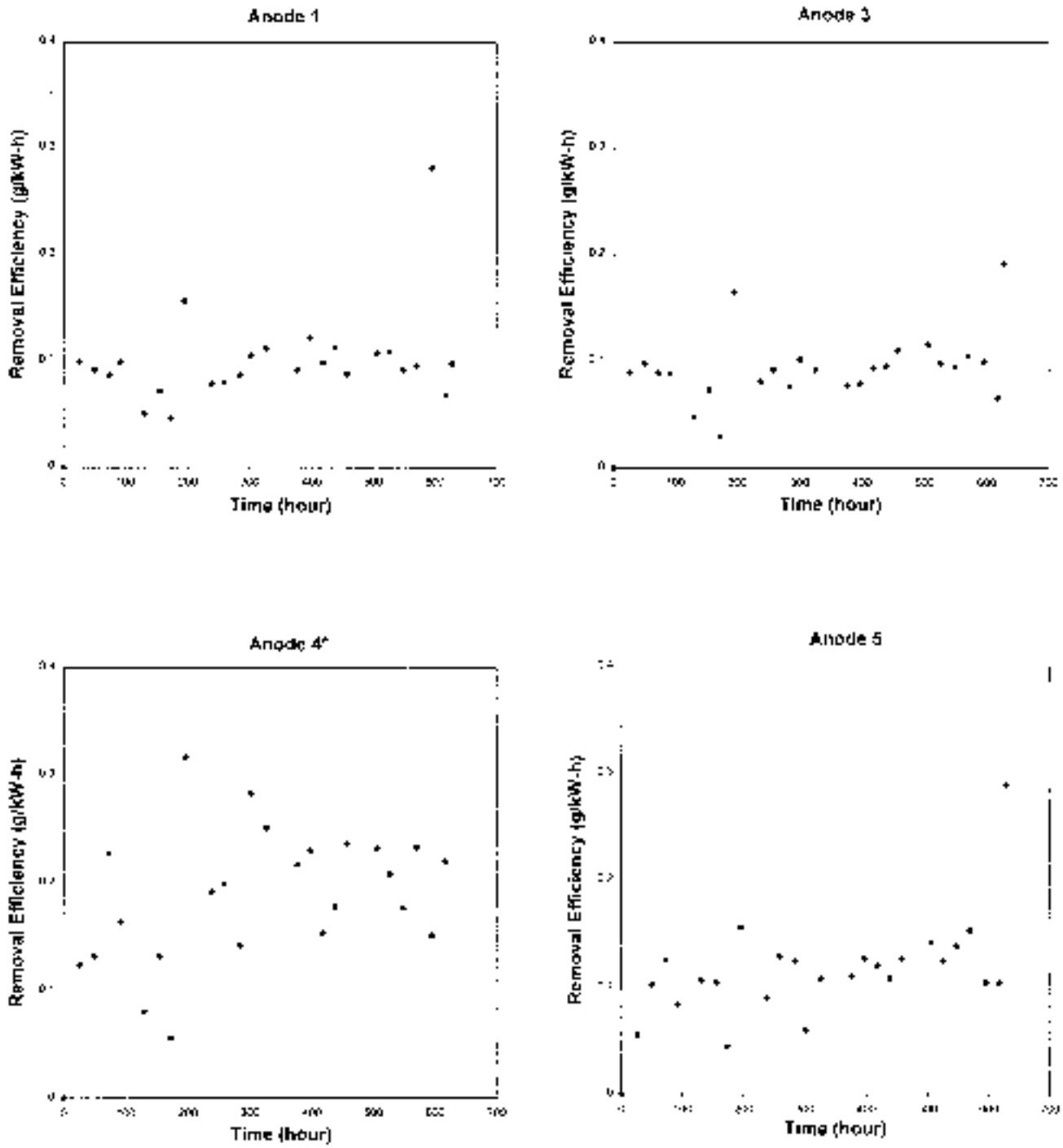
Predemonstration and postdemonstration hexavalent chromium concentrations in soil and their distributions were not suitable for any method of calculation of the total mass of hexavalent chromium in soil. A statistical summary of analytical results for hexavalent and total chromium is presented in Table 2-4. No trend was identified in the removal of hexavalent chromium from soil. In many cases, the standard derivation exceeded average concentrations. Soil results for hexavalent chromium possibly exhibited high spatial variability resulting from (1) the nonhomogeneous distribution of chromate concentrations in soil before the demonstration

Table 2-3. SNL ISEE System Performance Data

Phase No.	Test No.	Test Duration (hour)	Average Power Applied to the System (kW)	Energy Applied to the System (kW-h)	Hexavalent Chromium Mass Removed (g)[b]	Hexavalent Chromium Removal Rate (g/hour)	Hexavalent Chromium Removal Efficiency (g/kW-h)
1	1	106/512[a]	1.30	138.1	7.84	0.074	0.0569
	2	358/695[a]	1.63	619.9	35.73	0.097	0.0576
	3	293/618[a]	1.77	490.6	22.54	0.079	0.0459
	4	244/410[a]	4.69	1,143.4	56.02	0.230	0.0490
	5	34/64[a]	5.76	195.7	11.49	0.338	0.0584
	6	187/206[a]	4.56	821.7	38.24	0.211	0.0466
2	7	75/90[a]	4.14	310.5	11.14	0.149	0.0359
	8	68/92[a]	1.90	168.8	9.01	0.101	0.0534
	9	333/511[a]	1.87	622.1	58.55	0.176	0.0940
3	10	176/222[a]	2.70	477.3	35.97	0.204	0.0754
4	11	20/20[a]	2.38	50.1	4.71	0.236	0.0940
5	12	[illegible]/163[a]	2.86	317.5	25.46	0.229	0.0809
6	13	707/634[a]	2.10	1,494.3	209.73	0.298	0.140

Notes.

g = Gram
g/hour = Gram per hour
g/kW-h = Gram per kilowatt-hour
kW = Kilowatt
kW-h = Kilowatt-hour
a Time period for which the system was operational/total test duration
b Hexavalent chromium mass removed was estimated by multiplying the volume of analyte extracted with the concentration of hexavalent chromium in the analyte. During the entire demonstration, 520.73 g of hexavalent chromium was removed from soil.



*Note: Anode 4 had a removal efficiency of 0.584 g/kW-h at 628 hours.

Figure 2-1. Hexavalent chromium removal efficiency per electrode for Test 13.

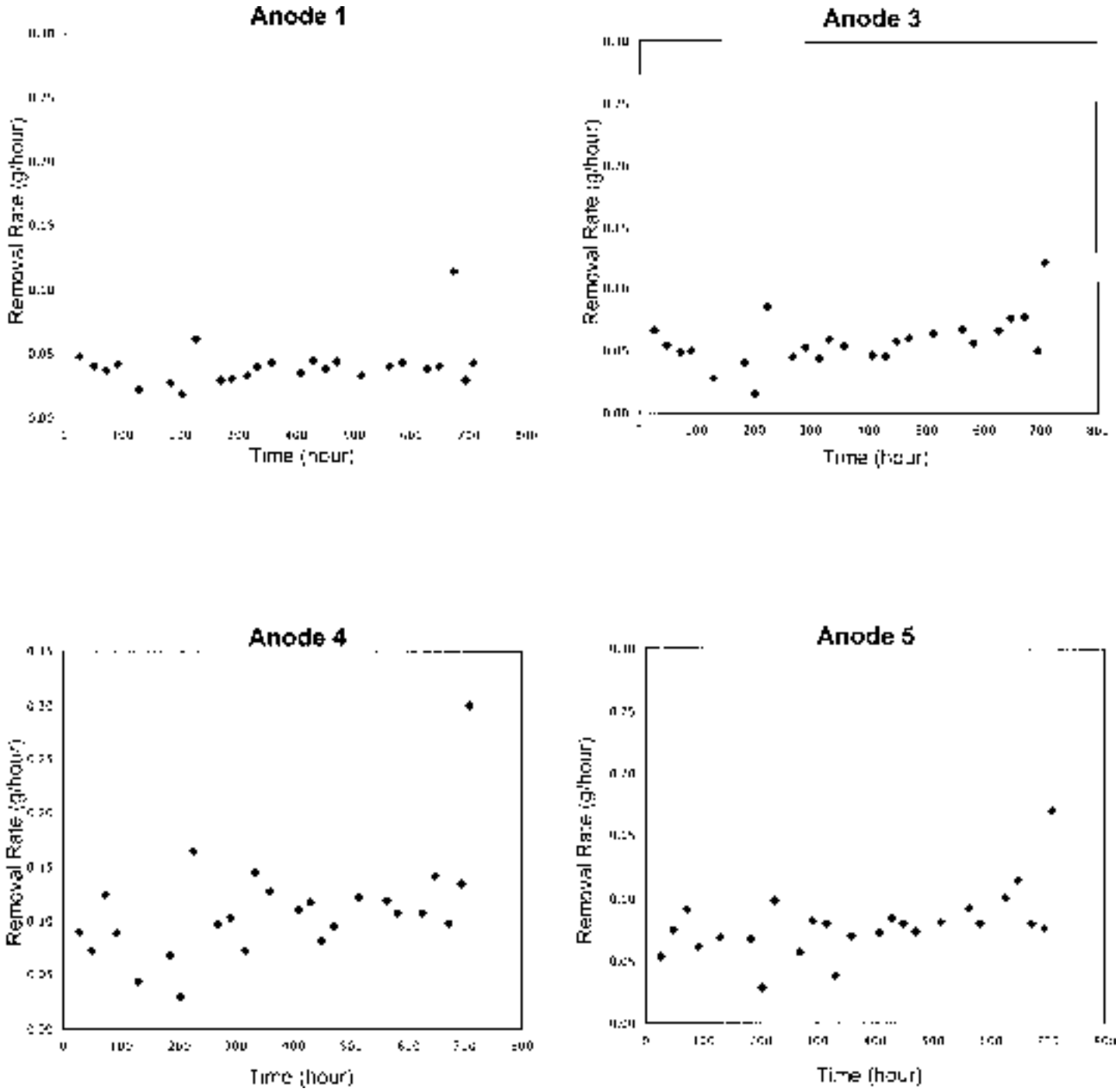


Figure 2-2. Hexavalent chromium removal rate per electrode for Test 13.

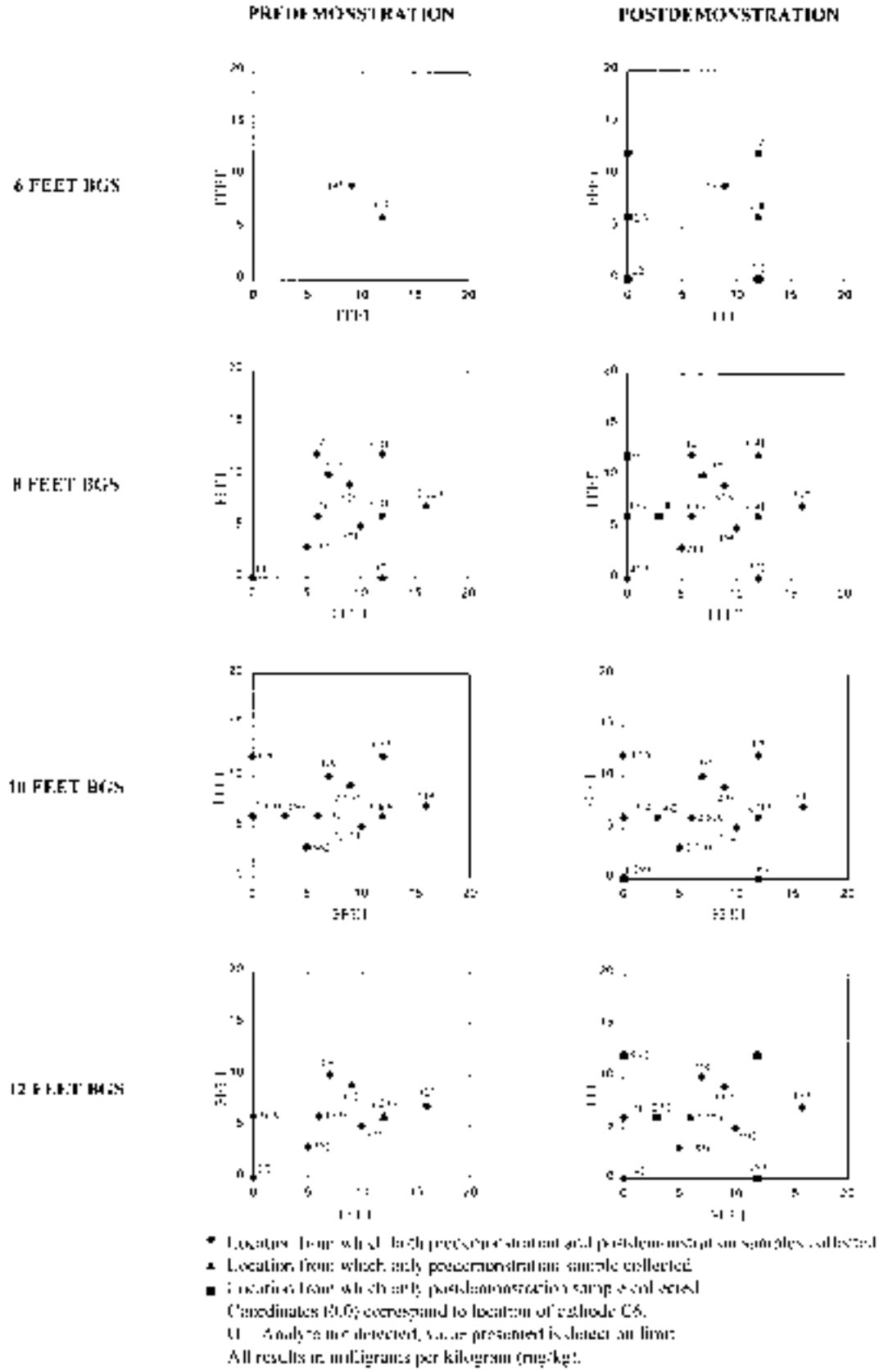


Figure 2-3. Spatial distribution of haxavalent chromium concentrations in soil.

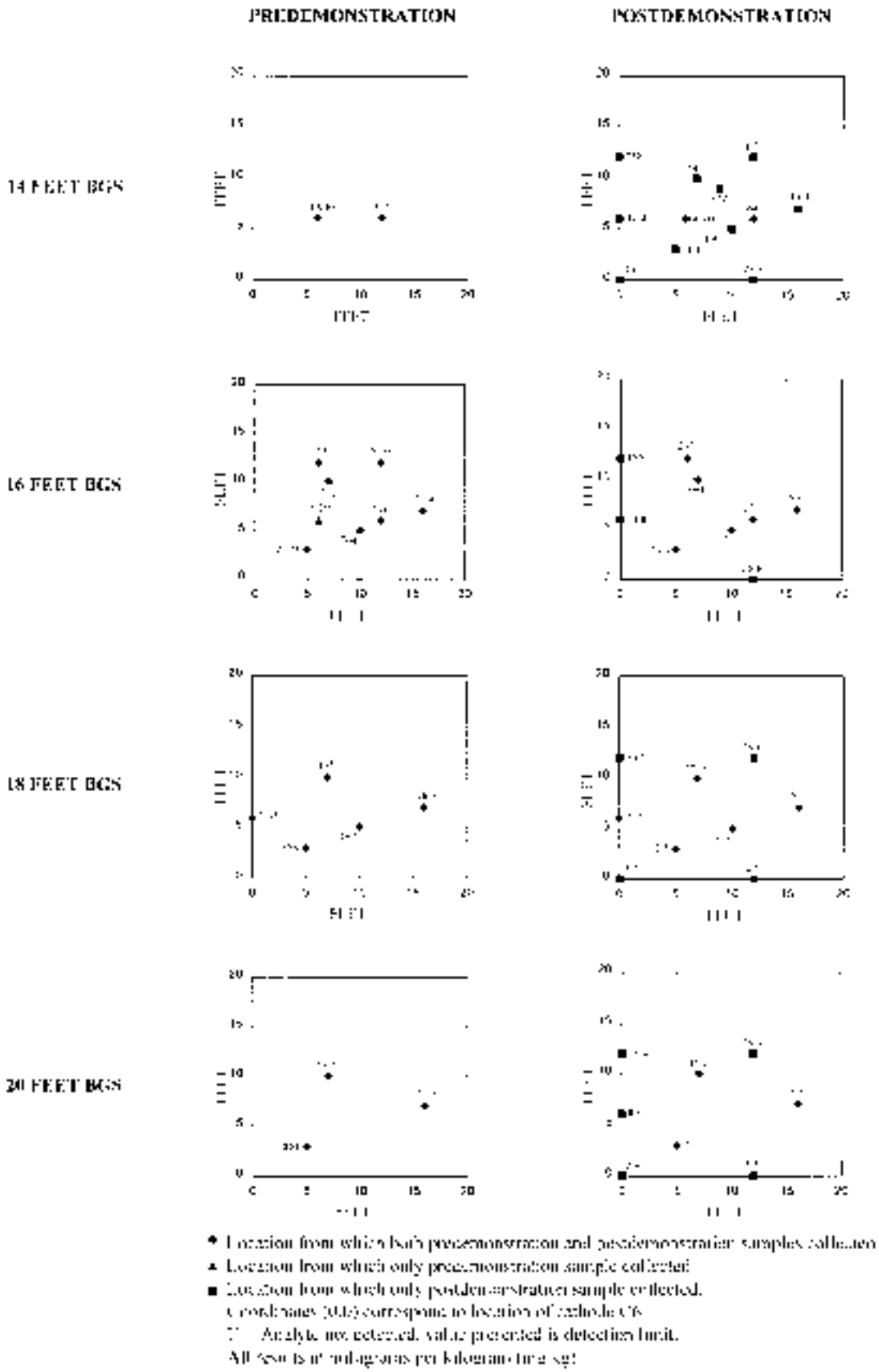


Figure 2-3. Spatial distribution of hexavalent chromium concentrations in soil (continued).

Table 2-4. Statistical Summary of Hexavalent and Total Chromium Analytical Results

Parameter	Sampling Depth							
	6 feet bgs		8 feet bgs		10 feet bgs		12 feet bgs	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
Hexavalent Chromium								
Number of Data Points	2	7	11	14	11	13	9	12
Average Concentration (mg/kg)	--	5.63	371	215	1,682	1,508	498	726
Standard Deviation (mg/kg)	--	7.63	620	359	2,326	1,458	438	940
Total Chromium								
Number of Data Points	2	7	11	14	11	13	9	12
Average Concentration (mg/kg)	--	81.6	1,202	1,843	5,105	6,149	1,319	1,898
Standard Deviation (mg/kg)	--	64.5	1,596	1,566	7,686	4,825	1,140	1,733

Parameter	Sampling Depth							
	14 feet bgs		16 feet bgs		18 feet bgs		20 feet bgs	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
Hexavalent Chromium								
Number of Data Points	2	12	8	9	5	9	3	8
Average Concentration (mg/kg)	--	611	1,227	236	534	53.0	--	24.4
Standard Deviation (mg/kg)	--	1,238	1,772	310	651	69.0	--	27.5
Total Chromium								
Number of Data Points	2	12	8	9	5	9	3	8
Average Concentration (mg/kg)	--	1,860	2,685	564	1,201	138	--	65.4
Standard Deviation (mg/kg)	--	3,351	4,016	877	1,582	193	--	78.3

Notes

-- = Not calculated because data points insufficient to represent treatment area

and (2) the fact that the demonstration was terminated before chromate removal was completed. In addition, limited data appear to indicate that contaminants had likely migrated from areas outside of and near the treatment area (see Figure 2-3). Thus, a determination of the mass of hexavalent chromium removed based on soil sampling results was not possible. Total chromium results are summarized and discussed in Section 2.2.3.

2.2.2 Compliance with TCLP Regulatory Criterion for Total Chromium

In order to meet the RCRA Research, Development, and Demonstration permit for the ISEE system (see Section 2.1.1), SNL collected predemonstration and postdemonstration soil samples and analyzed them for total chromium in TCLP leachate. Figure 2-4 presents the spatial distribution of TCLP chromium results for soil samples collected before and after the demonstration about 8 to 14 feet bgs. The results shown in Figure 2-4 represent 2-foot depth interval from the referenced depth. For example, the 12 feet bgs sample corresponds to soil from 12 to 14 feet bgs.

As shown in Figure 2-4, of the 43 predemonstration soil samples analyzed by TCLP, 18 exceeded the TCLP limit of 5 milligrams per liter (mg/L) of total chromium at concentrations ranging from 5.6 to 103 mg/L, with a median concentration of 15.4 mg/L. Postdemonstration results indicate that 18 out of 35 soil samples exceeded the TCLP regulatory criterion for chromium at concentrations ranging from 6 to 67 mg/L, with a median concentration of 20.4 mg/L.

2.2.3 Removal of Trivalent Chromium from Site Soil

Trivalent chromium concentrations were to be determined by calculating the difference between total and hexavalent chromium concentrations. Figure 2-5 presents the spatial distribution of total chromium concentrations in predemonstration and postdemonstration soil samples. A statistical summary of total chromium concentrations in soil samples is presented in Table 2-4. Total chromium sampling results can be summarized as follows:

- Predemonstration samples contained total chromium concentrations ranging from 7.7 to 26,800 mg/kg.
- Postdemonstration samples contained total chromium concentrations ranging from 8.2 to 16,200 mg/kg.
- Of the 48 locations sampled both before and after the demonstration, 31 locations contained postdemonstration trivalent chromium concentrations that exceeded predemonstration concentrations.

In general, the ratio of trivalent to total chromium concentrations ranged from 7.6 to 94.9 percent in predemonstration samples and from 27.6 to 99.6 percent in postdemonstration samples. This large variability precluded the calculation of the trivalent chromium mass removed as originally intended because it would have further increased the data uncertainty. The increase in total chromium concentrations at certain locations after the demonstration could have resulted from the migration of chromium in the treatment area in addition to the inherent variabilities of the test areas. Therefore, no conclusion was drawn regarding the ISEE system's ability to remove trivalent chromium.

2.2.4 Operating Problems

The ISEE system's operation was observed during the demonstration, and the problems and their resolutions were recorded by SNL personnel. The demonstration lasted over approximately 4,230 hours.

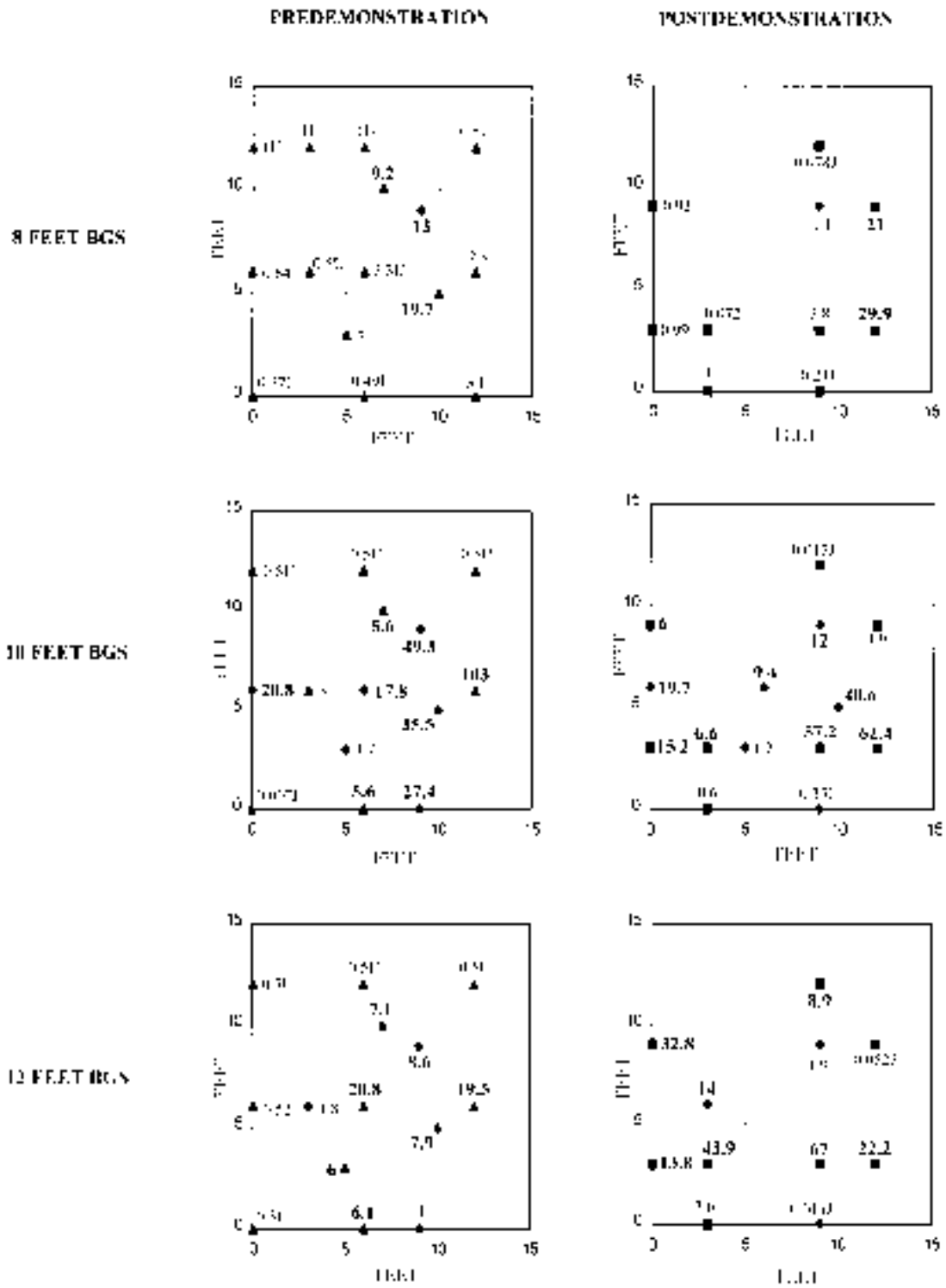
The system was not operable for 36 percent of the time. Table 2-5 presents the reasons for the shutdowns and the percentages of shutdown times relative to the entire duration of the demonstration. In addition, the system was not energized for 3 percent of the time (approximately 140 hours) to perform anolyte sampling and soil moisture measurements using the neutron hydroprobe.

2.3 Factors Affecting Performance

Factors affecting performance of the ISEE system include (1) waste characteristics, (2) operating parameters, and (3) maintenance requirements. These factors are discussed below.

2.3.1 Waste Characteristics

The ISEE system is applicable to treatment of soil contaminated with hexavalent chromium under unsaturated



Bold number indicates that total chromium concentration exceeded TCLP limit of 5 mg/L.

◆ Location from which both predemonstration and postdemonstration samples collected.

▲ Location from which only predemonstration samples collected.

■ Location from which only postdemonstration samples collected.

All results presented in milligrams per liter (mg/L).

Coordinates (0,0) correspond to the location of cathode C6.

Figure 2-4. Spatial distribution of TCLP leachable chromium concentrations in soil.

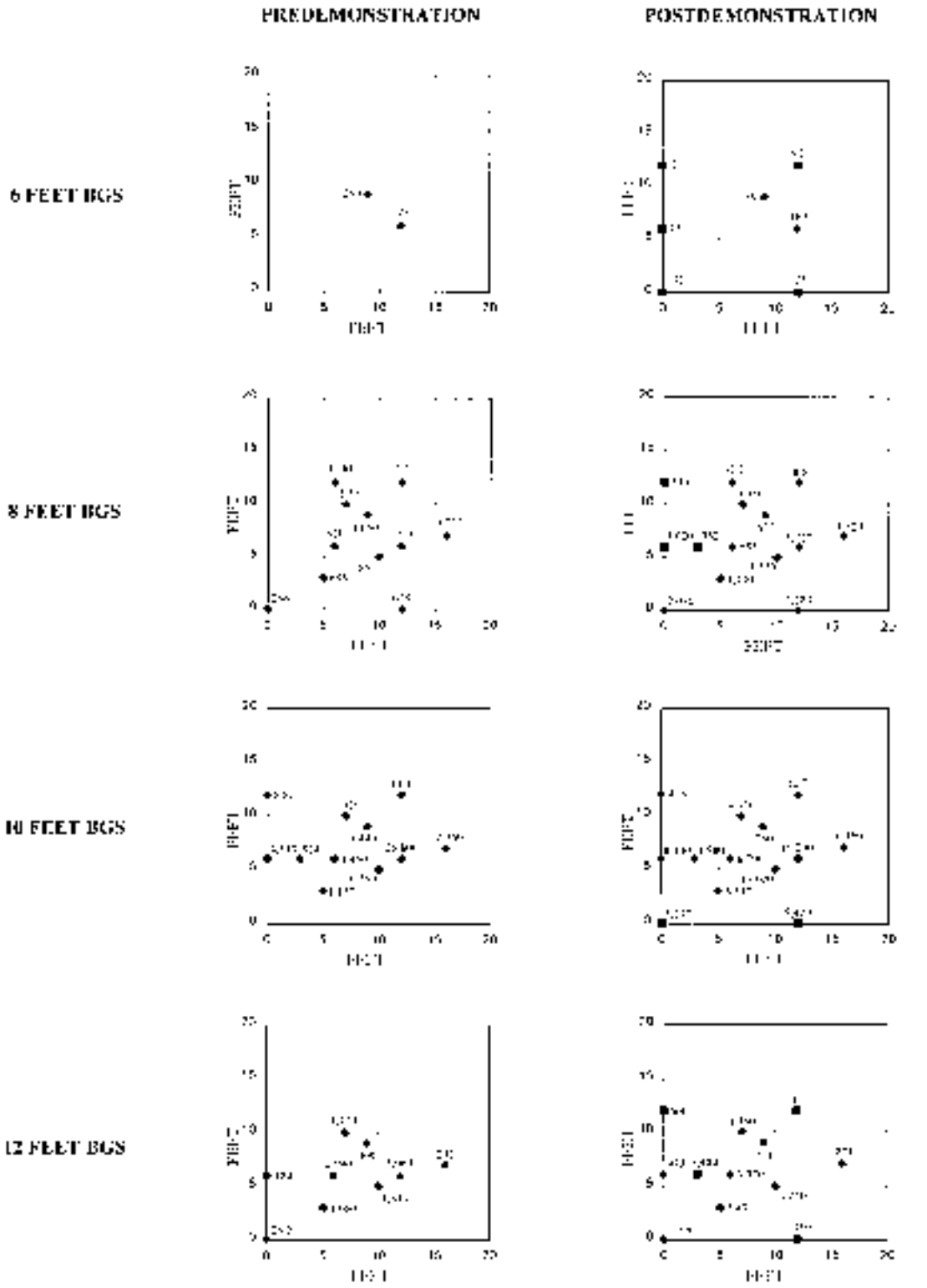


Figure 2-5. Spatial distribution of total chromium concentrations in soil.

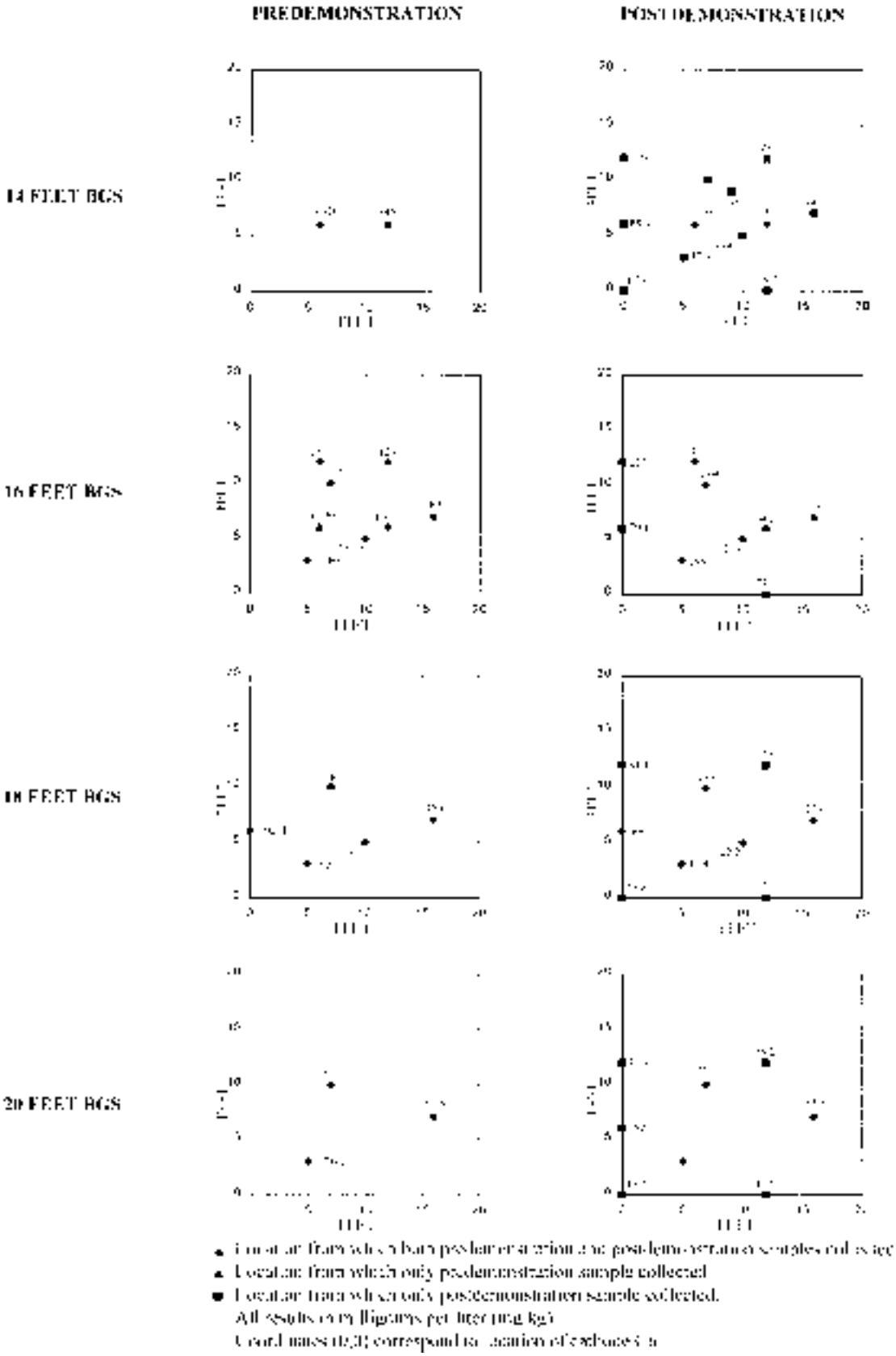


Figure 2-5. Spatial distribution of total chromium concentrations in soil (continued).

Table 2-5. System Shutdown Information

Reason for System Shutdown	Percent of System Shutdown Time
Intentional shutdown to perform maintenance and modifications to the system	21
Problems related to electrode water (such as bladder pumps, float switches, and chiller leakage)	7
Power supply failures and problems	4
pH control system problems	2
Data logger problems	2
Total	**36**

conditions as demonstrated at the UCAP. According to SNL, the ISEE system is also applicable to treatment of soil contaminated with anionic, heavy metals if the metal anions are water soluble. Water soluble anions such as $CrO4^{=}$, $HAsO4^{=}$, and $SeO4^{=}$ are potential target contaminants for the ISEE system.

The system has no absolute lower concentration limit to which it can treat contaminants unless the system's contaminant removal efficiency indicates otherwise; therefore, the system's contaminant removal efficiency needs to be determined on a site-by-site basis (Tetra Tech 1997). According to SNL, the technology is applicable to any type of soil except gravel. Buried metal objects, however, can short circuit the path of electric current through the soil (Tetra Tech 1997).

The presence of dissolved VOCs in general in the pore water does not affect system performance. However, the application of electric current may transport dissolved VOCs through electroosmosis toward the cathode, where they could enter the cathode casing. In the casing, vacuum applied would strip VOCs from the solution. These emissions need to be collected and treated as necessary. According to SNL, during the early stages of demonstration, air monitoring done at the cathode casing did not show the presence of VOCs above 150 parts per billion. However, the VOC levels significantly increased in the soil vapor when the soil temperature was about 50 °C. The use of cold finger cathodes that do not have an exhaust eliminated VOC emissions to atmosphere.

2.3.2 Operating Parameters

Operating parameters can be varied during the treatment process to achieve desired contaminant removal and treatment goals. Limited experimental data are currently available to define the behavior of the ISEE system used to remediate contaminated soils under unsaturated conditions. Experimental data are critical because soil electrochemistry is complex and because of the nonlinear interdependence of the parameters.

Laboratory testing was performed by SNL to evaluate the influence of soil moisture on the efficiency of electrokinetic technology applied to unsaturated soils under constant current conditions. Experimental results on UCAP soil show that near saturation, electromigration velocity increases as soil moisture content decreases. However, at lower moisture content, the nonlinear effect of tortuosity dominates and the electromigration velocity decreases sharply as moisture content decreases. Also, for the UCAP soil, experiments show that electromigration and thus remediation ceases at a moisture content of 3.5 percent by weight because of the loss of pore water connectivity (Lindgren and others 1991). The minimum moisture content required for the operation of the electrokinetic technology needs to be determined on a site-by-site basis.

A secondary factor that affects the performance of an electrokinetic extraction system is soil temperature. Thermal effects on saturated soil were studied at the laboratory scale. If the system is operated under constant current conditions, pore water temperature will increase, thereby slightly decreasing electroosmotic velocity but not affecting electromigration velocity (Mattson and Lindgren 1994). However, under constant voltage conditions, increased soil temperature will increase electromigration velocity, which could result in reduced remediation times (Mattson and Lindgren 1994; Krause and Tarman 1995). However, during the SITE

demonstration of the ISEE system, the tests performed did not directly target the evaluation of the system's performance based on the variation of operating parameters. Consequently, operating parameter effects were confounded and could not be dissociated.

2.3.3 Maintenance Requirements

Maintenance of a full-scale ISEE system is estimated to require 8 hours weekly. This estimate is based on the assumption that the design of parts of the system that caused frequent shutdowns during the SITE demonstration, such as bladders and float switches, would be modified to eliminate problems.

2.4 Site Characteristics and Support Requirements

Site-specific factors can impact the application of the ISEE system. These factors should therefore be considered before the system is selected for remediation of a specific site. Site-specific factors addressed in this section include site access, area, and preparation requirements; climate requirements; utility and supply requirements; support system requirements; and personnel requirements.

2.4.1 Site Access, Area, and Preparation Requirements

The site must be prepared for the mobilization, O&M, and demobilization of the equipment. Access roads are necessary for equipment transport. The site must be accessible to equipment necessary to install electrodes and ancillary equipment, such as Geoprobe® and drill rigs. The air space in the equipment installation area must be clear of obstacles (such as overhead wires).

In addition to the treatment area and corresponding exclusion zone, enough space should be available to accommodate the control trailer, hazardous waste storage area, water tanks, and supply storage. This additional area is estimated to require 8,800 square feet.

2.4.2 Climate Requirements

The demonstration took place in Albuquerque, New Mexico, a semi-arid region. The average winter temperature is about 50 °F (10 °C), and freezing conditions occur mainly during the night. A temporary structure was installed during the demonstration to protect the ISEE system and personnel from the weather and also to provide an exclusion zone when electrodes were energized. The data logger, control panels, and analytical equipment were housed in the control trailer.

If the ISEE system is used outdoors in a cold climate, provisions should be made for insulating exposed portions of the water control system to prevent freezing. In addition, equipment such as chillers should be designed for outdoor use.

2.4.3 Utility and Supply Requirements

The ISEE system demonstrated at UCAP was powered by four 10-kW power supply units. The units were capable of operating independently or in parallel. When connected in parallel, the maximum output was 64 amps at 600 V DC. According to SNL, a three-phase, 230-V, 150-kW power supply is necessary to operate a full-scale ISEE system.

Water is also necessary to operate the system. SNL estimates that for a full-scale system of 30 electrodes, a quantity of 360 L of water per day is required. Water could be obtained from a permanent source of potable water or stored in water tanks on site. In addition, water for decontamination activities is required as needed.

The monitoring system requires connection to a telephone line or cellular telephone to download data to an off-site computer and to transmit signals that the system has been shut down to maintenance personnel.

2.4.4 Support System Requirements

Several surveys are required to determine if the site is appropriate for electrokinetic treatment. Electromagnetic and magnetic surveys are necessary to determine if large metallic objects are buried in soil. These objects could short circuit the current in the soil, thus significantly decreasing the efficiency of the remediation process. Soil conductivity and soil moisture are also critical to application of the electrokinetic technology; therefore, surveys to determine these parameters for soil to be treated are also required.

Also, remediation progresses, anolyte containing chromate is removed. This effluent stream is a hazardous waste and needs to be handled, stored, and disposed of in accordance with applicable regulations.

2.4.5 Personnel Requirements

Based on the design of the ISEE system, which can transmit system information off site, no personnel are required to be present on site for system operation. The system is equipped with a CR7 data logger that monitors system parameters and can shut down the system (such as by cutting off power to the electrodes and terminating the water supply). The data logger consequently sends a coded signal to the system operator that identifies the problem. Technical service personnel should be available on an as-needed basis to remediate any problems.

Periodic visits to the site are necessary for activities such as collection of anolyte samples, replacement of full effluent barrels, addition of sodium hydroxide to the pH control barrels, and soil moisture measurement using neutron hydroprobes. The involvement of a chemist or technician is also periodically required for chromate analysis of anolyte samples collected. According to the vendor, maintenance and routine sampling and analysis activities for a full-scale system should require the on-site presence of a technician for 8 hours a week.

Before operating the ISEE system at a hazardous waste site, the technician should have completed training requirements under the Occupational Safety and Health Act (OSHA) outlined in Title 29 of the Code of Federal Regulations (40 CFR), Part 1910.120, which covers hazardous waste operations and emergency response. The operator should also participate in a medical monitoring program as specified by OSHA.

2.5 Material Handling Requirements

The only waste stream produced during the remediation of soil using the SNL ISEE system is effluent containing chromate extracted from the anode casings, which is a hazardous waste. In addition, decontamination activities (such as decontamination of the Geoprobe®) could also produce hazardous wastes. If the ISEE system is applied to soil that contains VOCs, VOCs would be stripped from the soil matrix because of heating that occurs when current is passed through the soil. Treatment area should be monitored for VOC air emissions to evaluate if special controls are needed.

In addition, a site plan is required to provide for personnel protection and special handling measures. Wastes need to be appropriately stored until sampling results indicate their acceptability for disposal or release to a treatment facility.

2.6 Technology Limitations

Prior to implementing electrokinetic remediation at a specific site, field and laboratory screening tests should be conducted to determine if the site is amenable to this technology. Field conductivity surveys are necessary to determine the soil's electrical conductivity. Also, buried metallic objects and utility lines could short circuit the current path, thereby influencing the voltage gradient and affecting the contaminant extraction rate. Electromagnetic surveys should be conducted to determine the presence of buried metallic objects.

In addition, if VOCs are present in soil undergoing electrokinetic treatment, the VOCs may be stripped from the soil to significantly increase the soil vapor VOC concentrations that would result in significant VOC migration from the treatment area, if soil temperature exceeds 50 °C. Special measures therefore need to be taken to contain and control VOC emissions.

2.7 Potential Regulatory Requirements

This section discusses regulatory requirements relevant to use of the ISEE system at Superfund RCRA corrective action sites. Regulations applicable to implementation of this system depend on site-specific remediation logistics and the type of contaminated soil being treated; therefore, this section presents a general overview of the types of federal regulations that may apply under various conditions. State requirements should also be considered, but because these requirements vary from state to state, they are not discussed in detail in this section. Table 2-6 summarizes the regulations discussed below. These regulations include the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); RCRA; the Clean Air Act (CAA); Toxic Substances Control Act (TSCA); Atomic Energy Act (AEA) and RCRA for mixed wastes; and OSHA requirements.

2.7.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA authorizes the federal government to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or

Table 2-6. Summary of Applicable Regulations

Act or Authority	Applicability	Application to SNL ISEE System	Citation
CERCLA	Superfund sites	This program authorizes and regulates the cleanup of environmental contamination. It applies to all CERCLA site cleanups and requires that other environmental laws be considered as appropriate to protect human health and the environment	40 CFR, Part 300
RCRA	Superfund and RCRA sites	RCRA defines and regulates the treatment, storage, and disposal of hazardous wastes. RCRA also regulates corrective action at generator and treatment, storage, or disposal facilities. The ISEE treatment residual (analyte) contains hexavalent chromium and should be characterized and disposed of as a RCRA hazardous waste	40 CFR, Parts 260 through 270
CAA	Air emissions from stationary and mobile sources	If VOC emissions occur or hazardous air pollutants are of concern, these standards may be applicable to ensure that air pollution is not associated with the use of this technology. State air program requirements should also be considered.	40 CFR, Parts 50 and 70
TSCA	Polychlorinated biphenyl (PCB) contamination	If PCB-contaminated wastes are treated, TSCA requirements should be considered to determine waste disposal requirements. RCRA also regulates solid wastes containing PCBs	40 CFR, Part 761
AEA and RCRA	Mixed wastes	AEA and RCRA requirements apply to the treatment, storage, or disposal of mixed wastes containing both hazardous and radioactive components. OSWER and DOE directives provide guidance that address mixed wastes	AEA (10 CFR) and RCRA (see above)
OSHA Requirements	All remedial actions	OSHA regulates on-site construction activities and the health and safety of workers at hazardous waste sites. Installation and operation of the system at Superfund or RCRA sites must meet OSHA requirements	29 CFR, Parts 1900 through 1926

contaminants that may present an imminent or significant danger to public health and welfare or the environment.

As part of the requirements of CERCLA, EPA has prepared the National Oil and Hazardous Substances Contingency Plan (NCP) for hazardous substance response. The NCP is codified in 40 CFR, Part 300, and delineates the methods and criteria used to determine the appropriate extent of removal and cleanup of hazardous waste contamination.

The Superfund Amendments and Reauthorization Act (SARA) amended CERCLA and directed EPA to do the following:

- Use remedial alternatives that permanently and significantly reduce the volume, toxicity, or mobility of hazardous substances, pollutants, or contaminants
- Select remedial actions that protect human health and the environment, are cost-effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent possible
- Avoid off-site transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist (Section 121(b))

In general, two types of responses are possible under CERCLA: removal and remedial actions. The SNL ISEE system is likely to be part of a CERCLA remedial action. Nine general criteria that must be addressed by CERCLA remedial actions are listed in Table ES-1 of the Executive Summary.

On-site remedial actions must comply with federal and more stringent state ARARs. ARARs are determined on a site-by-site basis and may be waived under six conditions: (1) the action is an interim measure and the ARAR will be met upon remedial action completion, (2) compliance with the ARAR would pose a greater risk to human health and the environment than noncompliance, (3) it is technically impractical to meet the ARAR, (4) the standard of performance of an ARAR can be met by an equivalent method, (5) a state ARAR has not been consistently applied elsewhere, and (6) ARAR compliance would not provide a balance between the protection achieved at a particular site and demands on Superfund for other sites. These waiver options apply only to Superfund actions taken on site, and justification for the waiver must be clearly demonstrated.

CERCLA requires identification and consideration of environmental laws that are ARARs applicable to site remediation before implementation of a remedial technology at a Superfund site. Additional regulations pertinent to use of the ISEE system are discussed below. No direct water discharges are generated by the ISEE treatment process; therefore, only regulations addressing anolyte characterization and disposal, potential fugitive air emissions from VOCs stripped from soil, and additional considerations are discussed below.

2.7.2 Resource Conservation and Recovery Act

RCRA, an amendment to the Solid Waste Disposal Act, was passed in 1976 to address the problem of how to safely dispose of the enormous volume of municipal and industrial solid wastes generated annually. RCRA specifically addressed the identification and management of hazardous wastes. The Hazardous and Solid Waste Amendments of 1984 greatly expanded the scope and requirements of RCRA.

The presence of RCRA-defined hazardous waste determines whether RCRA regulations apply to the SNL ISEE system. If soil or anode effluent are determined to be hazardous waste as defined by RCRA, all RCRA requirements regarding the management and disposal of hazardous wastes will need to be addressed. RCRA regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. Wastes defined as hazardous under RCRA include characteristic and listed wastes. Criteria for identifying characteristic hazardous wastes are included in 40 CFR, Part 261, Subpart C. Listed wastes from nonspecific and specific industrial sources, off-specification products, spill cleanups, and other industrial sources are discussed in 40 CFR, Part 261, Subpart D.

Treatment, storage, or disposal of hazardous waste typically requires issuance of a RCRA Part B treatment, storage, or disposal permit. At Superfund sites, the on-site treatment, storage, or disposal of hazardous waste must meet the substantive requirements of a treatment, storage, or disposal permit. RCRA administrative requirements (such as reporting and recordkeeping), however, are not applicable to on-site actions.

A Uniform Hazardous Waste Manifest or its state counterpart must accompany off-site shipment of hazardous waste, and transport must comply with U.S. Department of Transportation hazardous waste packaging, labeling, and transportation regulations. The receiving treatment, storage, or disposal facility must be permitted and in compliance with RCRA standards.

RCRA federal land disposal restrictions (LDR) in 40 CFR, Part 268, preclude the land disposal of hazardous waste that fails to meet stipulated technology or treatment standards. In situ treatment of media contaminated with hazardous waste does not trigger LDRs for soil or groundwater remaining in place. Consequently, soil treated in situ by the ISEE system does not have to meet LDRs but may have to meet other criteria in order to remain in place. Soil or groundwater removed and treated must meet LDRs prior to replacement. For the anolyte, this requirement means that treatment must reduce the concentrations of contaminants that make the anolyte hazardous and all other LDR-triggering contaminants to levels specified in 40 CFR, Part 268, before the anolyte can be land disposed. The technology or treatment standards applicable to residuals produced by the SNL ISEE system are determined by the type and characteristics of hazardous waste present in the soil being remediated. In some cases, variances from LDRs can be obtained from EPA.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR, Part 264, Subparts F (promulgated) and S (proposed). These subparts also generally apply to remediation at Superfund sites. Subparts F and S include requirements for initiating and conducting RCRA corrective actions, remediating groundwater, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements can be waived for temporary treatment units operating at corrective action sites. Thus, RCRA mandates requirements similar to CERCLA and as proposed allows treatment units such as the ISEE system to operate without the full set of permits.

2.7.3 Clean Air Act

The CAA as amended in 1990 regulates stationary and mobile sources of air emissions. CAA regulations are generally implemented through combined federal, state, and local programs. The CAA requires that treatment, storage, and disposal facilities comply with primary and secondary ambient air quality standards. Air emissions from the ISEE system may result from VOCs from the vacuum exhaust system and fugitive emissions such as drilling activities related to system installation (VOC or dust emissions), periodic sampling efforts, and the staging and storing of contaminated drill cuttings. VOC emission control equipment should be provided to reduce emissions, if the ISEE system is applied to soils that contain VOCs. Soil moisture should be managed during system installation to prevent or minimize impacts from fugitive emissions. State air quality standards may require additional measures to prevent fugitive emissions.

2.7.4 Toxic Substances Control Act

The disposal of PCBs is regulated under Section 6(e) of TSCA. PCB treatment and disposal regulations are described in 40 CFR, Part 761. Materials containing PCBs at concentrations of 50 to 500 parts per million (ppm) can either be disposed of in TSCA-permitted landfills or destroyed by incineration at a TSCA-approved incinerator; at PCB concentrations exceeding 500 ppm, the material must be incinerated.

Sites where spills of PCBs have occurred after May 4, 1987, must be addressed under the PCB spill cleanup policy in 40 CFR Part 761, Subpart G. This policy applies to spills of materials containing 50 ppm or more of PCBs and establishes cleanup protocols for addressing such releases based on the volume and concentration of the spilled material. PCBs were not anticipated to be present at the demonstration site; therefore, no analysis for PCBS was performed.

2.7.5 Atomic Energy Act and Resource Conservation and Recovery Act

As defined by the AEA and RCRA, mixed waste contains both radioactive and hazardous components. Such waste is subject to the requirements of both the AEA and RCRA; however, when application of both AEA and RCRA regulations results in a situation inconsistent with the AEA (for example, an increased likelihood of radioactive exposure), AEA requirements supersede RCRA requirements (EPA 1988). Use of the ISEE system at sites with radioactive contamination might involve treatment or generation of mixed waste.

OSWER, in conjunction with the Nuclear Regulatory Commission, has issued several directives to assist in the identification, treatment, and disposal of low-level radioactive mixed waste. Various OSWER directives include guidance on defining, identifying, and disposing of commercial, mixed, low-level radioactive and hazardous wastes (EPA 1987). If the ISEE system is used to treat low-level mixed waste, these directives should be considered. If high-level mixed waste or transuranic mixed waste is treated, internal DOE orders should be considered when developing a protective remedy (DOE 1988b).

2.7.6 Occupational Safety and Health Administration Requirements

OSHA regulations in 29 CFR, Parts 1900 through 1926, are designed to protect worker health and safety. Both Superfund and RCRA corrective actions must meet OSHA requirements, particularly Part 1910.120, "Hazardous Waste Operations and Emergency Response." Part 1926, "Safety and Health Regulations for Construction," applies to any on-site construction activities. For example, electric utility hookups for the ISEE system must comply with Part 1926, Subpart K, "Electrical." Product chemicals such as NaOH used with the ISEE system must be managed in accordance with OSHA requirements (for example, Part 1926, Subpart D, "Occupational Health and Environmental Controls," and Subpart H, "Materials Handling, Storage, and Disposal"). More stringent state or local requirements must also be met, if applicable. In addition, health and safety plans for site remediations should address chemicals of concern and include monitoring practices to ensure that worker health and safety are maintained.

2.8 State and Community Acceptance

Because few applications of the SNL ISEE system have been attempted beyond the bench- or pilot-scale, limited information is available to assess state and community acceptance of the system. The fact that the ISEE system allows in situ remediation of contaminated soils should improve the potential for community acceptance because excavation of contaminated soil often releases volatile contaminants. Although some contaminants may be released during electrode and ancillary equipment installation, the potential for emissions during drilling is substantially lower than during excavation. State acceptance of the technology may involve consideration of performance data from applications such as the SITE demonstration and results from on-site, pilot-scale studies using the actual wastes to be treated during later, full-scale remediation.

Section 3
Economic Analysis

3.1 Introduction

The primary purpose of this economic analysis is to provide a cost estimate (not including profit) for using the SNL ISEE system to commercially remediate unsaturated soils contaminated with hexavalent chromium. This analysis is based on the assumptions and costs provided by SNL and on the results and experiences gained from the SITE demonstration conducted over a 6-month period at SNL's UCAP. During the SITE demonstration, 13 tests were performed during six phases. The first 12 tests were conducted so that SNL could determine preferred ISEE system operating conditions for Test 13 and to facilitate the migration of hexavalent chromium toward the central portion of the test area. Therefore, this cost estimate is based on the preferred operating conditions documented during Test 13. Test 13 targeted a central portion of the demonstration area, utilizing four anodes and eight cold finger cathodes.

Economic calculations were performed for the SITE demonstration Test 13 treatment area, treatment depth, and operating parameters. SNL anticipates that the cost for operating the small-scale ISEE system used during Test 13 will be significantly higher than the cost for operating a full-scale, commercialized ISEE system. SNL states that a full-scale, commercialized system would be designed with significant improvements over the system operated during the demonstration. However, SNL has not yet completed the design. Therefore, it is not possible to prepare a cost estimate for operating the full-scale ISEE system. When the technology is ready for commercialization, further economic analysis should be performed to obtain the costs of operating the system during a site remediation.

A number of factors affect the cost of treatment. These include, but are not limited to, treatment area, treatment depth, initial contaminant concentration, final target contaminant concentration, soil characteristics, online percentage of system operation, hexavalent chromium removal rate, and hexavalent chromium removal efficiency. This economic analysis assumes that the SNL ISEE system will remediate unsaturated soils with the same characteristics as soil at the UCAP site.

During Test 13 of the SITE demonstration, the ISEE system treated a volume of approximately 16 cubic yards (yd^3) of soil contaminated with hexavalent chromium. This volume is based on the assumption that the effective treatment depth is 6 feet, the treatment area width is 6 feet, and the treatment area length is 12 feet. During Test 13, soil was treated for over 700 hours from October 21 to November 24, 1996. SITE demonstration results are presented in Section 2 of this report.

Treatment costs were estimated for using the Test 13 ISEE system configuration to treat 16 yd^3 of soil and remove 200 g of hexavalent chromium (the approximate mass of hexavalent chromium removed during Test 13).

Estimated treatment costs, issues and assumptions, and the basis for the economic analysis are discussed below.

3.2 Issues and Assumptions

The cost estimates presented in this economic analysis are representative of charges typically assessed to the client by the vendor but do not include profit. In general, assumptions are based on information provided by the developer and on observations during this and other SITE evaluation projects.

Many actual or potential costs are not included as part of this cost estimate. They were omitted because site-specific engineering designs that are beyond the scope of

this SITE project would be required. Also, certain functions were assumed to be the obligation of the responsible party or site owner and therefore are not included. These costs are site-specific. Thus, calculations are left to the reader so that relevant information may be obtained for specific cases. Whenever possible, applicable information is provided on these costs so that the reader can independently complete the calculations required to calculate relevant economic data.

Other important assumptions regarding operating conditions and task responsibilities that could significantly alter the cost estimate are discussed below.

- The site has been adequately characterized during previous investigations.
- Treatability studies or pilot-scale studies have already been performed.
- The site has suitable access roads.
- The site has electrical supply lines, telephone lines or cellular telephone service, and potable water.
- Hexavalent chromium is being removed from unsaturated soil similar to UCAP soil.
- Based on Test 13 results, the ISEE system will on average remove hexavalent chromium at a rate of 0.29 g/hour, with an overall removal efficiency of 0.14 g of hexavalent chromium per kW-h.
- Based on information from the developer, the online percentage will be 85 percent for the ISEE system.
- Based on the hexavalent chromium removal rate measured during Test 13 and an online percentage of 85 percent, the treatment time for the ISEE system is approximately 5 weeks to remove 200 g of hexavalent chromium.
- Based on information from the developer, the combined total operating and maintenance labor time during on-site treatment is 8 hours/week.
- Based on information from the developer, 80 hours of labor will be required for startup of the ISEE system.

3.3 Basis for Economic Analysis

To compare the cost effectiveness technologies evaluated under the SITE program, EPA breaks down costs into the following 12 categories (Evans 1993):

- Site and facility preparation costs
- Permitting and regulatory costs
- Equipment costs
- Startup and fixed costs
- Labor costs
- Supplies and consumables costs
- Utilities costs
- Effluent treatment and disposal costs
- Residuals and waste shipping, handling, and transport costs
- Analytical costs
- Facility modification, repair, and replacement costs
- Site restoration costs

These 12 cost categories reflect typical cleanup activities encountered at Superfund sites. Each of these cost categories is defined and discussed below and form the basis for the detailed estimated costs presented in Tables 3-1 and 3-2. Table 3-1 provides a detailed breakdown by cost category. Table 3-2 lists each category's cost as a percent of the total cost. Costs assumed to be the obligation of the responsible party or site owner are omitted from this cost estimate and are indicated by a line (---) in Tables 3-1 and 3-2. Categories with no associated costs are indicated by a zero (0) in Tables 3-1 and 3-2. Costs presented in this report are order-of-magnitude estimates as defined by the American Association of Cost Engineers, with an expected accuracy within +50 percent and -30 percent; however, because this technology is new, the actual range may be wider. The 12 cost categories examined and assumptions made are also described in detail below.

Table 3-1. Estimated Costs for Treatment Using the SNL ISEE System

Total Treatment Volume	16 yd^3
Mass of Hexavalent Chromium Removed	200 g
Treatment Time	5 weeks

Cost Categories	$/$yd^3$
Site and Facility Preparation Costs	
Site design and layout	---
Survey and site investigations	---
Legal searches	---
Access rights and roads	---
Preparation for support facilities	---
Auxiliary buildings	---
Transportation of waste feed	---
Technology-specific requirements	188
Total Site and Facility Preparation Costs	**188**
Permitting and Regulatory Costs	
Permits	---
System monitoring requirements	---
Development of monitoring and analytical protocols	---
Total Permitting and Regulatory Costs	---
Equipment Costs	
Annualized purchased equipment cost	48
Equipment rental/lease	25
Total Equipment Costs	**73**
Startup and Fixed Costs	
System installation	312
Startup labor	250
Equipment mobilization	94
Insurance and taxes	---
Initiation of monitoring programs	---
Contingency	---
Total Startup and Fixed Costs	**656**
Labor Costs	
Operator	125
Total Labor Costs	**125**
Supplies and Consumables Costs	
Anode casings	0
Cathode casings	0
Plumbing	0
PPE	2
Sodium hydroxide	7
Total Supplies and Consumables Costs	**9**
Utilities Costs	
Electricity	10
Water	[illegible]
Total Utilities Costs	**10**

Table 3-1. Estimated Costs for Treatment Using the SNL ISEE System (continued)

Total Treatment Volume	16 yd^3
Mass of Hexavalent Chromium Removed	200 g
Treatment Time	5 weeks
Cost Categories	$/$yd^3$
Effluent Treatment and Disposal Costs	
On-site facility costs	---
Off-site facility costs	
-anode effluent	46
-cathode effluent	0
Total Effluent Treatment and Disposal Costs	**46**
Residuals and Waste Shipping, Handling and Transport Costs	
Drill cuttings	98
PPE and small equipment	16
Total Residuals and Waste Shipping, Handling and Transport Costs	**114**
Analytical Costs	
Operations (for developer's purposes)	6
Environmental monitoring (regulatory)	---
Total Analytical Costs	**6**
Facility Modification, Repair, and Replacement Costs	
Design adjustments	0
Routine maintenance (materials and labor) [a]	0
Equipment replacement	0
Total Facility Modification, Repair, and Replacement Costs [a]	**0**
Site Restoration Costs	
Site cleanup and restoration	---
- Technology specific	141
Permanent storage	---
Total Site Restoration Costs	**141**
TOTAL OPERATING COSTS[b]	1,368
	(1,400)

Notes:

g = Gram
PPE = Personal protective equipment
yd^3 = Cubic yard
--- = Cost omitted because assumed to be responsible party or site owner obligation
< = Less than
[a] Maintenance labor is included under operating labor costs
[b] Total operating costs rounded off nearest $100.

Table 3-2. Estimated Cost Percentages for Treatment Using the SNL ISEE System

Total Treatment Volume	15 yd^3	
Mass of Hexavalent Chromium Removed	200 g	
Treatment Time	4 weeks	
Costs Units	($/$yd^3$)	%
Site Facility Preparation Costs	188	13.7%
Permitting and Regulatory Costs	---	---
Equipment Costs	73	5.3%
Startup and Fixed Costs	656	47.9%
Labor Costs	125	9.1%
Supplies and Consumables Costs	9	0.6%
Utilities Costs	10	0.7%
Effluent Treatment and Disposal Costs	46	3.4%
Residuals Shipping, Handling, and Transport Costs	114	8.3%
Analytical Costs	6	0.4%
Facility Modifications, Repair, and Replacement Costs	0*	0*%
Site Restoration Costs	141	10.3%
Total Costs ($/$yd^3$)	1,368	

Notes:

g = Gram
yd^3 = Cubic yard
--- = Cost omitted because assumed to be responsible party or site owner obligation
* Maintenance labor is included under operating labor costs

3.3.1 Site and Facility Preparation Costs

For the purposes of these cost calculations, "site" refers to the location of the contaminated area. It is assumed that preliminary site preparation will be performed by the responsible party or site owner. The amount of preliminary site preparation required depends on the site. Site preparation responsibilities include assessment of site design and layout, surveys and site investigations, legal searches, securing of access rights and construction of access roads, preparation of support and decontamination facilities, construction of fixed auxiliary buildings, and transportation of waste feed. Because these costs are site-specific, they are not included as part of the site preparation costs in this estimate.

The cost estimate assumes that the site has been characterized during previous investigations; therefore, characterization data are available to document the electrical conductivity of soil pore water, contaminant ion concentrations in the pore water, hydraulic conductivity, soil moisture content, subsurface conditions regarding any metallic objects, soil mineralogy, and the presence of VOCs in soil.

For these cost calculations, only technology-specific site preparation costs are included. These costs are limited to costs for connecting utilities to the ISEE system. It is assumed that the site has electrical supply lines, telephone lines (or a cellular telephone service), and potable water. The developer estimates the cost for utilities connection to be $3,000.

3.3.2 Permitting and Regulatory Costs

Permitting and regulatory costs are generally the obligation of the responsible party or site owner. These costs may include actual permit costs, system monitoring requirements, development of monitoring and analytical protocols, and health and safety monitoring. Permitting and regulatory costs can vary greatly because they are site- and waste-specific. No permitting costs are included in this analysis. Depending on the treatment site, these costs can be a significant factor because permitting can be expensive and time consuming.

3.3.3 Equipment Costs

Equipment costs include purchased and rented equipment. Purchased equipment costs are presented as annualized costs and are prorated based on the amount of time the equipment is used for the project. The annualized purchased equipment cost is calculated based on a 15-year equipment life and a 6 percent annual interest rate. The annualized equipment cost is based on the writeoff of the total initial capital equipment cost and scrap value (assumed to be zero) using the following equation (Douglas 1988; Peters 1980):

$$\text{Capital recovery} = (V - V_s)\,\frac{i(1+i)^n}{(1+i)^n - 1} \qquad (3\text{-}1)$$

where:

V	=	cost of the original equipment
V_s	=	salvage value of equipment
n	=	equipment life
i	=	annual interest rate

Purchased equipment for the ISEE technology includes four anodes, eight cold finger cathodes, a water control system, a vacuum control system, a power supply system, and a monitoring system. This cost estimate assumes that ISEE system used during Test 13 requires one vacuum pump, one air compressor, two chillers, four controllers (one for each anode), one rectifier, electrode cabling, one skid loader, and one hurricane sampler. The developer estimates the total capital cost of the ISEE system used during Test 13 to be $78,400. This cost was used to calculate the prorated annualized purchased equipment cost based on treatment time for the ISEE system. Based on the hexavalent chromium removal rate measured during Test 13 and an online percentage of 85 percent, the treatment time for the ISEE system is approximately 5 weeks to remove 200 g of hexavalent chromium.

Rented equipment includes a trailer at a rate of $200 per month based on a 30-day month. This cost estimate assumes that a trailer will be rented for 2 months for removing 200 g of hexavalent chromium.

If the ISEE system is applied to soils that contain VOCs, the VOCs would be stripped from the soil matrix and VOC monitoring equipment would be required. This requirement would result in increased costs for purchased equipment and increased costs for VOC migration control and monitoring (depending on the VOC migration control equipment selected).

3.3.4 Startup and Fixed Costs

For these cost calculations, startup and fixed costs include system installation (costs) estimated by the developer to be $5,000; startup labor costs estimated by the developer to be 80 hours at a rate of $50 per hour; and equipment mobilization costs estimated by the developer to be $1,500. System installation includes costs (including labor) for installing the anodes, the cold finger cathodes, plumbing, and all other aboveground ISEE system equipment. Startup labor includes shakedown testing of the ISEE system. Mobilization costs assume that all of the ISEE equipment (including the control trailer) can be mobilized to the site for $1.50 per mile for 1,000 miles. This cost estimate assumes that treatability studies or pilot-scale studies have already been performed. Technology-specific site preparation costs are discussed in Section 3.4.1.

No insurance and taxes, initiation of monitoring programs, or contingency costs are included because the demonstration system is not designed to be a commercial system. Often, insurance and taxes can be estimated to be 10 percent of the total annual purchased equipment costs. Also, depending on the site and location of the ISEE system, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring required may have significant impact on project costs. Contingency costs are often equal to the cost of insurance and taxes. Contingency costs allow for unforeseen or unpredictable cost conditions, such as strikes, storms, floods, and price variations (Peters 1980; Garrett 1989).

3.3.5 Labor Costs

Hourly labor rates for ISEE system operation are estimated at $50 per hour and include base salary, benefits, overhead, and general and administrative expenses. For this cost estimate, operating labor is assumed to consist of one worker for 8 hours per week during treatment. Operating labor includes time for general maintenance of the ISEE system. In addition, operating labor includes time for activities such as collection of anode effluent samples, replacement of full effluent barrels, addition of sodium hydroxide to the pH control barrels, soil moisture content measurement using neutron hydroprobes, and field analysis of hexavalent chromium in anode effluent samples.

3.3.6 Supplies and Consumables Costs

Supplies costs are limited to personal protective equipment (PPE), anode casings, cathode casings, and plumbing supplies. The cost of PPE is estimated at $5 per week. SNL does not expect to replace the anode casings, the cathode casings, or the plumbing while operating the ISEE system for removing 200 g of hexavalent chromium because of short duration of treatment.

Consumables costs are limited to sodium hydroxide. It is assumed that sodium hydroxide volume requirements are based on observations made by the developer during Test 13 of the SITE demonstration (65 g of sodium hydroxide per hour at a cost of $2 per kilogram of sodium hydroxide).

3.3.7 Utilities Costs

Utilities required are limited to electricity and water for the electrodes, chillers, and control equipment. Costs for a telephone line for remote access to the data logger are not included because they are assumed to be the obligation of the responsible party or site owner. The volume of water required is estimated to be 6 gallons per day based on the average volume of effluent collected during Test 13. Water rates are assumed to be $0.20 per 1,000 gallons. Electricity for the electrodes is based on the 0.14 g/kW-h hexavalent chromium removal efficiency calculated for Test 13. Based on information provided by the developer, electricity for the chillers is estimated to equal the electricity required for the electrodes, and electricity for the control equipment is estimated to be one-quarter of the electricity required for the electrodes. Electricity costs are based on an assumed removal efficiency of 85 percent and electricity rates of $0.05/kW-h.

3.3.8 Effluent Treatment and Disposal Costs

Anode effluent requires effluent treatment and disposal. For this cost estimate, it is assumed that the effluent disposal cost (including transportation) is $185 per 55-gallon drum. Effluent volumes generated are based on the average volume of anode effluent generated during Test 13 (approximately 6 gallons per day).

3.3.9 Residuals and Waste Shipping, Handling, and Transport Costs

It is assumed that the only residuals or solid wastes generated from use of the ISEE system will be drill cuttings and used PPE and small equipment. The disposal cost (including transportation) for solid waste is estimated at $260 per 55-gallon drum. If the solid waste is not classified as hexavalent chromium-contaminated, the disposal cost may be less. For this cost estimate, it is estimated that six 55-gallon drums of drill cuttings and one 55-gallon drum of used PPE and small equipment will be generated for removing 200 g of hexavalent chromium.

3.3.10 Analytical Costs

Only spot checks executed at the developer's discretion (to estimate hexavalent chromium concentrations in the anolyte and to verify that the ISEE system is functioning properly) are included in this cost estimate. The client may elect or may be required by local authorities to initiate a planned sampling and analytical program at the client's expense. The cost for the developer's spot checks is estimated at $5 per sample for field analysis. For the purposes of this cost estimate, it is assumed that one sample per week per anode will be field analyzed. Labor costs for collection of samples, field analysis of samples, and evaluation of field data are included under labor costs.

The analytical costs associated with environmental monitoring are not included in this estimate because monitoring programs are not typically initiated by the developer. Local authorities may, however, impose specific sampling and monitoring requirements; therefore analytical costs could contribute significantly to the cost of the project.

3.3.11 Facility Modification, Repair, and Replacement Costs

System maintenance costs are assumed to consist of maintenance labor and materials. Maintenance costs are limited to supplies and labor. Maintenance supplies are included under supplies and consumables costs. Maintenance labor costs are included as operating labor under labor costs. As stated above, the developer plans to significantly redesign the ISEE technology for full-scale remediation. Therefore, no facility modification costs are included for the ISEE demonstration system used for this cost estimate. Future cost analysis of the commercialized ISEE system should include site modification costs, and these costs would be more indicative of site modification costs for the ISEE system.

3.3.12 Site Restoration Costs

Site restoration requirements vary depending on the future use of the site and are assumed to be the obligation of the responsible party or site owner. Therefore, the only site restoration costs included are for technology-specific site restoration, including demobilization of ISEE system equipment and grouting the electrode boreholes. The developer estimates that technology-specific site restoration costs will be limited $1,500 for demobilizing the ISEE system equipment and $750 for grouting the boreholes.

3.4 Conclusions

Because the treatment volume is only 16 yd^3 and the ISEE system configuration used during Test 13 is currently at the pilot-scale level, the cost per yd^3 of treated soil is very high; the estimated treatment costs are about $1,400 per yd^3 for 200 g of hexavalent chromium removed. If SNL is able to further optimize the ISEE system configuration so that hexavalent chromium removal rate increases from that calculated for Test 13, treatment time and costs will be lower. As mentioned above, costs from economic analysis of a full-scale ISEE system would be more indicative of costs of a commercial-scale ISEE system.

Section 4
Technology Status

The SNL ISEE system SITE demonstration has shown that in situ remediation of chromate-contaminated, unsaturated sandy soil at the field scale is possible. Vendor claims for the ISEE system technology are discussed in the appendix. Chromate ions were transported electrically through soil to anodes and then extracted to the soil surface. Furthermore, the ISEE system controlled water addition so that the net addition of water to soil was negligible during the demonstration.

The SNL ISEE system electrode lysimeters can treat soil having virtually any moisture content. Previous electrokinetic treatment methods are confined to saturated soil and clay near saturation. The ISEE system's porous ceramic casings contain contaminants in electrolyte fluid that can be pumped out and disposed of. Unlike traditional electrokinetic extraction systems that use groundwater wells, the ISEE system's lysimeter system controls the amount of water pumped out of the electrodes.

Presently, the ISEE system demonstrated at UCAP is housed in a portable semitrailer. This trailer houses the electrode controls, power supply system, and data collection system. the trailer can also serve as a portable laboratory for on-site analyses. Up to 10 electrode pairs can be powered using the configuration used during the SITE demonstration.

Data obtained from this demonstration allowed SNL to develop a three-phase, sequential approach to evaluate a potential site for electrokinetic remediation. During Phase 1, SNL will collect existing information and perform a preliminary assessment of the applicability of electrokinetic remediation to a site. If the site looks promising, Phase 2 will be conducted to further evaluate site soil and contaminants and to provide additional information for Phase 3. Phase 3 consists of design of the remediation system and calculation of the total costs of remediation.

Site information pertinent to electrokinetic remediation includes the following:

General information

- Contaminated area size and depth
- Utilities layout
- Depth to groundwater
- Soil type and moisture content profile

Chemical information

- Contaminant type
- Contaminant concentrations and distribution
- Pore water electrical conductivity
- Soil buffering capacity
- Sorption isotherm contours
- Concentration of other ions and their distribution

Other information

- Electrical conductivity distribution
- Electrical conductivity functionality with respect to moisture content
- Zeta potential measurements
- Surface geophysical surveys

Phase 2 would involve a bench-scale feasibility study to evaluate potential cleanup levels. Soil collected from the proposed site would be placed in electrokinetic plexiglass

cells with an electrode at each end. A constant current would be applied to each cell, and periodic measurements would be taken to evaluate contaminant movement as a function of applied current (in amperes) per hour. Overall removal efficiency and residual contaminant concentrations would then be calculated. Additional testing would also be conducted during Phase 2, such as chemical and electrical analysis of soil, if this information was not obtained during Phase 1.

During Phase 3, full-scale system design would be performed, and parameters such as electrode spacing, length of time for remediation, expected power requirements, and total cost of remediation could be determined.

Section 5
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Appendix A
Vendor's Claimsfor the Technology

The Superfund Innovative Technology Evaluation (SITE) demonstration of the In Situ Electrokinetic Extraction (ISEE) system developed by Sandia National Laboratories (SNL) confirms that electrokinetic extraction is a viable in situ remediation alternative for the removal of heavy metals from unsaturated soils. Electric current is applied to soil to be remediated, thereby causing soluble metals to migrate to an electrode where they are removed using the patented SNL technology. Advantages and innovative features of the ISEE system and the status of the electrokinetic technology are discussed below.

Advantages and Innovative Features

Advantages and innovative features of the ISEE system are as follows:

- Works in soil with low moisture content and effective in sandy and clayey soils
- Contaminant removed from unsaturated soil
- No net water addition to soil
- Soil remediated to less than toxicity characteristic leaching procedure (TCLP) limits
- Compatible with biodegradation remediation systems
- Can be used as a contaminant barrier under landfills
- Remaining soil not sterile when remediation completed

Electrokinetic Technology Status

Although electrokinetics was discovered by Reuss in 1809, it was not until the mid-1980s that the idea to remediate soil using electrokinetic technology appeared. Since 1985, numerous laboratory studies and small-scale tests have been conducted to further characterize electrokinetics. This emerging technology has the potential for removing heavy metals, radionuclides, and many organic species dissolved in pore water from contaminated soil. Presently, large field-scale demonstrations of electrokinetic technologies are being conducted in the United States.

Removal of many inorganic contaminants by electrokinetic remediation in saturated or near saturated soils has been documented in literature. Metal cations such as copper, zinc, chromium, iron, cobalt, nickel, arsenic, cadmium, lead, mercury, and uranium ions, as well as anions such as chloride, cyanide, nitrate, and sulfate, have been successfully removed from soil using electrokinetics. Although the focus of electrokinetics has been on inorganic contamination, organic contaminants such as polynuclear aromatic hydrocarbons have been also removed (EPRI 1994). No theoretical or technical reasons are documented to indicate that organic and inorganic contaminants cannot be removed using electrokinetic technology on unsaturated soils.

Recently, bench-scale studies of the use of citrate to remove uranium from unsaturated soils were conducted (SNL 1997). In unsaturated soil, uranium normally exists primarily as a cation in the +6 state as UO_2^{+2} because of prevailing oxidation conditions. In this oxidation state, the cation will readily sorb to soil. During the bench-scale studies, citrate was injected at the cathode electrode casing. The citrate electromigrated across the test cell and chemically interacted with the uranium cations to form the anionic complex $(UO_2Citrate)^{-2}$. This complex continued electromigration to the anode. The uranium complex was then extracted from soil through the electrode casings of the ISEE system.

It is important to note that the system evaluated during this SITE demonstration is an SNL research prototype system

and not a system that would be used for actual remediation. The SNL ISEE system used for electrokinetic remediation during the demonstration monitors many parameters necessary to evaluate electrokinetics. To conduct an actual remediation project, SNL's current research efforts have developed a low-maintenance extraction system that can operate unsupervised for long periods of time. This new system is to be implemented simply through initial setup, periodic inspection of system operation, and final dismantlement and removal of system equipment. Cost of remediation using the new system will be dramatically reduced because of the passive nature of its operation.

This SITE demonstration shows that electrokinetics is applicable to unsaturated sandy soil. Contaminants can be transported through soil pore water and collected and removed at the electrodes. By utilizing surfactants or complexents, electrokinetic remediation can be applied to many contaminants besides heavy metals.

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