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Cost and Performance Report
(ER-0112)

Electronically Induced Redox Barriers for Treatment of Groundwater

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COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
c-DCE	cis-dichloroethene
COTS	commercial off-the-shelf
CSU	Colorado State University
DC	direct current
DoD	Department of Defense
e-barrier	electrically induced redox barrier
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FRTR	Federal Remediation Technologies Roundtable
GC	gas chromatography
HDPE	high density polyethylene
ID	inner diameter
MCL	maximum contaminant level
NPV	net present value
O&M	operation and maintenance
PCD	Pueblo Chemical Depot
PQL	practical quantification limit
PRB	permeable reactive barrier
PVC	polyvinyl chloride
RAB	Remedial Action Board
RDX	hexahydro-trinitro-triazine
SERDP	Strategic Environmental Research and Development Program
TCA	trichloroethane
TCE	trichloroethene
t-DCE	trans-dichloroethene
TDS	total dissolved solid
TLV	Threshold Limit Value
TNT	trinitrotoluene

USACOE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
VC	vinyl chloride
VOC	volatile organic compound
WDEQ	Wyoming Department of Environmental Quality
ZVI PRB	zero valent iron permeable reactive barrier

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1.0 EXECUTIVE SUMMARY

This report summarizes results from a 3-year collaboration between the Environmental Security Technology Certification Program (ESTCP) and Colorado State University (CSU). Comprehensive documentation is presented in the Final Report for the project, Sale, et al. (2005). The focus is an innovative electrolytic approach for managing redox-sensitive contaminants in groundwater, referred to as electrically induced redox barrier (e-barriers). The overarching objective of the work is to demonstrate/validate a new technology for managing contaminated groundwater at the Department of Defense (DoD) facilities that holds promise in terms of efficacy and cost.

The premise underlying the technology is that closely spaced permeable electrodes can be installed through a groundwater contaminant plume in the format of a permeable reactive barrier. Application of low voltage direct current (DC) drives sequential oxidation and/or reduction of contaminants with the net benefit of reducing contaminant flux.

Primary factors motivating this demonstration/validation are:

- The potential for effective degradation of contaminants and reaction intermediates through sequential oxidation and reduction
- The potential to control accumulation of mineral precipitates via periodic reversal of electrode potentials
- Low operation and maintenance costs.

The demonstration/validation includes the following:

- Identification of an appropriate field site at F.E. Warren AFB, Wyoming
- Predesign laboratory studies
- Design and installation of a 17-m^2 demonstration barrier
- Performance monitoring over 18 months.

The site selected for the demonstration is a shallow alluvial plume containing approximately 300 µg/L of trichloroethene (TCE). The e-barrier was designed and fabricated at CSU in May through July 2002 and was installed at F.E. Warren Air Force Base (AFB) in August 2002. Following installation, the e-barrier was allowed to equilibrate with the contaminant in the plume for 5 months. Power was applied to the e-barrier in January 2003, and as of August 2004, the e-barrier has been operating continuously (approximately 19 months). As implemented, the e-barrier met the functional objective of the demonstration, and experience gained through the demonstration provides insight into avenues for optimization.

Electrical cost and performance is monitored continuously using a remote data acquisition system. Eighteen months of operation indicates that the electrical components are reliable and power costs low (an average of \$0.013/m^2/day).

Effects on water quality are defined using 144 sampling points located up and down gradient of the e-barrier. The primary efficacy-related result is sustained TCE flux reduction for 18 months. At the highest imposed potential (6.5 V), bulk TCE flux reduction of 90% is demonstrated. Data from the primary transect through the center of the e-barrier indicates TCE flux reduction of 95%.

In general, no adverse reaction intermediates were observed. An exception is the apparent formation of chloroform at the center of the e-barrier. Plausible explanations include highly toxic conditions developed at the e-barrier and/or unanticipated reactions with polyvinyl chloride (PVC) pipe cement that can be excluded from future systems.

Cost components associated with the demonstration e-barrier include:

- Capital expenses of $\$409/ft^2$ of intercepted plume
- Operation and maintenance (O&M) expense of $\$10/ft^2$/year.

Including opportunities for cost reduction and economies of scale, cost for full-scale systems are anticipated to be 25 to 50% lower than the demonstration cost. Using this assumption, a typical full-scale e-barrier will have capital and O&M costs similar to those of current proven technologies for TCE. On a site and/or contaminant specific basis, e-barrier technology may have advantages. Specifically, the e-barrier may have advantages for contaminants such as energetic compounds that can be difficult to treat with existing technologies.

Building on the potential for management of energetic compounds, complementary studies have been funded by the Strategic Environmental Research and Development Program (SERDP) and the U.S. Army Corps of Engineers (USACOE). Laboratory results indicate favorable reaction kinetics, high levels of flux reduction, and low power requirements. This has led to an initiative to apply the technology to energetic compounds in groundwater. To date, progress along this path includes:

- Identification of Pueblo Chemical Depot (PCD) as a promising demonstration location
- Completion of preliminary laboratory studies using site soils
- Secured funding for an hexahydro-trinitro-triazine (RDX) e-barrier demonstration at PCD.

Given success with a demonstration, there is an opportunity for a full-scale e-barrier that could replace an existing high-cost pump-and-treat system.

In summary, data presented in this report describes substantive progress in demonstrating a new technology for managing contaminated groundwater at DoD facilities. At present, it is not clear that either cost or efficacy results will drive near-term widespread use of the technology for chlorinated ethenes. On the other hand, the technology holds promise for energetic compounds in groundwater. Our hope is that success with energetic compounds will lead to further refinement and broad use of the technology.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The concept of an e-barrier is that a panel of closely spaced permeable electrodes is installed in a trench that intercepts a plume of contaminated groundwater. Application of an electrical potential to the electrodes imposes oxidizing conditions at the positive electrode and reducing conditions at the negative electrode. Using electrodes to deliver and recover electrons, thermodynamic conditions are shifted to drive transformation of target compounds to nontoxic products. A field-scale conceptualization of an e-barrier is illustrated in Figure 1.

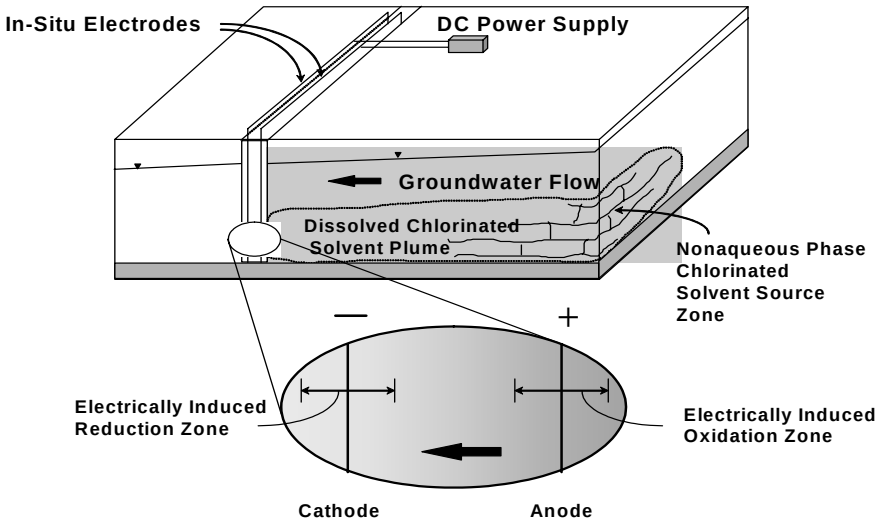

Figure 1. Conceptualization of a Field-Scale E-Barrier.

2.2 PREVIOUS TESTING OF THE TECHNOLOGY

Research into e-barriers has been underway at CSU since September 1998. A summary of projects and results is provided in Table 1.

Table 1. Summary of E-Barrier Research.

Sponsor	Period	Activities	Results To Date
Solvents-in-Groundwater Research Consortium	1998-present	Laboratory column and tank proof-of-concept experiments for chlorinated solvents, testing of panel materials, design/installation of a small prototype (CFB Borden), prototype operations, and monitoring (1/25/02-6/15/04)	Laboratory studies indicate efficacy for 1,1,1-trichloroethane (TCA), PCE, TCE; Titanium electrodes and HDPE spacers shown to be stable (>16 months); techniques for scale management demonstrated; successful installation of prototype; field results indicate potential to achieve flux reduction. Removal of e-barrier materials following 18 months of field testings indicates stability of construction materials.
United Technologies Corporation	2000-2002	Column proof-of-concept experiments for arsenic	Removal of arsenic via in situ precipitation, MCLs sustained in active column effluent after 14 months of operation. Titanium-mmo electrodes stable after 14 months of operation .
National Science Foundation	2000-2002	Enhanced biological attenuation of contaminants via electrolytic manipulation of redox conditions	Laboratory methods developed to test electrolytic enhanced biodegradation. Results inconclusive due to difficulties in sustaining anaerobes in column studies.
ESTCP	2001-present	17m^2 field demonstration and validation of an electrolytic reactive barrier	Described herein.
SERDP	2002 - 2004	Electrolytic batch reactor experiments for RDX, HMX, TNT and DNT. Flow-through reactor experiments for TNT and RDX	High fractional transformation of energetic compounds observed in laboratory column experiments. Minimal formation of detrimental intermediates observed. Preliminary work on reaction pathways.
USACOE	2003-present	The influence of pH on electrolytic transformation of dissolved energetic compounds	Results indicate that alkaline conditions developed at the cathode surface are not a necessary mechanism for electrolytic transformation of dissolved TNT or RDX.

2.3 FACTORS AFFECTING COST AND PERFORMANCE

Based on this demonstration, primary cost categories associated with the e-barrier include capital expenditure (96.5% of total) and O&M (3.5% of total). Primary capital costs include e-barrier installation (29.7%), electrode materials (15.5%), and labor for panel fabrication (9%). Total observed capital and O&M costs, normalized to the cross-sectional area of the e-barrier, are \$409/ft^2/year and \$10/ft^2/year, respectively. Accounting for economies of scale, promising design modifications, and opportunities to use lower cost installation techniques (e.g., biopolymer slurry trench) costs for full-scale systems are anticipated to be 25 to 50% lower than the demonstration costs. Opportunities for cost reduction are described in detail in Section 5.2.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Promising aspects of e-barrier technology include:

- The method is environmentally benign in that no chemicals are introduced.
- Electrical power costs associated with driving transformations are low (total power cost for the $17m^2$ barrier over 18 months is $110).
- Rates of chemical transformation can be modified remotely by adjusting applied voltage.
- The electrode potentials can be reversed or shifted to remove inorganic precipitates (e.g., $CaCO_3$ scale a common constraint of other technologies).
- Sequential oxidation and reduction has the potential to degrade a wide range of contaminants, including mixtures that are difficult to address with current technologies.

Observed limitations include:

- Deep installation of an e-barrier would be challenging. In general, shallow applications are the most feasible from a construction perspective.
- In waters containing high total dissolved solids (TDS), scale formation may challenge performance.
- Costs observed in this project are similar to cost for proven technologies that fill similar niches. The potential for an e-barrier to provide significant cost savings, relative to a zero valent iron permeable reactive barrier (ZVI PRB) for chlorinated solvent plumes, will require technology improvement.
- Demonstrated flux reductions on the order of 90 to 95% may be insufficient to achieve groundwater concentrations that meet regulatory compliance at many sites.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary objective of the demonstration is to resolve whether e-barriers are a viable option for managing plumes of chlorinated solvents (and potentially other contaminants) at DoD sites. Primary performance metrics are contaminant flux reduction and cost.

3.2 SELECTION OF TEST SITE

The location selected for the field demonstration is F.E. Warren AFB near Cheyenne, Wyoming. The primary mission of F.E. Warren is maintenance of Peacekeeper missiles. The selection of F.E. Warren reflected favorable geologic conditions, presence of the desired target compound, and proximity to Colorado State University.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

F.E. Warren is a 7,000-acre facility underlain by shallow eolian and fluvial deposits. The Ogallala Formation underlies the alluvium. Locally, the Ogallala Formation consists of interbedded gravel, sand, and silt with varying clay content and cementation. Through historical maintenance and disposal activities, chlorinated solvents (primarily TCE) have been inadvertently released to the subsurface. Figure 2 presents the major features at F.E. Warren, plumes of TCE in groundwater, and the location selected for the e-barrier demonstration.

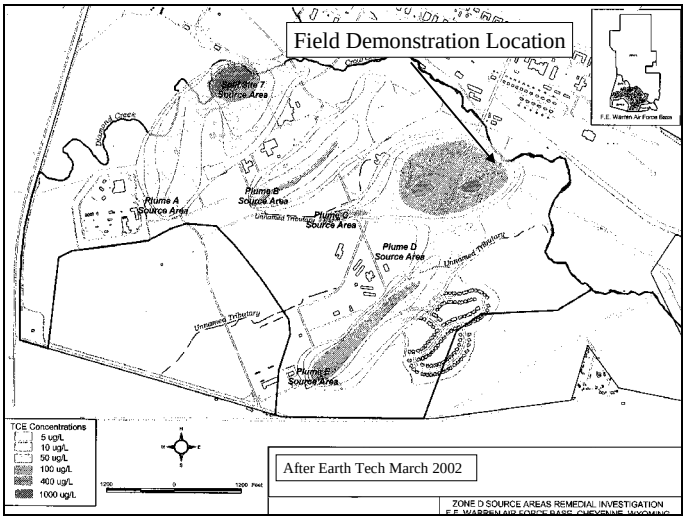

Figure 2. F.E. Warren Base Map Showing TCE Plumes and Demonstration Location.

In 2001, sites at F.E. Warren AFB were screened as potential locations for the field demonstration. Figure 3 presents a photo of the selected location (MW038) prior to e-barrier installation. Selection criteria included the presence of target compounds, shallow groundwater, and compatibility with base operations. Verification of site characteristics, definition of baseline

conditions, and acquisition of design data was accomplished by installing a local network of five monitoring wells and quarterly monitoring of water quality and water table elevation for 1 year.

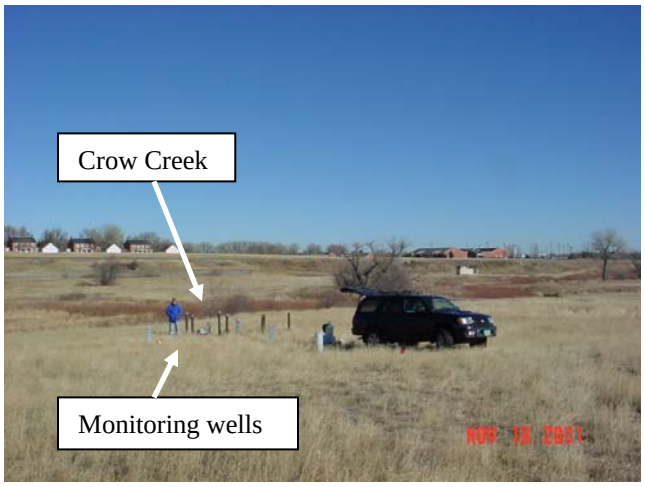

Figure 3. Photo of MW-038 Site Looking Northwest Across Crow Creek.

Primary site attributes include:

- Background TCE concentration of approximately 300 µg/L
- Depth to groundwater approximately 12 ft (below grade)
- Groundwater seepage velocity of 0.37 ft/day
- A calcium carbonate type water with total dissolved solids of ~660 mg/L.

Figure 4 presents a geologic cross section depicting conditions along the installed e-barrier alignment.

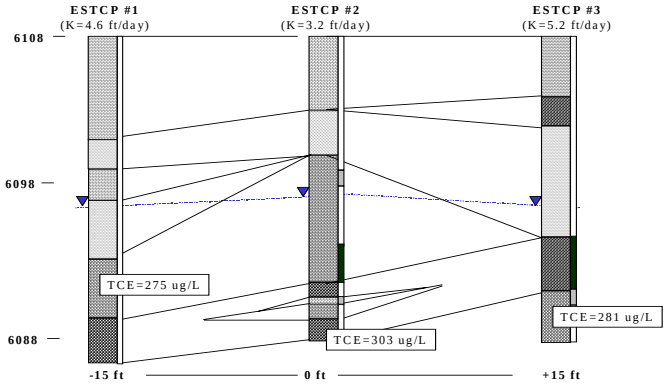

Figure 4. Geologic Cross Section Along the E-Barrier Alignment.

Patterns in the stratigraphic columns reflect dominant grain size in bedding (silt to coarse sand). Vertical bars adjacent to the columns depict cementation (white=poorly cemented; black=well-cemented).

3.4 PHYSICAL SETUP AND OPERATION

The demonstration e-barrier consists of 17 individual panels each 0.3m x 2m (Figure 5). Concentric interlocks link individual panels. The overall as-built dimension of the demonstration e-barrier was 9.2 m x 1.9 m. The effective cross-sectional area is 17 m^2. Each panel contains three Ti-mmo electrodes (ELTECH Systems, Chardon, Ohio), four layers of Geotextile™, and six layers of Triplanar Geonet™ (Figure 6).

The electrodes are expanded metal with the form of a heavy screen. They are commercially available with the most common application being dimensionally stable anodes for cathodic protection systems. Panels are framed in slotted 3-in inner diameter (ID) PVC pipe. The Geotextile™ and Triplanar Geonet™ are commercially available geotechnical products (TENAX Corporation, Baltimore, Maryland). Each e-barrier module includes discrete electrical connection, gas vents, and washout tubing that are conveyed to the surface via 3-in PVC riser pipes.

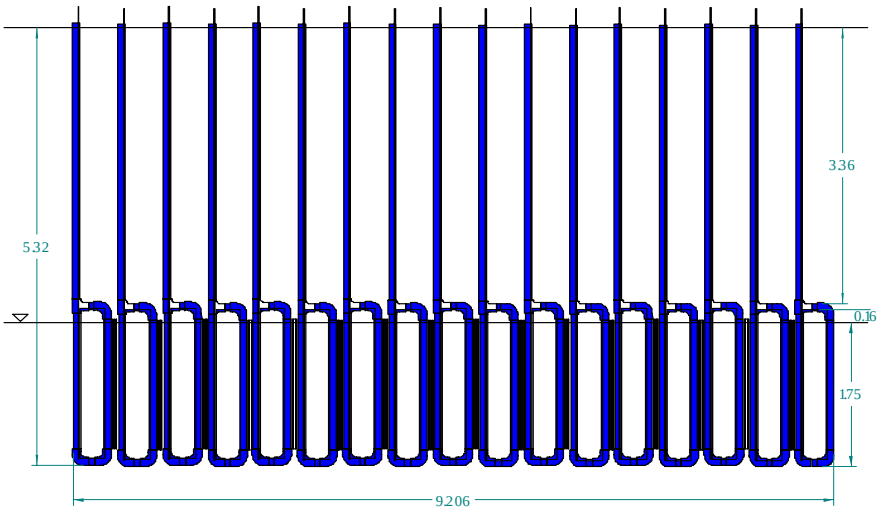

Figure 5. Cross Section of Demonstration E-Barrier Design Indicating 17 Individual Modules (dimensions in meters).

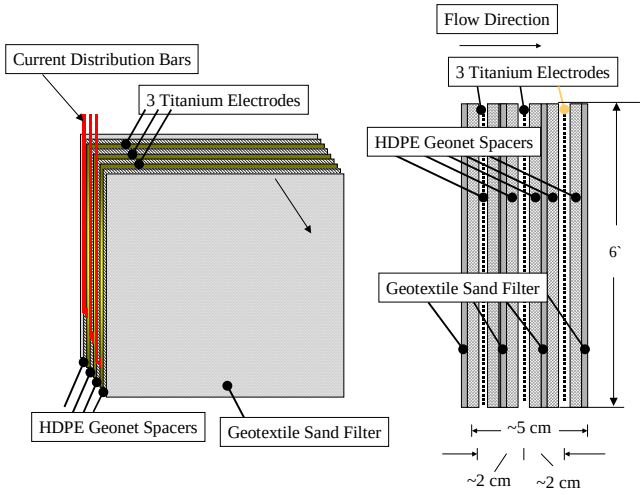

Figure 6. Detail of Composite E-Barrier Panels.

The demonstration e-barrier was installed August 27-28, 2002. The excavation was completed using an excavator and trench box. The assembled e-barrier was installed in two sections. Figure 7 illustrates nine of the 17 e-barrier panels being installed.

Figure 7. Placement of Nine Linked E-Barrier Panels into the Trench.

Washed granular backfill from the Crow Creek alluvium was placed about the e-barrier to an elevation ~ 1 ft above the barrier. Electrical connections, washouts, and the multilevel sampling system were routed to grade via 3-in PVC risers. Sediments from the initial excavation were used to close the excavation. Backfill and near surface connections are illustrated in Figure 8.

Figure 8. Backfill and Shallow Completion.

Electrodes in individual module panels were connected in parallel, and all wiring was placed below grade in PVC conduit. Power was supplied by a 30V DC 200 amp single-phase rectifier (Corrpro Companies, Medina, Ohio). The rectifier was connected to a 110V AC 60 amp electrical service. The final completion of the demonstration e-barrier is presented in Figure 9.

Figure 9. Final Grade Showing Sampling Shelter and Rectifier.

3.5 SAMPLING/MONITORING PROCEDURES

Performance monitoring includes electrical and water quality parameters. Water quality monitoring is achieved using 144 groundwater-sampling points located about the e-barrier. Figure 10 illustrates the position of sampling points in cross section and plan view. Each sampling point is constructed of 0.5mm ID Teflon tubing with a Nytex™ screen. Multiple sampling points are bundled to form a multilevel sampling device, and samples are drawn using a peristaltic pump. Multilevel sampling bundles are placed on the e-barrier surfaces and 0.5m up and 0.5m down gradient of the e-barrier (on centering guides) along seven transects. These sampling points were installed in conjunction with the e-barrier. Eight additional multilevel sampling bundles were placed in the formation at the ends of the e-barrier and at positions 1m and 2m up and down gradient of the e-barrier.

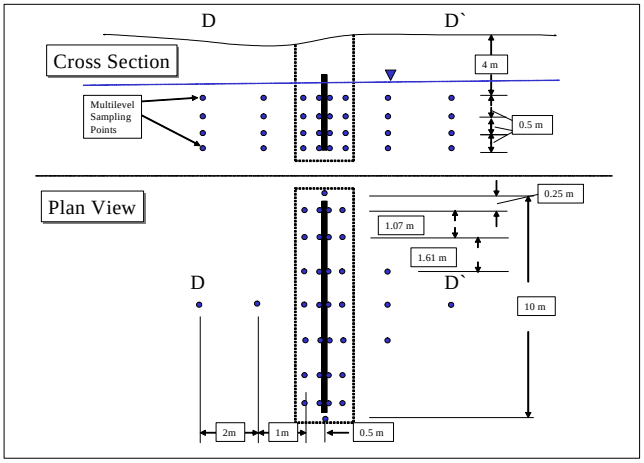

Figure 10. Monitoring Network Including Multilevel Bundles and Sampling Points.

Electrical parameters are monitored using an eight-channel data recorder with wireless modem (Rohrback Cosasco Systems, Santa Fe Springs, California). The system records applied voltage, resultant current, and electrode potential relative to the reference electrodes on the surface of the e-barrier. Data is recorded on 15-minute intervals and downloaded via a wireless connection on a weekly basis.

3.6 ANALYTICAL PROCEDURES

The e-barrier demonstration involved imposing a fixed potential between the electrodes and measuring the electrical and water quality responses. Table 2 presents an operation schedule and Table 3 a summary of analytical procedures by parameter.

Table 2. Applied Potential Differences and Corresponding Time Periods for the E-Barrier Demonstration.

Start Day/End Day	Total Number of Days	Applied Potential Difference
Pre-startup	151	0
0/120	120	3.1 V
121/290	169	6.5 V
291/399	108	4.9 V
400/500	100	3.1 V

Table 3. Summary of Analytical Methods.

Parameter	Method	Detection Limit or Accuracy	Notes
Water levels	Electronic water level meter (e.g., Solinst ™ 101)	± 0.01 ft	
pH	Environmental Protection Agency (EPA) Method 150.1 - Denver Instruments AP25 and glass combination electrode (Ag/AgCl reference)	± 0.01 pH units	
Temperature	Denver Instruments AP25 and glass combination electrode (Ag/AgCl reference)	± 0.1°C	
Eh	Denver Instruments AP25 and platinum combination electrode (Ag/AgCl reference)	± 0.1 mV	Correction to standard hydrogen electrode conducted during data analysis for Eh measurements
Specific conductivity	Orion 130 conductivity meter and cell	± 1 uS/cm	
Voltage	Cordcom datalogger	± 0.001 V	
Amperage	Cordcom datalogger	± 0.01 mA	
Electrode potential	Ag/AgCl reference cells, Cordcom datalogger	± 0.001 V	
TCE and degradation products (c-1,2-DCE, t-1,2-DCE, 1,1-DCE, and vinyl chloride (VC)	EPA Method 502.2—analytical instrumentation consists of a Hewlett Packard 5890 Gas Chromatograph and Electron Capture Detector.	Reported detection limit of 0.02 µg/L. Practical quantification limit (PQL) determined through instrument calibration.	No expected complications associated with the sample matrix
Aluminum, arsenic, barium, cadmium, chromium, copper, iron, manganese, nickel, zinc	EPA Method 6010—Jarrell Ash Inductively Coupled Plasma-Atomic Emission Spectroscopy	Reported detection limit of 50 µg/L. PQL determined through instrument calibration	Chemical interference not anticipated, given available data from the F.E. Warren AFB
F^-, Cl^-, NO_3^-, NO_2^-, SO_4^{-2}, PO_4^{-3}	EPA Method 300.0 Analytical Instrumentation consists of a Dionex Ion Chromatograph	Reported detection limit of > 0.3 mg/L. PQL determined through instrument calibration	
Alkalinity	EPA Method 310.1 Titration to a pH of 4.5	1 mg/L	
Evolved gas	Fixed gases standard methods 2770C GC/TCD chlorinated volatile organic compounds (VOC) EPA TO-14 gas chromatography (GC)/MS	0.5% 1000 ppbv	Commercial analysis

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4.0 PERFORMANCE ASSESSMENT

This section summarizes performance of the demonstration e-barrier. Comprehensive analysis of this topic is presented in the Final Report for the project, Sale et al. (2005). Per ESTCP (2004), topics addressed include performance data, performance criteria, data assessment, and technology comparison.

4.1 PERFORMANCE DATA

The primary effect of the e-barrier is shifts in thermodynamic conditions (pe and pH) in the vicinity of the electrodes. This drives oxidation and/or reduction of the dissolved contaminants. Figure 11 presents conditions observed along the central transect of the e-barrier as a function of imposed electrical potentials. As expected, the overall affect of the e-barrier is oxidation followed by reduction (see Figure 11 A). Effects on pH are small. Local to the e-barrier, the groundwater becomes more acidic (~ 1 pH unit). Limited change in pH is attributed to carbonate buffering.

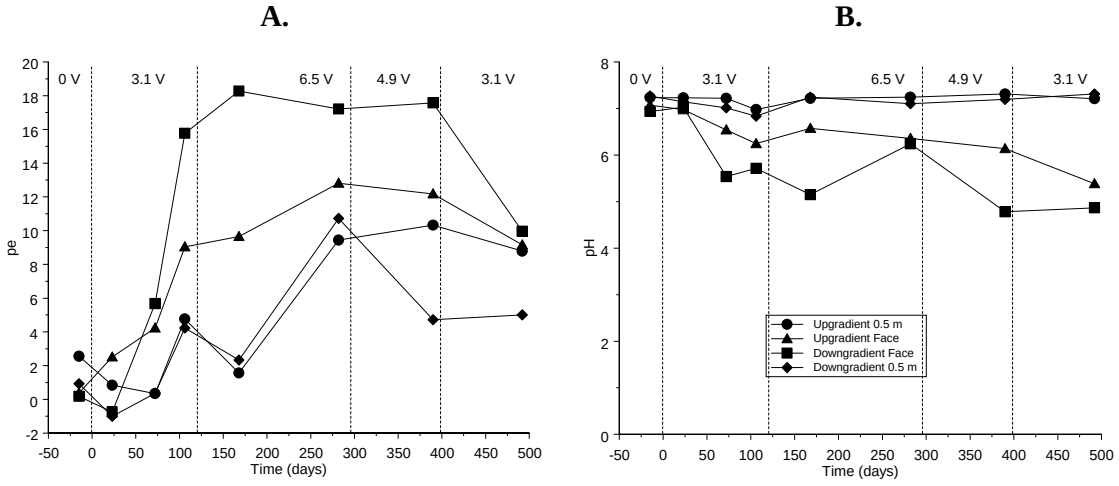

Figure 11. pe (A) and pH (B) Measured Along a Transect Parallel to Flow at the E-Barrier Midpoint. Measurements are averaged from readings taken 0.5m upgradient of the barrier (circles), upgradient face of the barrier (triangles), downgradient face of the barrier (boxes), and 0.5m downgradient of the barrier (diamonds). Power was applied to the e-barrier at day 0.

Resultant effects on TCE concentrations are presented in Figure 12. On day 290 at the highest applied potential, a 95% reduction in TCE concentration is seen between 0.5m up and the down gradient face of the e-barrier. TCE concentrations 0.5m downgradient of the e-barrier are slightly higher than those at the downgradient face of the e-barrier. Plausible explanations for this include desorption of contaminants from the matrix and/or flow of contaminants around or through joints in the e-barrier.

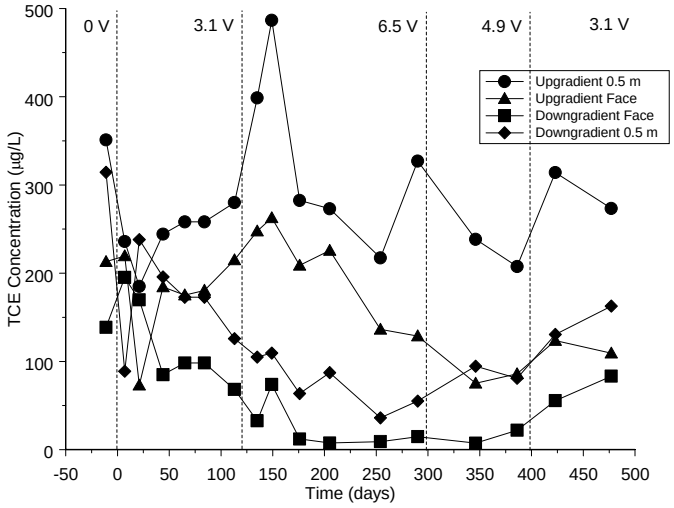

Figure 12. Average TCE Concentrations Along a Transect Parallel to Groundwater Flow at the E-Barrier Midpoint.
Values are arranged from 0.5m upgradient of the e-barrier (circles), upgradient face of the e-barrier (triangles), downgradient face of the e-barrier (boxes), and 0.5m downgradient of the e-barrier (diamonds). Power was applied to the e-barrier at day 0, E_{appl} values are denoted in the corresponding time periods.

The spatial distribution of TCE is depicted in cross section in Figure 13. This data illustrates the same trends described in association with Figure 12.

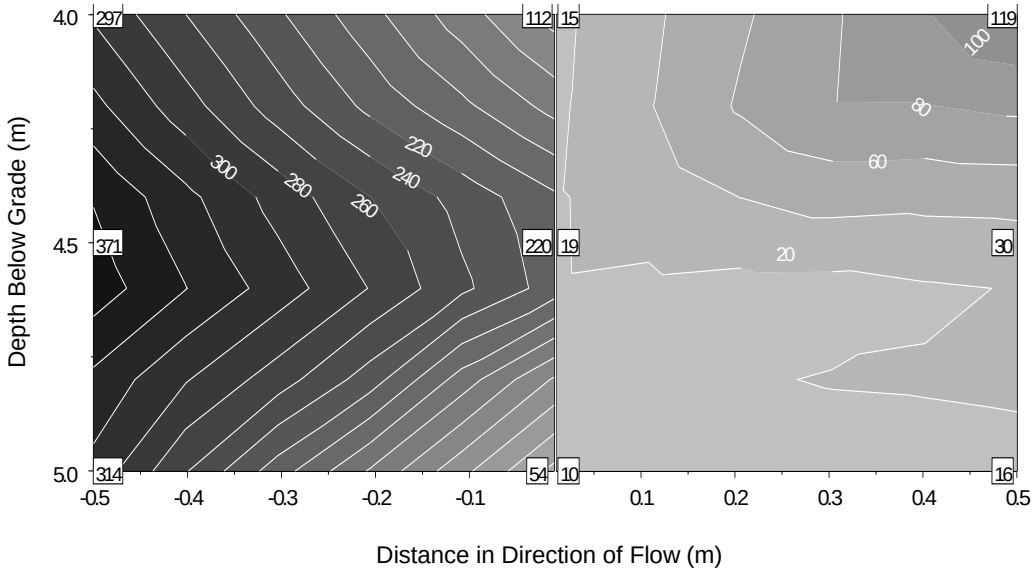

Figure 13. TCE Concentrations in Cross Section Along a Plane Parallel to Groundwater Flow Through the Midpoint of the E-Barrier (on day 290, 6.5 V).
Positive distances are downgradient and the e-barrier is at the 0 m position.
TCE concentration is reported in µg/L.

Concentrations of 1,2 cis-dichloroethene (c-DCE); 1,2 trans-dichloroethene (t-DCE); and VC were also evaluated. Of these compounds, only c-DCE was observed. The spatial distribution of c-DCE is depicted in cross section in Figure 14. Object A in Figure 14 indicates an apparent increase in c-DCE downgradient of the e-barrier prior to operation of the e-barrier. This may be due to a catalytic effect between the electrode coating (iridium oxides) and the TCE. After energizing the e-barrier (object B in Figure 14), c-DCE production associated with the degradation of TCE was not observed.

Additionally, inorganic compounds were characterized during the demonstration. Operation of the e-barrier had no apparent impact on mobility of inorganic constituents. Chloroform was apparently generated along the primary transect at 6.5V. Available data suggests this may be related to unanticipated reactions with PVC pipe cement that can be excluded from future systems.

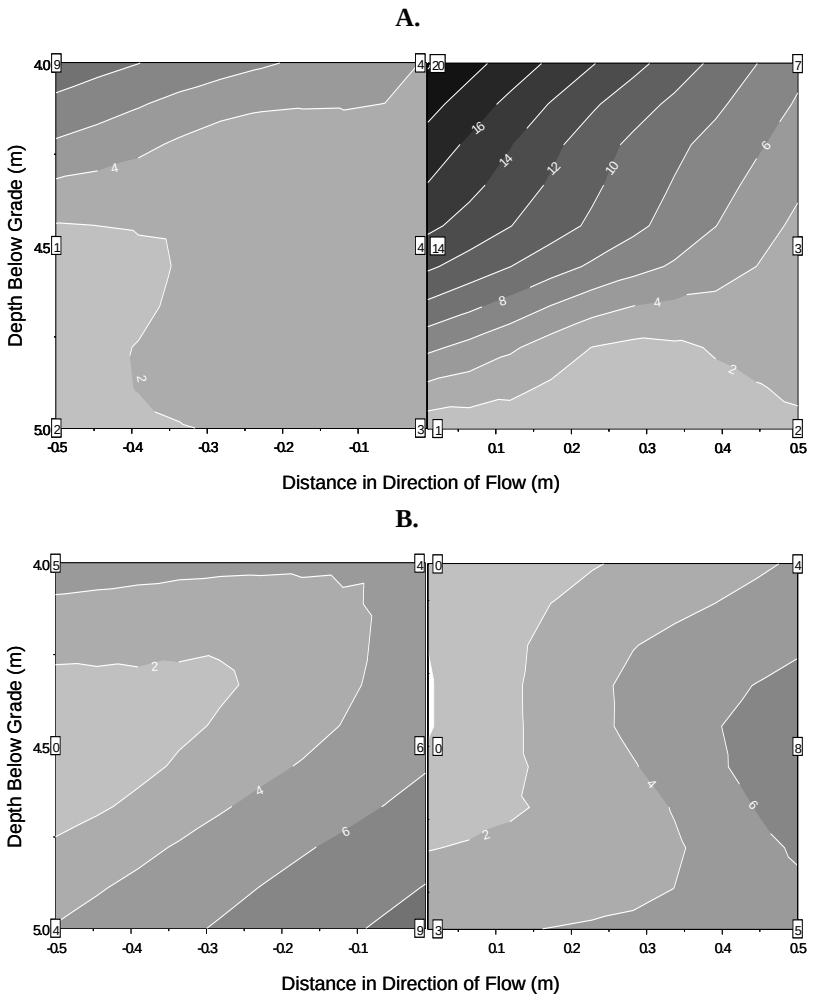

Figure 14. c-1,2-DCE Concentration Plots Along the Transect, Parallel to Groundwater Flow, Through the Midpoint of the Barrier at Day 11 (A) and Day 83 (B).
The e-barrier is located at 0 m, and concentrations are reported in µg/L.

Figure 15 presents current density as a function of imposed potential and time. Periodic spikes in the data reflect electrode polarity switching to manage scale formation. The overall steady current densities suggest the scale control approach was effective. Multiplying the current density by the imposed potentials indicate power requirements in the range of 3 to 30 watts/m^2. Considering the base's power cost of $0.05/kW-hour, this equates to energy costs of $0.004 to $0.04 per m^2/day. The total power cost during the 18 months of operation is approximately $110 or an average of $0.013/$m^2$ day.

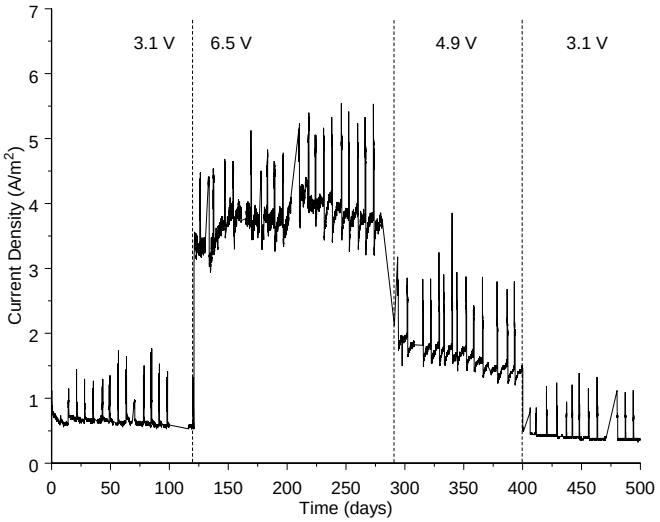

Figure 15. System Current Normalized to the Total Wetted Electrode Area.

4.2 PERFORMANCE CRITERIA

The criteria used to evaluate the performance of the e-barrier are listed in Table 4. The table lists performance criteria, performance metrics, confirmation methods, and actual performance. An explanation of confirmation methods is included in the Demonstration Plan (Sale and Gilbert, 2002).

Table 4. Demonstration Performance Criteria.

Performance Criteria	Expected Performance Metric (Pre Demo)	Performance Confirmation Method	Actual (Post Demo)
Primary Criteria (Quantitative)			
TCE mineralization	Decreased groundwater TCE concentration downgradient of barrier	Sampling and analysis of water samples	Reduced TCE mass flux and lowered concentrations at downstream location to levels near the MCL
Hazardous materials	Concentrations of reaction intermediates less than maximum contaminant level (MCL)	Sampling and analysis of water samples	Only c-1,2-DCE observed; levels decreased after power was applied
Factors affecting technology performance	Carbonate precipitates minimal	Current density and downgradient concentrations as a function of time, excavations and inspection at time of decommissioning	Treatment efficiencies and current densities suggest this was not a significant problem over the period of operations
Primary Criteria (Qualitative)			
Ease of use	Operator training limited	Experience from demonstration operation	Operations simple, minimal special training
Versatility	Suitable for a wide range of contaminants in shallow alluvium	TCE concentration measurements and field installation experience	Effective for TCE in shallow alluvium
Maintenance	Gas venting requirements and precipitate management inspection	Experience from demonstration and operation	Nominal level of effort required for system maintenance
Secondary Criteria			
Contaminant mobility	Minor changes in pH and inorganic water quality	Sampling and analysis of water samples to evaluate water quality	Redox conditions affected, but no species mobilized
Process waste	Low gas generation rates, minimal impact of secondary reactions	Observation	No adverse gas emissions observed, chloroform production observed
Reliability	Power loss to the barrier would result in disruption	Datalogger monitoring of applied potential difference will identify power loss to the barrier	Minimal power loss and no effect on performance
Scale-up constraints	Ease of construction	Experience from demonstration installation	Modular design allows expansion, opportunities for improvement exist

4.3 DATA ASSESSMENT

4.3.1 Performance

The primary niche for e-barriers is reducing contaminant flux in plumes. The TCE concentration data illustrates 90-95% reduction in contaminant concentrations. Assuming uniform flow, this correlated to 90 to 95% reductions in contaminant flux. The homogeneous backfill used during installation minimizes flow heterogeneity immediately upgradient and downgradient of the e-barrier, minimizing the error associated with use of this assumption. No major obstacles to implementation or sustainability were identified.

4.3.2 Regulatory Standards Attained

A concern at some sites may be an ability to achieve state and federal MCLs at the downgradient side of the e-barrier. The typical target of 5 μg/L was attained at only a few of the downgradient face monitoring points. Levels of c-1,2-DCE, the only degradation intermediate detected, were below the EPA MCL of 70 μg/L throughout the demonstration.

4.3.3 Personnel Training/Requirements

A minimum amount of specialized training was required. This is attributed to the overall simplicity of the system.

4.3.4 Health and Safety Requirements

No major health or safety issues were identified during the design, installation, and operation of the e-barrier. The formation of chloroform at high anode potentials poses a potential health and safety concern since concentrations may be in excess of standards for total disinfection byproducts. Chloroform formation can be minimized, as discussed in Section 6.3.

4.3.5 Ease of Operation

The effort required to operate the e-barrier was minimal. The only routine activities were switching the polarity of the electrodes and downloading data from the remote data acquisition system. These activities could easily be automated in full-scale systems.

4.3.6 Limitations

As deployed, the primary limitations of the technology are seen as insufficient flux reduction at some sites and uncertainties regarding the long-term sustainability of operations. Areas for additional study, identified through the demonstration, include advanced panel/barrier designs and a need for extended operations.

4.4 TECHNOLOGY COMPARISON

Technologies that achieve similar results as the e-barrier are ZVI PRBs and hydraulic containment systems (pump and treat). For shallow plumes (where e-barriers could be applied)

ZVI PRBs are often more effective than pump-and-treat systems. As such, the bench mark for analysis of e-barriers for chlorinated ethenes is ZVI PRBs. In general, the data presented herein does not support e-barriers being more effective than ZVI PRBs for chlorinated ethenes. Specifically, performance data collected from ZVI PRBs suggests that more than 99% reduction in contaminant concentration may be achieved at some sites (FRTR, 2002). In addition, costs associated with ZVI PRBs are similar to those expected for a full-scale e-barrier application (see Section 5.2). Given similar cost, the higher concentration reduction typically reported for ZVI PRBs compared to the e-barrier demonstration makes ZVI PRBs more competitive for many applications involving chlorinated ethenes.

Further refinement of the technology would likely be needed for e-barriers to compete successfully in terms of efficacy and cost for chlorinated ethenes at many sites. Specific refinements that would allow e-barriers to be competitive with ZVI PRBs for treatment of chlorinated ethenes include:

- addition of fourth electrode
- automation of polarity reversals
- minimizing the number of geonet layers in the barrier
- improved installation methods
- elimination of washout tubing and other unnecessary components
- improvements to the power supply
- alternative electrode materials.

Details regarding each of these potential refinements are included in Section 5.2.

On the other hand, ZVI PRBs and pump and treat are not effective for all contaminants. A primary area of opportunity for e-barriers is energetic compounds in groundwater. Building on this application, SERDP and USACOE have funded research to evaluate the application of e-barrier technology to dissolved 2,4,6-trinitrotoluene (TNT) and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX). Laboratory results indicate favorable reaction kinetics, high levels of flux reduction, and low power requirements. This has led to an initiative to apply the technology to plumes of energetic compounds in groundwater. To date, progress along this path includes:

- Identification of PCD as a promising demonstration location
- Completion of preliminary laboratory studies using site soils
- Secured funding for an RDX e-barrier demonstration at PCD.

Given success with a demonstration, there is an opportunity for a full-scale e-barrier that could replace an existing high cost pump-and-treat system.

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5.0 COST ASSESSMENT

The following section presents a cost assessment for the e-barrier field demonstration. Formatting and content of this section follows the recommendation of the Federal Remediation Technologies Roundtable (FRTR) as described in EPA (1988) and cost metrics for permeable reactive barriers (PRB) reported in EPA (2002).

5.1 COST REPORTING

Table 5 presents primary costs associated with design, construction, operation, and maintenance of the demonstration e-barrier. Detailed description of each item is presented in the Final Report for the project, Sale et al. (2005). With the following exceptions, all costs in Table 5 reflect actual cost incurred in design, fabrication, installation, and operation of the e-barrier:

- cost for design and oversight during construction are assumed to be 5% of total capital costs
- current plans are to decommission the barrier in August 2005. It is assumed this will involve removal of all elements to a depth of 3 ft below grade at a cost of $3,000
- monitoring of the in situ performance of the barrier and interpreting related data is based on the assumptions of annual sampling/reporting for two wells up and downgradient per 100 ft of barrier length, given a 10 ft saturated thickness, at a cost of $3,500/well/year. Actual costs for the demonstration/validation project are in excess of what would be required in an actual field application.

5.2 COST ANALYSIS

Cost Drivers—Building on Table 5, 96.5% of the total cost is attributed to design and construction. The remaining 3.5 % of the total cost is attributable to operations and maintenance. Primary cost components include barrier installation (29.7%), electrodes (15.5%), and labor for panel fabrication (9%). Reflecting the demonstration status of the project, small-scale, and "first time experience" with many project aspects, reported costs are likely higher than those that would be incurred in a full-scale application.

Cost Comparison—Common metrics for evaluating permeable reactive barriers is cost per unit cross section of plume intercepted and cost per 1,000 gallons treated (EPA 2002). Costs are not normalized to the mass of contaminant removed. This reflects the fact that e-barriers are not viewed as a means of reducing contaminant mass. Their intended niche is reducing contaminant flux.

Table 5. Cost Tracking

Cost Category	Sub Category	Comments	Cost ($)	% ff Capital + O&M Costs
Capital cost	Design investigations	Hydrogeologic and geotechnical data	3,829	4.9%
	Electrodes	Elgard titanium mesh with mixed metal oxide coating	12,000	15.5%
	Rectifier	CorrPro DC power supply	3,720	4.8%
	PVC pipe	Panel framing	1,919	2.5%
	Geonet	Electrode spacing/cover material	1,608	2.1%
	Data logger/and cell connection	Logs total voltage and allows remote data acquisition	3180	4.1%
	Reference electrodes	(6) Ag/AgCl reference electrodes	600	0.8%
	Miscellaneous e-barrier hardware	Wiring, electrical relays, conduit, fitting, monitoring systems	4,033	5.2%
	Labor for e-barrier panel fabrication	Cutting materials and assembly	6,973	9.0%
	Barrier installation	Contractor cost for installation	23,038	29.7%
	Utilities	Installation of conduits for power under a road	2,275	2.9%
	Drilling	Installation of groundwater sampling systems	1,882	2.4%
	Decommissioning of the e-barrier	Assumed cost for removal of all elements to a depth of 3 ft below grade (to be completed 8/05)	3,000	3.9%
	Design	Engineering design services estimated @ 5% of startup and capital cost	2,703	4.5%
	Construction oversight	Engineering field services estimated @ 5% of startup and capital cost	2,703	4.5%
	Design and construction cost subtotal		**$74,863**	**96.5%**
Operating costs	Electrical power	2,240 kW-hours over 500 days @ $0.05/kW-hour	112	0.1%
	Remote monitoring and electrode reversals	0.5 – hour/ week @ $17/hour over 71 weeks	603	0.8%
	Performance monitoring	Assumes annual sampling/reporting for two wells up and downgradient per 100 ft of barrier length, given a 10-ft saturated thickness, at a cost of $3,500/well/year	1,811	2.4
	Cell phone	$10.28/month for 17 months	175	0.2%
	Operating cost subtotal		**$2,701**	**3.5%**
Total cost for design, construction, operations, and maintenance			**$77,565**	**100%**

Table 6 presents capital costs on the basis of ft^2 of intercepted plume. The unit cost for design and construction is $\$409/ft^2$. The unit cost for O&M is $\$10/ft^2$/year. For comparison purposes, Table 7 lists capital costs and 1-year O&M costs for full-scale continuous ZVI PRBs reported in EPA (2002).

Table 6. Unit Cost for E-Barrier Components.

Category	Cost ($)/Ft^2
Barrier installation	125.89
Electrodes	65.57
Panel fabrication	38.10
Miscellaneous barrier components subtotal	22.04
Hydrogeologic investigation	20.93
Rectifier	20.33
Design (5% of construction)	18.60
Construction oversight (5% of construction)	18.60
Data logger	17.38
Demobilization	16.39
Utility conduits	12.43
PVC pipe frame	10.49
Drilling for monitoring points	10.29
Geonet	8.79
Reference electrodes	3.28
Subtotal - Design and Construction Costs	**$409.11**
Performance monitoring (annual basis) – Assumes annual sampling/reporting for two wells up and downgradient per 100 ft of barrier length, given a 10 ft saturated thickness, at a cost of $3,500/well/year.	7.00
Tracking electrical performance (annual basis)	2.41
Cell phone connection (annual basis)	0.68
Power (annual basis)	0.43
Subtotal - Operations and Monitoring Costs	**$10.52**
Total	**$419.63**

Table 7. Comparison of E-Barrier Demonstration Costs to Full-Scale ZVI PRB Projects Reported in EPA (2002).

Site	Capital Cost	Annual O&M	Depth (Ft)	Active Area (Ft^2)	Capital Cost/Ft^2	O&M Cost /Ft^2
Industrial Site, South Carolina	$400,000		29	9,425	$42	
Somersworth Landfill Superfund Site	$2,515,000		40	32,000	$79	
Cape Canaveral, Florida	$760,150		45	6,300	$121	
Industrial Site , New York	$1,000,000		18	6,600	$152	
Pease AFB, New Hampshire	$750,000	$35,000	33	4,950	$152	$7.07
Watervliet Arsenal	$387,000	NA	10	1,900	$204	
U.S. Coast Guard (USCG) Support Center	$835,000	$85,000	24	3,648	$229	$23.30
Former Manufacturing, Fairfield, New Jersey	$875,000	$25,000	25	3,175	$276	$7.87
Warren AFB Spill Site 7, Wyoming	$2,350,000		15	8,520	$276	
Kansas City Plant , Missouri	$1,300,000		39	3,900	$333	
e-barrier at F.E. Warren AFB	**$75,000**	**$2,700**	**6**	**183**	**$409.84**	**$14.75**

Table 7 indicates that the e-barrier demonstration had a higher capital cost than all the full-scale field applications by a factor of 1.2 to 9.7. Because of similar physical settings, the best basis for comparison is the Warren AFB Spill Site 7 ZVI PRB. The e-barrier demonstration was more expensive by a factor of 1.5 than the full-scale F.E. Warren ZVI PRB. Building on this, the following observations are presented:

Considering potential cost reductions described in the next section, of 25 to 50%, it is concluded that a full-scale e-barrier at F.E. Warren AFB would have a similar capital cost to the existing ZVI PRB.

- It is likely that Conditions that favor lower cost for ZVI PRBs would be likely to favor lower costs for e-barriers also. With this, it is concluded that e-barriers can have similar capital costs to ZVI PRBs at other locations.

As a footnote, iron prices have doubled in 2004 due to strong global demand and iron is the primary cost component of ZVI PRBs. As such, the cost for PRBs presented in Table 7 may be lower than current costs. If high iron prices continue, the economics of e-barriers relative to ZVI-PRBs will improve. Lastly, O&M costs for e-barriers on a unit area basis are also similar to those for ZVI PRBs.

Alternatively, e-barrier costs can be evaluated on the basis of dollars per 1,000 gallons treated. This metric is used in EPA (2002) to compare the relative cost of full-scale pump and treat systems and PRBs. Over the 500-day period of operation, the e-barrier treated approximately 63,000 gallons of water. This equates to an annual treatment rate of 46,000 gallons. With this as a basis, capital and 1-year annual O&M cost for the e-barrier are $1,620 and $116 per 1,000 gallons, respectively. Note: following EPA 2002, the normalized capital cost is the capital cost divided by the 1-year treatment volume.

Table 8 compares these costs to pump and treat costs cited in EPA (2002). In general the e-barrier demonstration costs are at the high end of costs associated with full-scale pump-and-treat systems.

Table 8. Comparison of E-Barrier Costs to EPA (2002) Pump-and-Treat Costs.

Site	P&T Construction Cost/Annual Treatment Volume	Annual P&T O&M Cost
USCG Support Center	$188	$75
Intersil Site	$279	$122
Watervliet Arsenal	$1,608	Not available
Somersworth Landfill Superfund Site	$357	$47
Former Manufacturing, Fairfield, New Jersey	$101	$28
e-barrier at F.E. Warren AFB	**$1,622**	**$116**

Life-Cycle Costs—Table 9 presents an estimate of life-cycle costs. Primary assumptions include:

- all costs are in 2004 dollars
- all systems (including electrodes) will have to be replaced every ten years
- discount rates of 0%, 2%, 4% and 6% are in effect.

Notes:

1) The discount rate takes into account both the inflation rate and the real interest rate. An estimate of the current sum of inflation and real interest rate for government investment can be made from 10-year Treasury notes, which currently stand at ~ 4.25%.

2) Preliminary results from ongoing ESTCP-funded studies suggest the electrodes may be viable for more than 30 years as applied, well past the 10-year life expectancy assumed in the life-cycle cost estimate. Based on this, the life-cycle cost estimate is viewed as conservative.

Potential Cost Reductions—The process of fabrication, installation, operation, and maintenance provides numerous insights into opportunities for improvement that could reduce cost and/or improve efficacy. Table 9 focuses on potential cost savings.

Addition of a Fourth Electrode—The demonstration e-barrier relied on a three-electrode sequence. Future designs should consider using a four-electrode sequence. Envisioned benefits include:

- *Greater flux reduction*—Laboratory studies indicate flux reduction through a second set of electrodes, immediately behind the first set, provides similar flux reduction to the first. As such, if each set achieves 90% flux reduction, the total flux reduction of a system of two-electrode sets would be 99%. If each set achieved 95% flux reduction, the total flux reduction would be 99.8%.
- *Better scale control*—System longevity and performance likely can be improved with better scale control. A promising option is having all electrodes see periodic reversals in polarity. The three-electrode system employed polarity switches at only the second electrode. Given a four-electrode sequence, the polarity of all four electrodes can be switched without significantly compromising the overall treatment approach of oxidation followed by reduction.

Automated Electrode Switching, Data Downloads, and Status Messaging—The primary operation and maintenance activity was periodic downloading of electrical performance data and switching of electrode polarities for scale control. In a full-scale system, automation of these steps would provide significant reduction in life-cycle costs. In addition, system automation should include automated messaging regarding operational status.

Table 9. Estimated Life-Cycle Costs at 0%, 2%, 4%, and 6% Discount Rates.

Year	Capital	Annual O&M	Net Present Value (NPV) 0%	Net Present Value (NPV) 2%	Net Present Value (NPV) 4%	Net Present Value (NPV) 6%
0	$75,000		$75,000	$75,000	$75,000	$75,000
1		$2,700	$2,700	$2,647	$2,596	$2,547
2		$2,700	$2,700	$2,595	$2,496	$2,403
3		$2,700	$2,700	$2,544	$2,400	$2,267
4		$2,700	$2,700	$2,494	$2,308	$2,139
5		$2,700	$2,700	$2,445	$2,219	$2,018
6		$2,700	$2,700	$2,398	$2,134	$1,903
7		$2,700	$2,700	$2,351	$2,052	$1,796
8		$2,700	$2,700	$2,304	$1,973	$1,694
9		$2,700	$2,700	$2,259	$1,897	$1,598
10	$75,000	$2,700	$77,700	$63,741	$52,491	$43,387
11		$2,700	$2,700	$2,172	$1,754	$1,422
12		$2,700	$2,700	$2,129	$1,686	$1,342
13		$2,700	$2,700	$2,087	$1,622	$1,266
14		$2,700	$2,700	$2,046	$1,559	$1,194
15		$2,700	$2,700	$2,006	$1,499	$1,127
16		$2,700	$2,700	$1,967	$1,442	$1,063
17		$2,700	$2,700	$1,928	$1,386	$1,003
18		$2,700	$2,700	$1,890	$1,333	$946
19		$2,700	$2,700	$1,853	$1,282	$892
20	$75,000	$2,700	$77,700	$52,290	$35,461	$24,227
21		$2,700	$2,700	$1,781	$1,185	$794
22		$2,700	$2,700	$1,746	$1,139	$749
23		$2,700	$2,700	$1,712	$1,095	$707
24		$2,700	$2,700	$1,679	$1,053	$667
25		$2,700	$2,700	$1,646	$1,013	$629
26		$2,700	$2,700	$1,613	$974	$593
27		$2,700	$2,700	$1,582	$936	$560
28		$2,700	$2,700	$1,551	$900	$528
29		$2,700	$2,700	$1,520	$866	$498
30		$2,700	$2,700	$1,491	$832	$470
Total Cost			**$306,000**	**$247,469**	**$206,585**	**$177,430**

Fewer/Thinner Geonet Layers in the Barrier—In the electrode panels, each electrode is bounded on each side by a layer of high density polyethylene (HDPE) geonet. Removal of the layer of geonet downstream of each electrode would reduce materials cost and potentially improve performance.

Use of Conventional HDPE Curtain Walls for Framing—Limitations of the employed panel design include:

- *Expense of frame/interlock fabrication*—Labor and materials associated with the e-barrier framing/interlocks were large components of the overall cost.
- *Potential leakage between panels*—As fabricated, it is likely that some contaminant passed through interlock portions of the e-barrier.
- *Potential for overtopping at high water levels*—Portions of the plume may have overtopped the e-barrier.
- *Undesired reaction by products*—Cement used in framing the electrode panels appears to have been a factor in the apparent generation of chloroform at the e-barrier.

Mounting the electrode panels on conventional HDPE curtain walls (or vinyl sheeting) with sealing joints could solve many of these problems. Active electrode panels would be mounted as windows in the sheeting. The standard seals linking the sheeting would be more effective in limiting flow of contaminants between or over active portions of the barrier. All glues could likely be eliminated.

Elimination of washout hoses, reference electrodes, and multilevel sampling systems—A challenge of the installation was the extensive tubing and wiring routed to the surface from the individual panels in the barrier. Washout tubing for managing scale could likely be eliminated given the more rigorous four-electrode scale control strategy. Reference electrodes provided data that would likely not be required in full-scale systems. Multilevel sampling systems also provided a level of performance monitoring that is not required in full-scale systems.

DC Solar Power Supply—Use of line current requires a rectifier to transform AC line power to DC power. Use of a DC solar power supply will eliminate the need for the rectifier. It would simplify wiring and eliminate the need to pull line power to the rectifier. Preliminary analyses suggest that associated cost saving can cover the cost of solar panels with battery backup. In remote locations, solar power may provide significant cost advantages.

Alternative Electrode Materials—Electrodes are a primary element of the e-barrier cost. Lower cost electrodes could significantly reduce overall cost. Supplemental funding provided to this project is currently being used to evaluate other electrode materials. Unfortunately, results are not available at this time but plans are to present this information in a project addendum that will also cover a proposed additional year of performance monitoring.

Lower Cost Installation Techniques—The trench box approach to installation was selected for the demonstration because of the high likelihood of success and minimal chemical interferences

with groundwater. Building on the experience in recent years using biopolymer for ZVI PRBs, it seems that the most cost-effective approach for e-barrier installation (at many locations) will be biopolymer trenches. As with ZVI PRBs, this holds the promise of significantly lower PRB costs.

Considering the opportunities and economies of scale outlined above, cost reduction on the order of 25-50% (over those developed from the demonstration) is attainable.

6.0 IMPLEMENTATION ISSUES

6.1 ENVIRONMENTAL CHECK LIST

The following describes steps involved in obtaining permission to conduct the e-barrier field demonstration.

1. Permission was obtained from base personnel, state regulators, and EPA Regulators. This involved:
   - initial discussions
   - presentations at Remedial Action Board (RAB) meetings
   - providing work plans for review and approval

2. Utility clearances were obtained for all subsurface investigations and excavations.

As no chemicals were introduced and no known adverse byproducts were produced, no special permits were required. The primary issues with the e-barrier installation were the standard worker safety concerns encountered at construction sites where potentially hazardous compounds are present in soil and water.

6.2 TECHNOLOGY TRANSFER

To date, e-barrier presentations have been made at 11 national conferences, including:

- ESTCP/SERDP—Partners in Environmental Technology meetings, 2001, 2002, and 2003
- Battelle—Chlorinated and Recalcitrant Compounds Conference, 2002 and 2004
- American Geophysical Union—Hydrology Days Conference, 2003 and 2004
- Air Force Center for Environmental Excellence (AFCEE)—Annual Meeting, 2003
- Solvents in Groundwater Research Consortium—Annual Meeting, 2003 and 2004
- Geological Society of America—Annual Meeting, 2002

Future efforts to disseminate information will include conference presentations and peer reviewed publications.

6.3 END-USER ISSUES

Potential End Users—Building on our e-barrier demonstration efforts, SERDP and the USACOE have provided complementary funds to evaluate the use of e-barriers for energetic compounds in groundwater. Promising results have led to preliminary discussions with the PCD in Pueblo, Colorado, regarding use of e-barrier technology for RDX in groundwater. The long-range hope is that an e-barrier can provide a cost effective alternative to an existing high cost pump-and-treat system. PCD related activities to date include:

- 2002-2003—Preliminary meeting and information exchanged with PCD staff
- 2003—Collection of site soils for laboratory studies from PCD

- 2004—Completion of preliminary PCD treatability studies
- 2004—Secured funding for a field demonstration of e-barriers for RDX at PCD through ESTCP.

Our current hope is that a successful field demonstration will lead to a full-scale e-barrier at PCD. Other areas of prominent interest in e-barrier technology are groundwater plumes containing chlorinated ethanes. In general, these compounds are not suitable for ZVI PRBs.

Potential Concerns—This project has greatly improved our understanding of the efficacy and cost of e-barriers. Unfortunately, the issues of efficacy and cost still have relatively large uncertainties compared to proven technologies such as ZVI PRBs and pump and treat. The path forward to resolve these issues is seen as finding a site where proven technologies are less certain (e.g. energetic compounds in groundwater) and using this to further develop/demonstrate the technology.

As stated in Section 4.1, chloroform was detected in the effluent groundwater at the highest imposed potential difference. Follow-up laboratory studies suggested that chlorine, generated from the oxidation of background chloride, reacted with the acetone-based PVC cement to form chloroform. Chloroform generation was minimized during the demonstration by decreasing the imposed potential difference. In future implementations, avoiding acetone and methyl-ketone-based construction materials and minimizing applied voltage will help mitigate the occurrence of byproducts typical of disinfection processes.

Other potential concerns center on the practicality of installing continuous e-barrier panels, the longevity of the components (primarily the electrodes), and long-term management of scale formation on electrodes.

Ease of Use—In general all elements of the technology are commercial off-the-shelf (COTS) items. In this regard there are no significant hurdles. Patents covering the technology include Sale and Gilbert (2002) and (2004). These are not viewed as impediments to implementation of the technology.

7.0 REFERENCES

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APPENDIX A

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