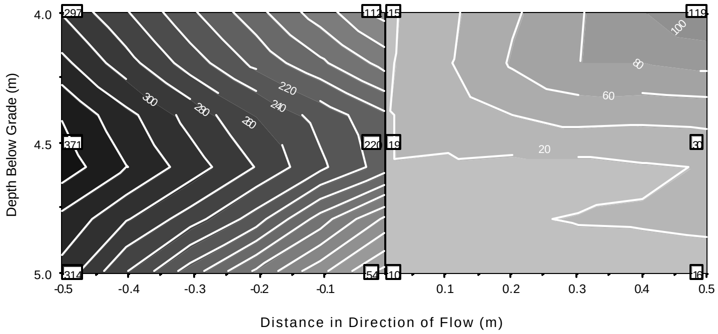
Final Report
Electrically Induced Redox Barriers for Treatment of Groundwater
(CU-0112)



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Executive Summary

This report documents results from a three-year collaboration between the Environmental Security Technology Certification Program (ESTCP) and Colorado State University (CSU). The focus is an innovative electrolytic approach for managing redox sensitive contaminants in groundwater, referred to as e^-barriers. The overarching objective of the work is to demonstrate/validate a new technology for managing contaminated groundwater at DoD facilities that 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:

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

The demonstration/validation includes the following:

1) Identification of an appropriate field site at F.E. Warren AFB, WY,
2) Pre-design laboratory studies,
3) Design and installation of a 17 m^2 demonstration barrier, and
4) Performance monitoring over a period of 18 months.

The site selected for the demonstration is a shallow alluvial plume containing approximately 300 µg/L of trichloroethene. The e^-barrier was designed and fabricated at CSU in May through July 2002. It was installed at F.E. Warren AFB in August 2002. Following installation, the e^-barrier was allowed to equilibrate with the contaminant in the plume for a period of 5 months. Power was applied to the e^-barrier in January 2003. As of August 2004, the e^-barrier has been operating continuously (approximately 18 months). As implemented, the e^-barrier met the functional objective of the demonstration. In addition, 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 are 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 over a period of 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 oxic conditions developed at the e^-barrier and/or unanticipated reactions with PVC pipe cement that can be excluded from future systems.

Cost components associated with the demonstration e^-barrier include:

1) Capital expenses of $\$409/\text{ft}^2$ of intercepted plume, and
2) Operation and maintenance (O&M) expense of $\$10/\text{ft}^2$/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:

1) Identification of Pueblo Chemical Depot (PCD) as a promising demonstration location,
2) Completion of preliminary laboratory studies using site soils, and
3) 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.

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.

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Acknowledgements

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List of Acronyms and Abbreviations

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
BRAC	Base Realignment and Closure
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
COTS	Commercially available off-the-shelf
CFR	Code of Federal Regulations
CFB	Canadian Forces Base
CSU	Colorado State University
DCA	dichloroethane
c-DCE	cis-dichloroethene
t-DCE	trans-dichloroethene
DoD	Department of Defense
e^-barrier	Electrically Induced Redox Barrier
ECD	Electron capture detector
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FRTR	Federal Remediation Technologies Roundtable
GC	Gas Chromatography
H&SP	Health and Safety Professional
HASP	Health and Safety Plan
HAZWOPER	Hazardous Waste Operations and Emergency Response
HDPE	High density polyethylene
IC	Ion chromatography
ID	Inner Diameter
MCL	Maximum Contaminant Level
MSDS	Material Safety Data Sheet
OD	Outer diameter
OSHA	Occupational Safety and Health Administration
OVA	Organic Vapor Analyzer
OVM	Organic Vapor Monitor
PCD	Pueblo Chemical Depot
PQL	Practical Quantification Limit
PID	Photoionization Detector
PI	Principal Investigator
PPE	Personal Protective Equipment
PRB	Permeable Reactive Barrier
PVC	Polyvinyl chloride
QAPP	Quality Assurance Project Plan
RAB	Remedial Action Board
RCRA	Resource Conservation and Recovery Act
SERDP	Strategic Environmental Research and Development Program
SOP	Standard Operating Procedure
SSO	Site Safety Officer

TCA	trichloroethane
TCE	trichloroethene
TDS	Total Dissolved Solids
TLV	Threshold Limit Value
USACOE	U.S. Army Corps of Engineers
URS	URS Consultants, Inc.
UXO	unexploded ordnance
VC	Vinyl Chloride
VOC	volatile organic compound
WDEQ	Wyoming Department of Environmental Quality
ZVI	Zero Valent Iron

1. Introduction

1.1 Background

In 2002 ESTCP funded a three-year field demonstration of an Electrically Induced Redox Barrier for Treatment of Groundwater (CU 0112). The concept of an electrolytic reactive barrier (e^-barrier) is that of a permeable reactive barrier (PRB) driven by low voltage direct current. The following is the final report for the project. Content and organization follows ESTCP guidance (ESTCP, 2004).

1.2 Objective of the Demonstration

The overarching objective of this demonstration/validation project is to develop a new technology for managing chlorinated solvents and other organic contaminants in groundwater at DoD facilities that provides significant advantages over existing technologies in terms of efficacy and cost. To meet this objective, the project was designed to provide a rigorous evaluation of performance, estimation of full-scale cost, and information regarding technology implementation.

1.3 Regulatory Driver

Regulations under CERCLA and RCRA, and their equivalents at the state level, require cleanup of groundwater to "strict numerical concentrations" (USEPA, 1992). However, current remedial technologies are often ineffective in eliminating in situ sources of contamination. Consequently, long-term containment is often required for plumes emanating from source zones (NRC, 1994). The primary factor challenging long-term containment is that it can be labor and cost intensive. The focus of this effort is to develop a new containment technology that is effective and has low operations and maintenance costs.

1.4 Stakeholder/End-User Issues

Information generated through this project provides a basis for stakeholders and end users to assess the potential of an e^-barrier to manage plumes of contaminated groundwater. This includes analysis of efficacy, cost, limitations, and implementation.

2. Technology Demonstration

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 non-toxic products. A field-scale conceptualization of an e$^-$barrier is illustrated in Figure 1.

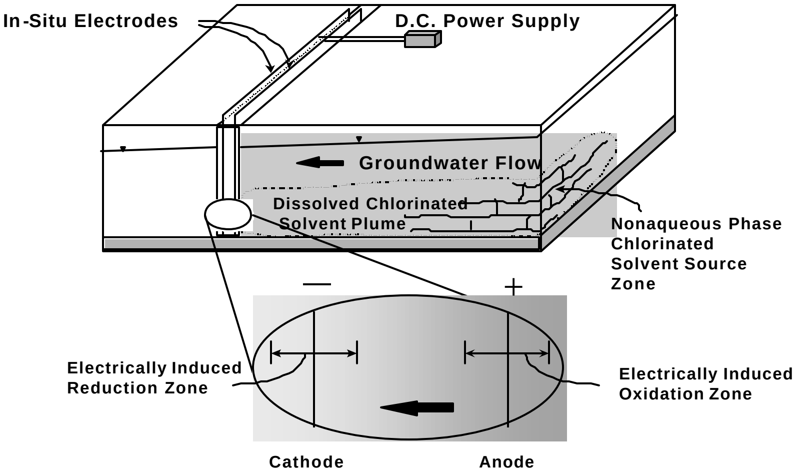


Figure 1. Conceptualization of a field scale e$^-$barrier

2.2 Previous Testing of the Technology

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

Table 1. Summary of ebarrier 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-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 testing 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 were inconclusive due to difficulties in sustaining anaerobes in column studies
ESTCP	2001-Present	17 m^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.
U.S. Army Corps of Engineers	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 the demonstration, primary cost categories associated with the e$^-$barrier include capital expenditure (96.5% of total) and operations and maintenance (O&M) (3.5% of total). Primary capital costs include 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 barrier, are 409/ft^2 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. Cost savings opportunities are discussed in more 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 potential at electrodes can be reversed or shifted to remove inorganic precipitates (e.g. $CaCO_3$ scale) a common constraint of other technologies, and
- Sequential oxidation and reduction has the potential to degrade a wide range of contaminants including mixtures that are difficult to address with current technologies (most of which are based on either oxidation or reduction, not both).

Observed limitations include:

- Deep installation of an e$^-$barrier will be challenging. In general, shallow applications will be 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 ZVI PRB) for chlorinated solvent plumes will require technology improvement, and
- Demonstrated flux reductions on the order of 90 to 95% may be insufficient to achieve groundwater concentrations that meet regulatory compliance at many sites.

3. Demonstration Design

3.1 Performance Objectives

The primary focus of the demonstration was to resolve whether e^-barriers are a viable option for managing plumes of chlorinated solvents (and potentially other contaminants) at DoD sites. Performance objectives for the field demonstration are presented in Table 2.

Table 2. Performance Objectives – Field Demonstration

TYPE OF PERFORMANCE OBJECTIVE	PRIMARY PERFORMANCE CRITERIA	EXPECTED PERFORMANCE (METRIC)	ACTUAL PERFORMANCE OBJECTIVE MET?
Qualitative	Documentation of efficacy, cost, and the niche in which e^-barriers can be effective	ESTCP acceptance of Final Technical and Cost & Performance Reports.	Yes
Quantitative	Contaminant removal	TCE and associated degradation products below MCLs, immediately downgradient of the e^- barrier.	In Part – See Section 4
	Long term viability	Sustained contaminant removal as above with no measurable increases in head loss through the impacted interval, loss in electrical properties of the e^-barrier, or degradation of physical properties of the barrier components.	Yes – See Section 4
	Implementability	Documentation of construction and operation experience in the final reports. This will include insight regarding the optimal niche for e^- barriers.	Yes – See Section 4
	Cost	Documentation of construction, operation, maintenance and monitoring costs in the final reports	Yes – See Section 5

3.2 Selecting Test Site

The location selected for the demonstration is F.E. Warren Air Force Base (AFB). F.E. Warren AFB is located near Cheyenne, Wyoming. The base's primary mission is maintenance of Peacekeeper missiles. The selection of F.E. Warren AFB reflects favorable geologic conditions, presence of the desired target compound, and proximity to Colorado State University. Principal screening criteria for a location at the base include:

1. Depth to Groundwater less than 20 feet – shallow depths limit project cost and simplify monitoring activities.

2. TCE concentrations on the order of 1 mg/L – Typical of many plumes at DoD sites.

3. Groundwater seepage velocities greater than 0.2 feet/day – lower velocities would make it difficult to evaluate performance based on downgradient water quality during the ~ 1-year demonstration period.

4. Basal aquitard – ideally the barrier would be completed into a low permeability unit with low groundwater and contaminant flux.

5. Proximity to line power – a nearby source of 110-volt power will simplify operation of the demonstration barrier.

6. Low total dissolved solids (TDS) –Locations with lower TDS are preferred in that they have lower potential for adverse fouling of the electrodes by inorganic precipitates.

7. Minimal interference with base activities

3.3 Test Site Description

3.3.1 Facility History/Characteristics

F.E. Warren AFB is an approximately 7,000-acre facility underlain by shallow eolian and fluvial deposits. The Ogallala Formation lies below the alluvium. Locally the Ogallala Formation consists of interbeds of gravel, sand, and silt with varying clay content. Through historical maintenance and disposal activities, chlorinated solvents (primarily TCE) have been inadvertently released to the subsurface. A primary concern associated with releases is the risk posed to surface waters including Diamond Creek and Crow Creek. Figure 2 presents the major features at F.E. Warren and plumes of TCE in groundwater.

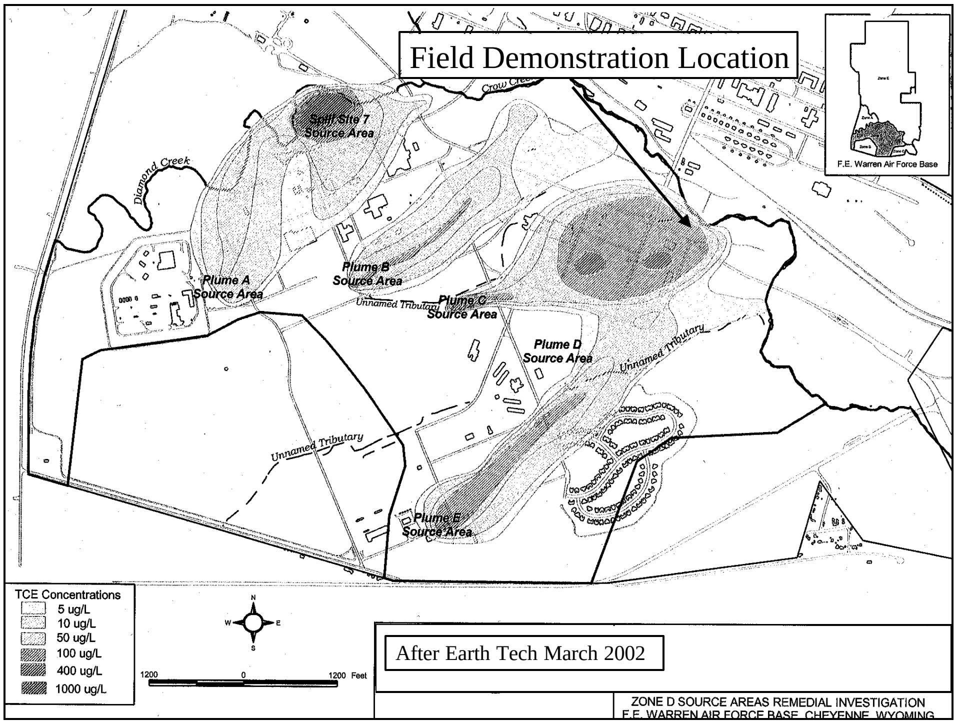


Figure 2. F.E. Warren Base map showing TCE plumes and demonstration location

3.3.2 Ongoing Restoration Activities

The F.E. Warren Installation Restoration Project currently includes 20 sites. These have been divided into seven investigation zones (zones A-G). Comprehensive remedial investigation activities and feasibility studies are presently being completed. Remedial actions that have been implemented at F.E. Warren include:

- A ZVI PRB at Spill Site 7.
- Two pump and treat systems.
- Ongoing assessments of natural attenuation.

These remedial actions provide useful data for comparison of the e$^-$barrier to other similar niche technologies. In addition, analysis of field trials of chemical oxidation, methane sparging, and zero valent iron (ZVI) injection are ongoing.

3.4 Pre-Design Testing and Analysis

Pre-Design activities completed between March 2001 and February 2002 include:

- Selection of a suitable location at F.E. Warren for the demonstration.

- Field investigations at the selected demonstration location (MW038) in support of design and definition of baseline conditions.

- Collection of representative soils and groundwater for the pre-demonstration treatability studies.

- Pre-design laboratory studies. Objectives were to:

    - Evaluate performance using site soils and groundwater,
    - Test materials of construction,
    - Optimize design (e.g. electrode spacing), and
    - Evaluate operational strategies (e.g. applied voltage and scale management)

Results provided a primary basis for the project work plan (Sale and Gilbert, 2002) and final demonstration design. Results are reviewed in the following text.

3.4.1 Demonstration Location

In 2001, several sites at F.E. Warren were screened as potential locations for the field demonstration. Based on the criteria listed in 3.2, a preferred location (MW-038) was identified (Figure 2). Verification of the desired conditions was accomplished by completing four temporary monitoring wells (ESTCP 1- ESTCP 4) in the vicinity of MW-038 (Figure 3). Temporary wells were installed using hollow stem auger drilling techniques per methods outlined in the Pre-Demonstration Activities Work Plan (Final 12/27/01). Results are described in the following text.

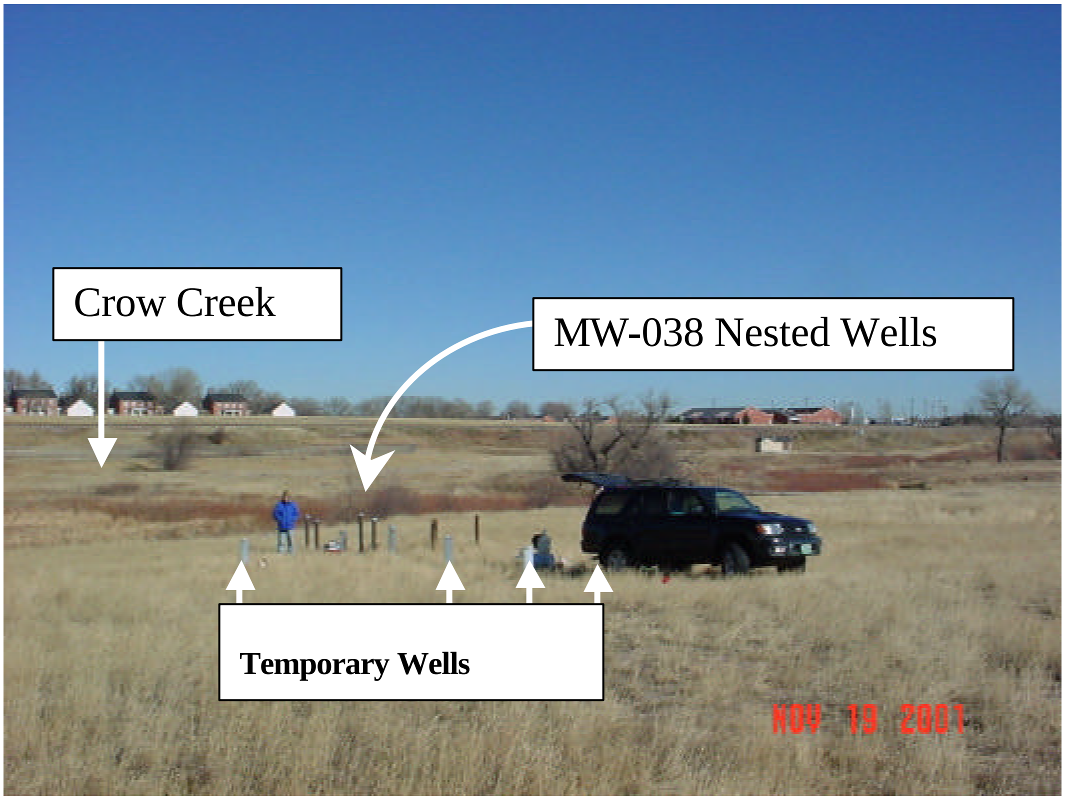


Figure 3. Photo of MW-038 site looking northwest across Crow Creek

Depth to Water and Hydrogeology – Figure 4 presents the layout of wells at the MW-038 site. The existing wells (MW-038, MW-038I, and MW-038S) were installed as part of a prior site-wide plume investigation. These wells indicate upward gradients with the deepest well flowing at grade. The ESTCP wells were installed in October 2001 as part of this program. Figure 5 and Figure 6 present geologic cross-sections based on well logs. Figure 7 provides a symbol legend. Geologic logs are included in the Appendix A bid package.

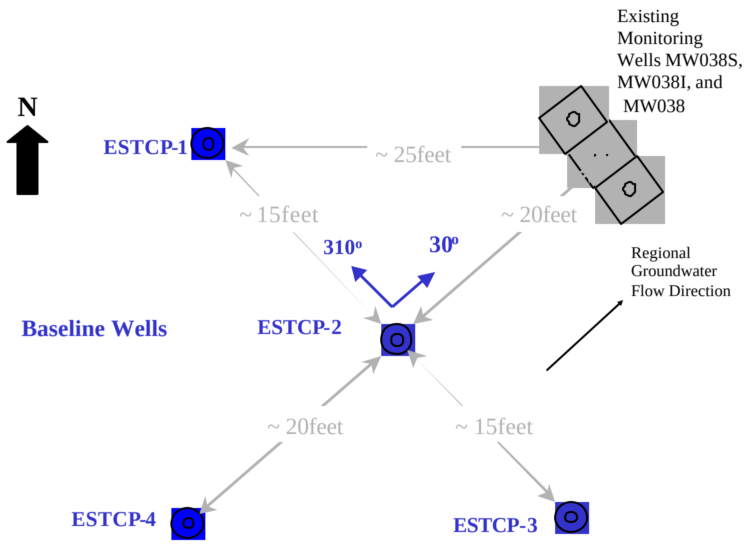


Figure 4. Layout of existing and temporary wells at the selected demonstration location

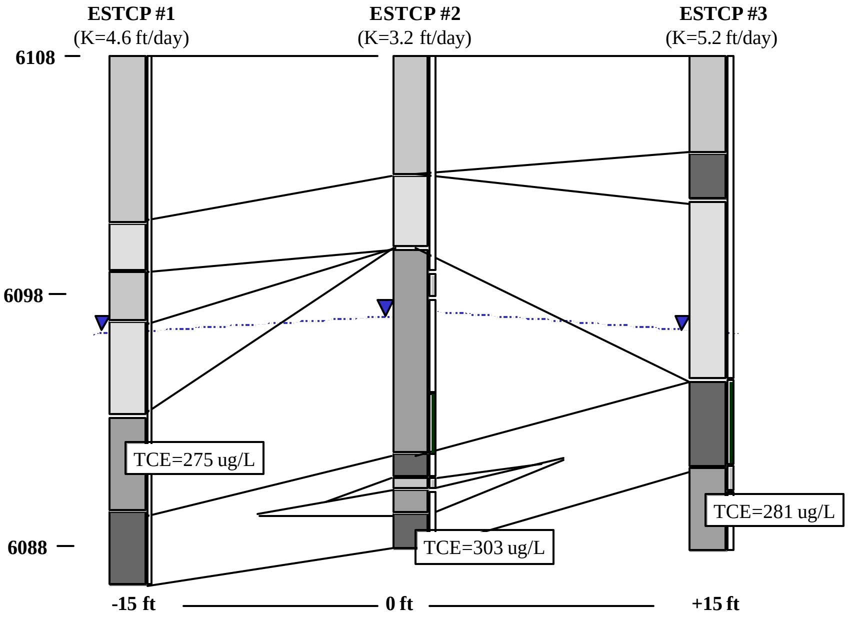


Figure 5. Geologic cross-section perpendicular to flow

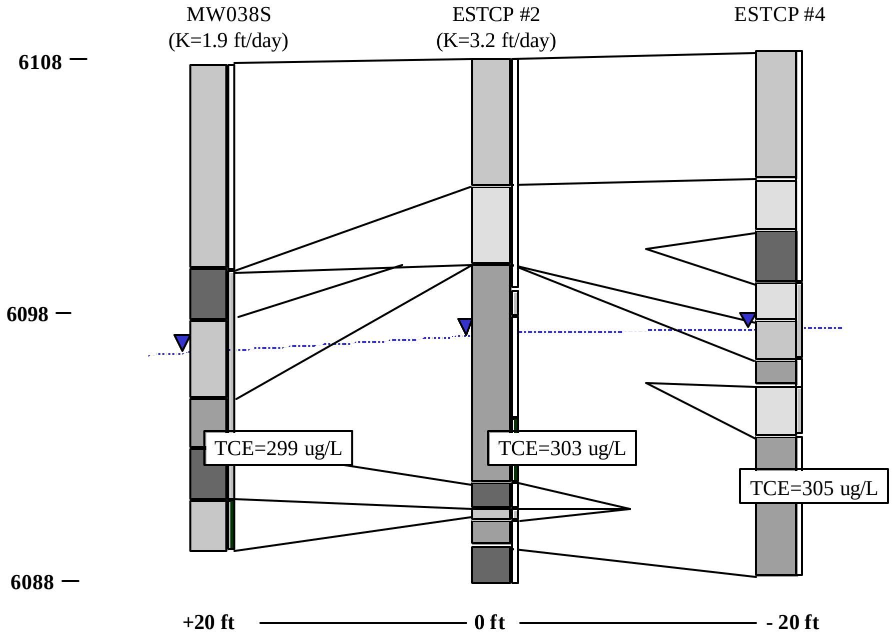


Figure 6. Geologic cross-section parallel to flow

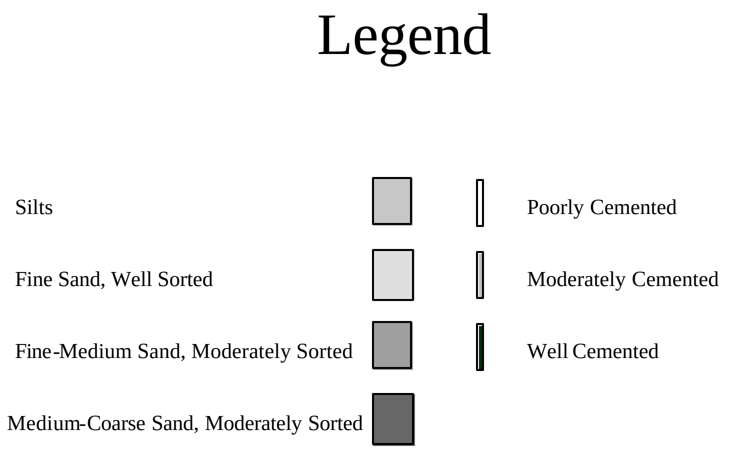


Figure 7. Symbols used in geologic cross-sections

Groundwater occurs at 11 to 12 feet below ground surface. Sediment encountered consists of eolian silt to a depth of 5-8 feet. A weathered portion of the Ogallala Formation underlies these sediments. Locally the Ogallala consists of interbedded layers of moderately sorted silts, sands, and gravels that are poorly to well cemented. Primary minerals are quartz and potassium feldspar. Minor amounts of hornblende, biotite, and muscovite were also observed. This suggests that the source of the sediments was granite such as that found in the Laramie Range approximately 50 miles to the west of F.E. Warren AFB. Almost all of the sediments encountered reacted to addition of weak solutions of hydrochloric acid. This suggests carbonate cementatation and is consistent with observations of caliche in soils during excavation activities. Based on the geologic cross-sections individual beds are highly discontinuous laterally. This likely reflects repeated reworking of the deposits by a combination of alluvial and fluvial depositional processes.

In December 2001, low flow pump tests (~ 100 mL/min) were conducted at the temporary wells ESTCP 1 – ESTCP 3. This activity served the dual purpose of obtaining water for laboratory studies and provided a basis for estimating the hydraulic conductivity of the formation. Due to the low flow rates, drawdown was only observed at the pumped wells. Consequently, estimates of the specific yield could not be determined. Hydraulic conductivity values were obtained using the Jacob-Cooper approximation of the Theis Solution. Results are summarized in Table 3. These values are similar to a reported hydraulic conductivity value of 1.9 ft/day for MW-038 based on a slug test conducted as part of site remedial investigations.

Table 3. Formation hydraulic conductivity based on low flow pumping tests

WELL	HYDRAULIC CONDUCTIVITY (FT/DAY)
ESTCP 1	4.6
ESTCP 2	3.2
ESTCP 3	5.2
Average	4.3

Pre-installation water levels were measured to determine placement depth and orientation of the demonstration e$^-$barrier. Hydrographs are presented in Figure 8.

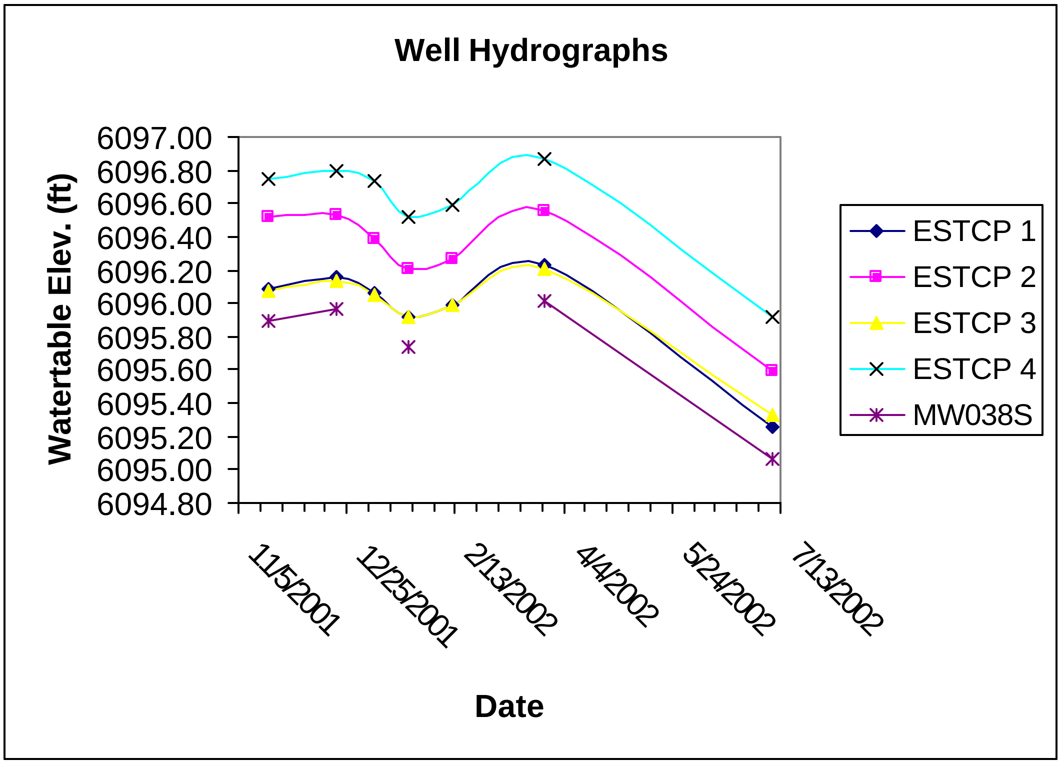


Figure 8. ESTCP well hydrographs

Figure 9 presents a potentiometric surface map developed using data collected on 11/18/01. Using the average of the hydraulic conductivity values, the observed gradient, and an assumed porosity of 25%, the seepage velocity through the demonstration location is 0.37 ft/day.

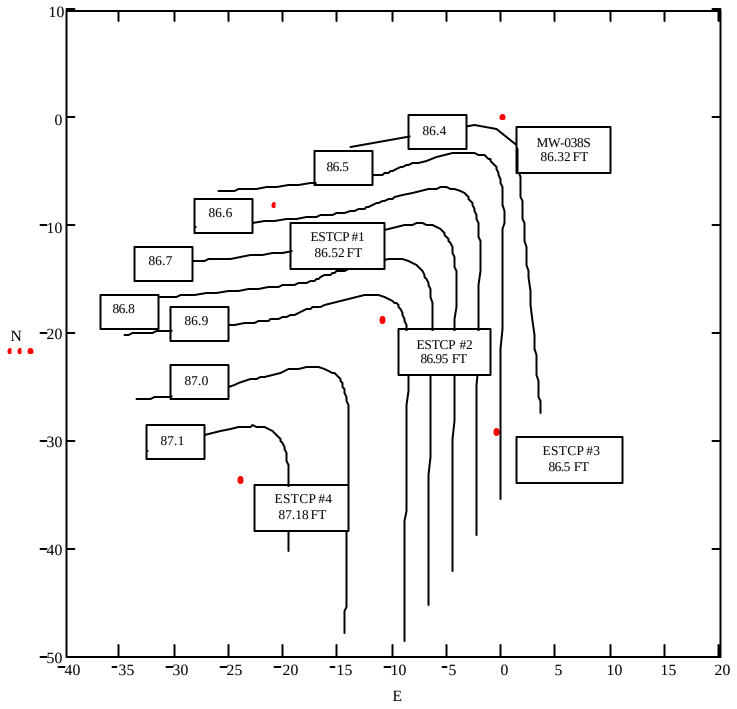


Figure 9. Potentiometric surface (11/18/2001)

Water Quality – In monitoring conducted prior to this study, TCE was the only chlorinated compound observed in samples collected from MW038. As part of pre-installation activities, four sets of samples were collected and analyzed for field parameters and chlorinated solvents. Samples were collected and analyzed per methods outlined in the Pre-Demonstration Activities Work Plan (12/27/01). Results are presented in Table 4. Analytical methods for chlorinated solvents are described in the subsequent Section 3.5.3 describing column studies.

Table 4. Pre-installation Water Quality - TCE and Field Parameters

Sample Location	**Date**	**pH**	**Eh (mV SHE)**	**Conductivity (µS/cm)**	**Temp. (^{o}C)**	**TCE (µg/L)**
MW038	3/15/01	-	-	-	-	220*
	11/18/01	7.22	287	816	-	341
	11/18/01	-	-	-	-	316
	12/20/01	7.26	365	720	8.7	319
	3/26/02	7.26	367	782	11.2	310
	7/9/02	7.26	326	780	20.7	293
Average		**7.25**	**336**	**775**	**13.5**	**300**
ESTCP 1	11/18/01	7.19	278	1084	-	305
	11/18/01	-	-	-	-	278
	12/20/01	7.15	355	1015	9.3	242
	3/26/02	7.03	394	1018	11.2	274
	7/9/02	7.18	309	924	19.0	254
Average		**7.14**	**334**	**1010**	**13.2**	**271**
ESTCP 2	11/18/01	7.23	269	-	-	334
	11/18/01			-	-	272
	12/20/01	7.26	311	-	9.0	302
	3/26/02	7.30	362	788	9.8	323
	7/9/02	7.22	303	793	18.8	275
Average		**7.25**	**311**	**791**	**12.5**	**301**
ESTCP 3	11/18/01	7.39	257	-	-	335
	11/18/01	-	-	-	-	233
	12/20/01	7.32	347	630	-	286
	12/20/01	-	-	-	-	268
	3/26/02	7.18	368	939	11.3	256
	7/9/02	7.27	317	761	21.9	303
Average		**7.29**	**322**	**777**	**16.6**	**280**
ESTCP 4	11/18/01	7.16	248	-	-	302
	11/18/01	-	-	-	-	321
	12/20/01	7.10	361	1005	-	292
	3/26/02	7.02	393	820	9.0	317
	7/9/02	7.24	307	924	19.6	265
Average		**7.13**	**327**	**916**	**14.3**	**299**

*Sample collected and analyzed as part of a site-wide investigation conducted by URS.

In addition, a set of samples was analyzed for major anions and cations. Results are presented in Table 5. Table 4 and Table 5 indicate a relatively uniform water quality. Parameters are within the ranges identified in our site selection criteria.

Table 5. Water Quality – Inorganic Parameters

	MW03 8	**ESTCP 1**	**ESTCP 2**	**ESTCP 3***	**ESTCP 4**	**AVERAGE**
Anions (mg/L)						
Chloride	51	103	70	67/82	94	78
Nitrate	29	31	38	27/34	36	33
Sulfate	42	76	62	74/46	59	56
Carbonate (as $CaCO_3$)	0.21	0.18	0.22	0.21/0.21	0.16	0.20
Bicarbonate (as $CaCO_3$)	224	239	234	187/193	238	225
Cations (mg/L)						
Calcium	133	168	129	138/133	133	140
Potassium	4.0	3.9	3.6	3.1/2.5	4.0	3.7
Magnesium	21	21	18	17/17	21	20
Sodium	52	49	37	22/21	52	42
TDS (mg/L)	587	760	652	596/589	707	670

*Duplicate samples

Major cations in acidified samples were quantified using a Sievers ICP spectrometer. Quantification of major anions in unadjusted-pH samples was achieved using a Dionex ion chromatograph (IC) with an Allsep Anion 7u (150mm * 4.6mm) Alltec column and carbonate eluent. In order to complete the ion balance, carbonate total was quantified using a Jarrell Ash total organic carbon analyzer (TOC). The speciation of the ions present was achieved using the measured pH and the quantified totals from above. The result of these calculations and the completeness of the analysis was verified using a charge balance. Standards and blanks were used for all analyses as well as duplicate samples to establish quality control.

In addition to the samples noted in Table 4 and Table 5, sampling equipment rinse, field blanks, and duplicate samples were collected. All rinse samples contained less than 5 µg/L TCE. TCE in field blank samples were below method detection limits of 1 µg/L. Based on a total of four samples collected from ESTCP 4 on 11/18/01 the 95% confidence interval for the mean of 308 is ±16 µg/L. In addition, two duplicate samples were sent to the University of Waterloo for analysis of TCE. Results were within 10 percent of the values reported in Table 4. The only QA/QC samples for inorganic compounds were duplicate samples collected from ESTCP 3. These results show reasonably close agreement.

Variance from Selection Criteria – In general, the area of MW-038 conforms to the selection criteria outlined in the Pre-demonstration Work Plan. The only variance from the criteria is that a basal low permeability layer is not present. In the absence of this layer performance is evaluated based on water quality that lies in the "shadow" of the barrier. This is not seen as a critical flaw.

3.4.2 Column Studies

The following section reviews methods and results associated with pre-design column studies. More rigorous development of this topic is presented in Petersen (2003).

Experimental Setup - Column treatability studies were conducted using four Plexiglas columns 90 cm in length with interior diameters of 10 cm. All columns were loaded with soils obtained during construction of the temporary ESTCP monitoring wells at MW-038. Three of the columns were electrically active employing different electrode spacing. The fourth column was a no-power (open circuit) control. Water used in the treatability studies was acquired from the wells at the proposed barrier location (ESTCP-1 through ESTCP 3; Figure 4). Figure 10 presents one of four columns employed in the treatability studies. The top half presents the entire column. The bottom presents the detail of the electrode panel.

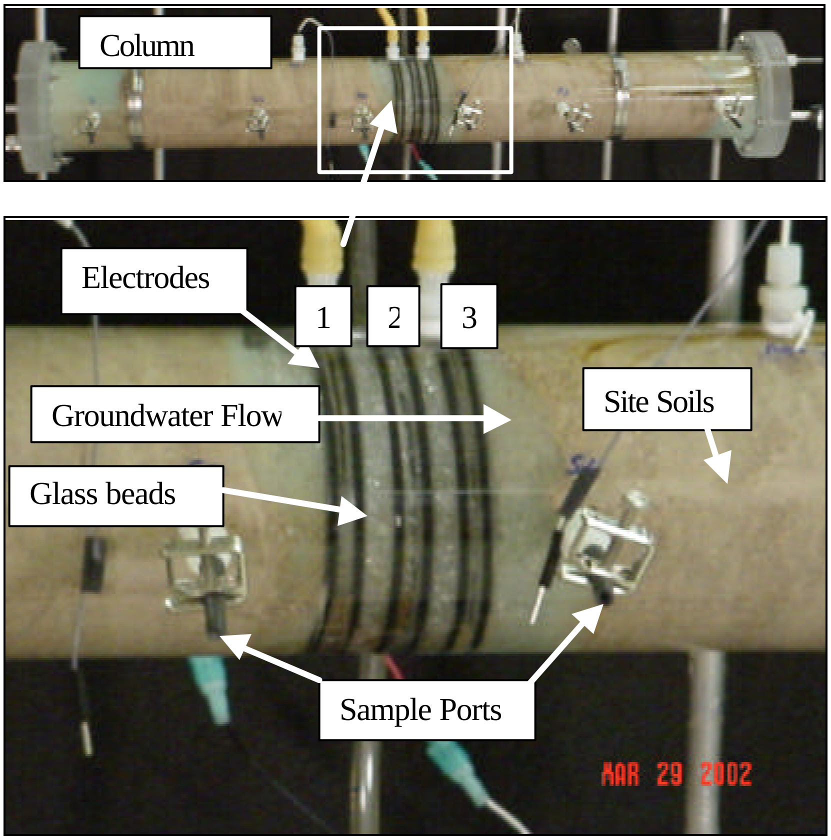


Figure 10. Treatability study column

Three mesh electrodes were placed in the columns (center electrode at the mid point) perpendicular to flow and across the entire cross sectional area of the column. The electrodes consist of mixed metal oxides sintered onto an expanded titanium mesh substrate (ELGARD™ 300 Anode Mesh, ELTECH Systems, Chardon, OH). The mesh has 70% open area (Figure 11). Electrode spacing of 0.5 cm, 1.0 cm, and 2.0 cm were used in the three active columns. Intervals around the electrodes were filled with glass beads to prevent the site soils from infiltrating the electrodes (Figure 10).

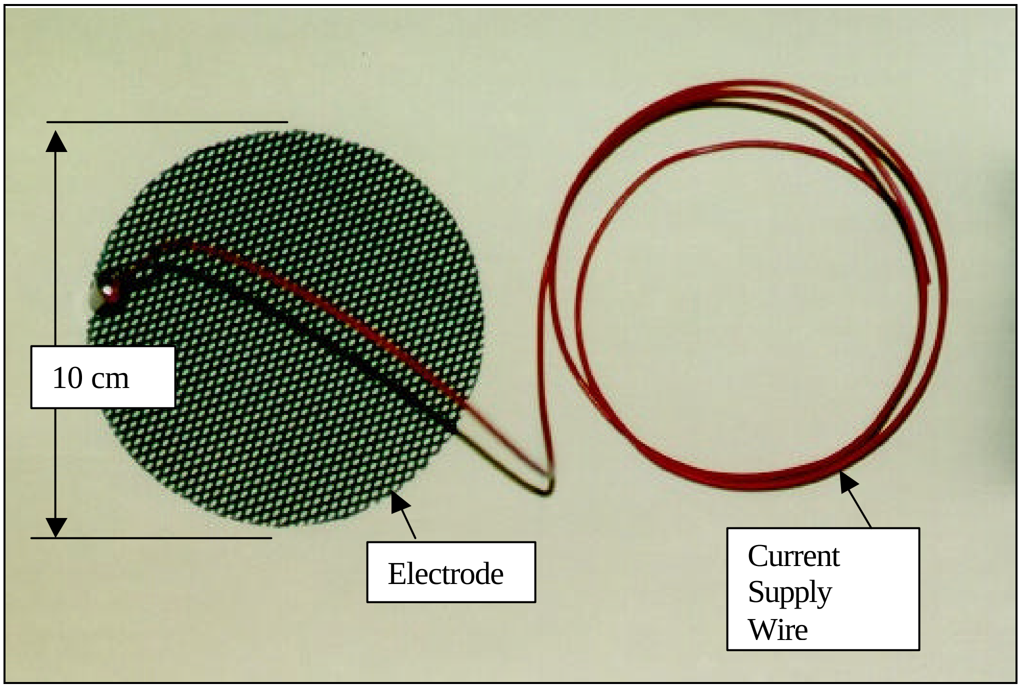


Figure 11. Electrode with current supply wire

A constant voltage was applied between two adjacent electrodes in each of the active columns using a DC Power Supply (GW Laboratory model GPS-3030D). Potentials of the anode and cathode were measured using DRIREF-5 (World Precision Instruments, Sarasota, FL) reference electrodes placed 2 cm distal from the electrode pack.

Feedstock was stored in 25 liter Tedlar bags (SKC Inc., Eighty Four, PA) with minimum headspace in order to minimize TCE partitioning to the atmosphere. This approach is essential to maintaining constant influent concentrations. TCE concentrations in the collected groundwater were ~100 µg/L. Field characterization indicated *in situ* TCE concentrations of approximately 300 µg/L. The discrepancy is attributed to TCE volatilization during collection and transportation of groundwater to the laboratory. To compensate for the loss, the site water was spiked with a saturated (1100 mg/L) aqueous solution of TCE (Fisher Scientific, 99.9%) to achieve concentrations in the feedstock between 300 and 350 µg/L. The feedstock was pumped though the columns using a multi-channel variable speed peristaltic pump (Ismatec™) equipped with Viton™ tubing.

Treatability Study Operating Protocol – Direct current was applied to three of the four columns. The fourth column was a control. In each active column, the upstream electrode was operated as an anode and as such, the initial effect is oxidation. The second electrode downstream was operated as a cathode and the second treatment is reduction. The third (farthest downstream) electrode was normally inactive. Carbonate scale that accumulated at the cathode was periodically removed by switching the electrode configuration such that the second electrode was the anode and third electrode was the cathode. This preserves the oxidation-reduction treatment sequence while changing the polarity at the second electrode to positive. The low pH condition at the second electrode (associated with oxidation of water ($2H_2O \rightarrow 4H^+ + O_2 + 4e^-$) removes accumulated scale. This strategy has been successfully employed in laboratory and fieldwork associated with the Borden e^-barrier Field Prototype.

Produced gases were collected in 1 L Tedlar bags connected to vent ports located above the electrodes. Analysis of gas samples indicated the produced gases to be primarily hydrogen and oxygen. Minor amounts of CO_2 and chlorinated solvents were also detected. Based on a steady state mass balance on TCE through the column, less than 1% TCE feed to the column was removed by gas stripping. This supports *in situ* degradation of the chlorinated compounds versus removal via gas stripping.

Flow rates through the columns were 0.7 mL/min. This rate results in a seepage velocity of 0.25 ft/day. This velocity was based on earlier site characterization studies. Four different voltages (2.5, 5, 10, and 20 V) were studied during the experiment. Columns were operated for a period of two to three weeks at each voltage before sampling. After sampling, the voltage was increased (2.5 ➔ 5 ➔ 10 ➔ 20 V).

Eight sample ports (including influent and effluent) were placed along the column, four upstream and four downstream of the electrodes. Samples from each port were analyzed for TCE and associated degradation products. TCE was the only constituent quantified in the analysis. Analysis suggested that DCE was present in trace amounts (below detection). This is consistent with other TCE column studies that indicate formation of intermediates at concentrations one or more orders of magnitude less than influent TCE concentrations.

Eh, pH, and temperature were measured using a low volume flow-through cell connected directly to the sample ports. Conductivity was measured using the effluent from the flow cell under atmospheric conditions. TCE concentration, Eh, pH, temperature, and conductivity were determined for each voltage setting. One duplicate and sampling equipment rinse sample were taken per sample period to ensure no cross contamination during the sampling event. All duplicates were reasonably close in TCE concentration. Rinse samples were below TCE detection limits, indicating no cross contamination had occurred during any of the sample periods. Daily measurements of resultant amperage and electrode potentials were recorded throughout the lifetime of the experiment.

Analytical Methods - Water samples were taken from the columns and analyzed for TCE using an HP 5890 Series II GC, Agilent DB-624 column and electron capture detector. TCE was extracted from the aqueous sample using MTBE (Fisher Scientific, HPLC Grade) and using an extraction protocol adapted from USEPA Method 551.1 (Methods for Determination of Organic Compounds in Drinking Water Supplement II). Standards were run after every eight samples to account for detector drift. Extraction efficiency ranged from 85 to 98% over each sample period.

pH and temperature measurements were made using a combination pH/reference electrode (Ag/AgCl) and Denver Instrument Model AP25 meter. Calibration of the pH electrode was conducted prior to each round of measurements. Eh (pe) measurements were made with a combination platinum/reference (Ag/AgCl) electrode and Denver Instrument AP25 meter. All Eh measurements were corrected to reference the standard hydrogen electrode. Calibration check of the Eh electrode is conducted according to ASTM Practice D1498-00 (Standard Practice for Oxidation-Reduction Potential of Water), using a pH 7 buffer solution saturated with quinhydrone. Conductivity measurements were made with a YSI model 32 conductivity meter. Calibration of the conductivity electrode was conducted using 0.01 M KCl prior to each measurement round.

Results – Figure 12 presents TCE removal as a function of voltage. Primary results are; 1) TCE flux reduction of 80-90 percent with no quantifiable intermediates (20 volts) and 2) removal is not a strong function of electrode spacing.

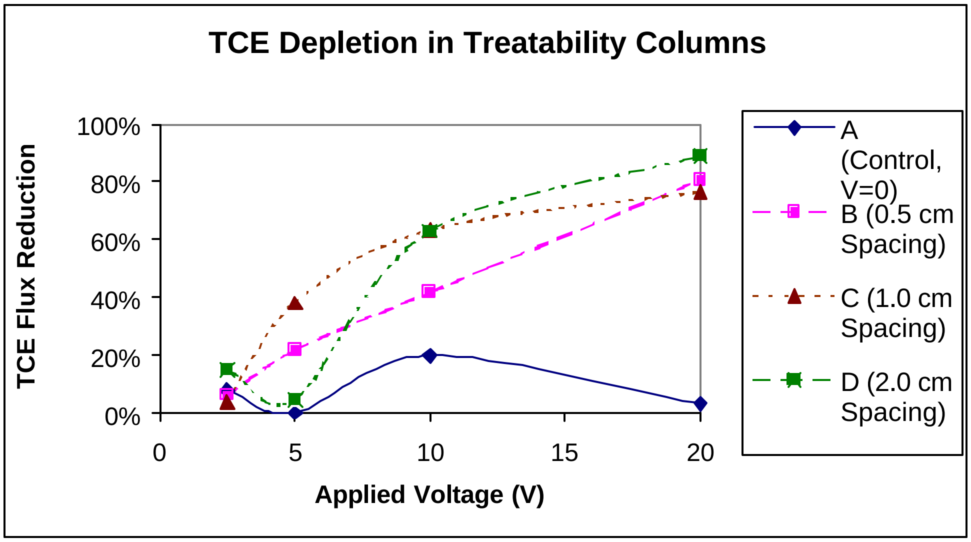


Figure 12. TCE removal as a function of applied voltage

Figure 13 presents power/m^2 of active electrode (watts/m^2) as a function of voltage and spacing. In general, lower power requirements at the larger spacing resulted in selection of 2 cm spacing for design of the demonstration e$^-$barrier. The other factor in selecting electrode spacing is scale formation. Figure 14 presents photos of the three primary negative electrodes employed in the study. Since there is no apparent difference in scale accumulation, the larger spacing (2-cm) was selected for use in the field demonstration. The accumulated scale reflects conditions prior to electrode reversal.

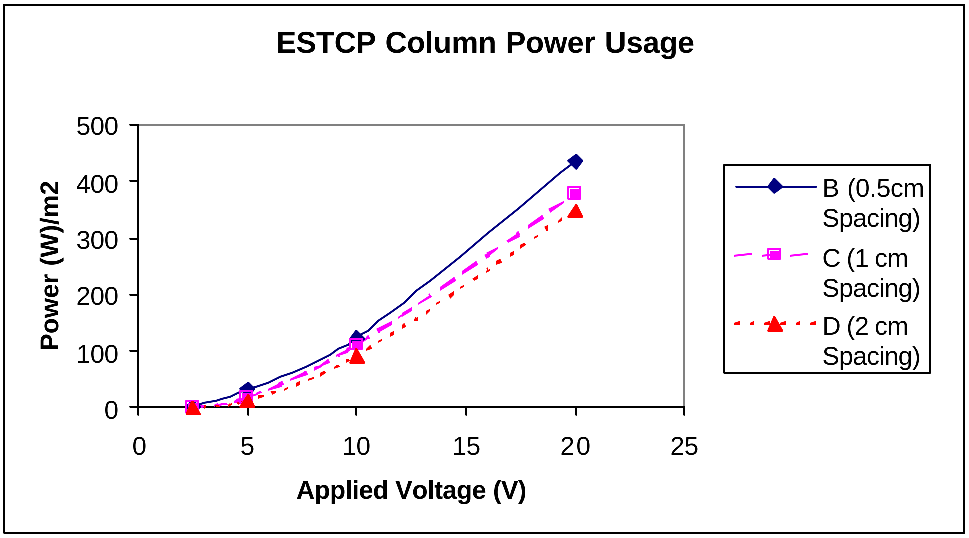


Figure 13. Power as a function of voltage and spacing

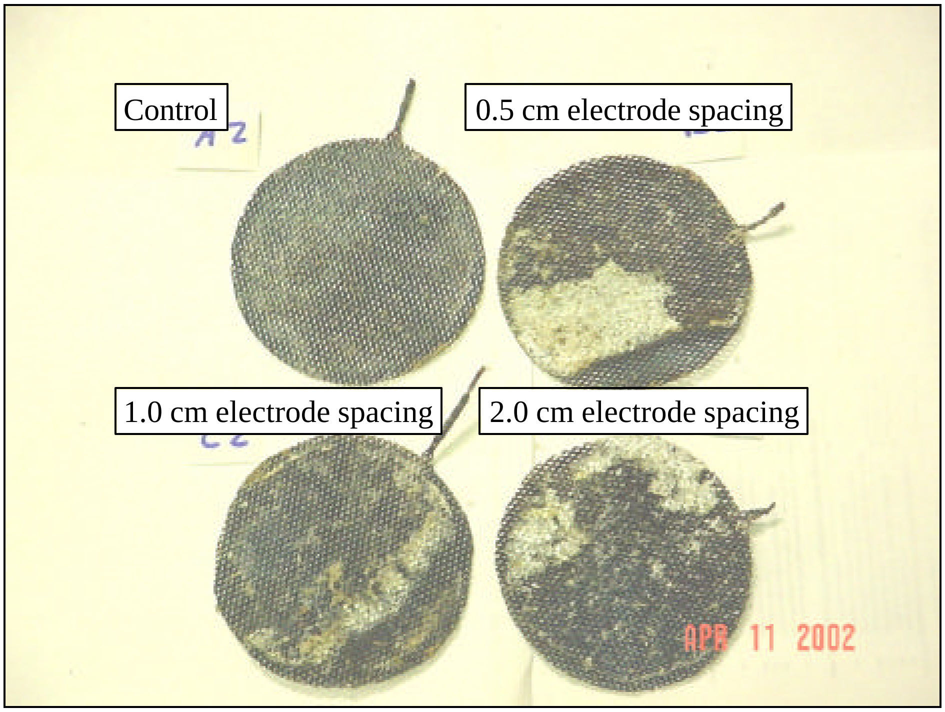


Figure 14. Scale formation on primary negative electrodes at the conclusion of the 10 week treatability study

Figure 15 presents profiles of TCE concentration along the column (the electrodes are at position 0). This suggests that most of the treatment appears to be occurring in the immediate vicinity of the electrodes. Figure 16 presents pe and pH as a function of position in the columns at 20 V. This data illustrates the geochemical affect of the e^- barrier within the context of site soils and groundwater. As a reference, pe+pH ~4 corresponds to sulfate-sulfide and carbon dioxide-methane in equilibrium.

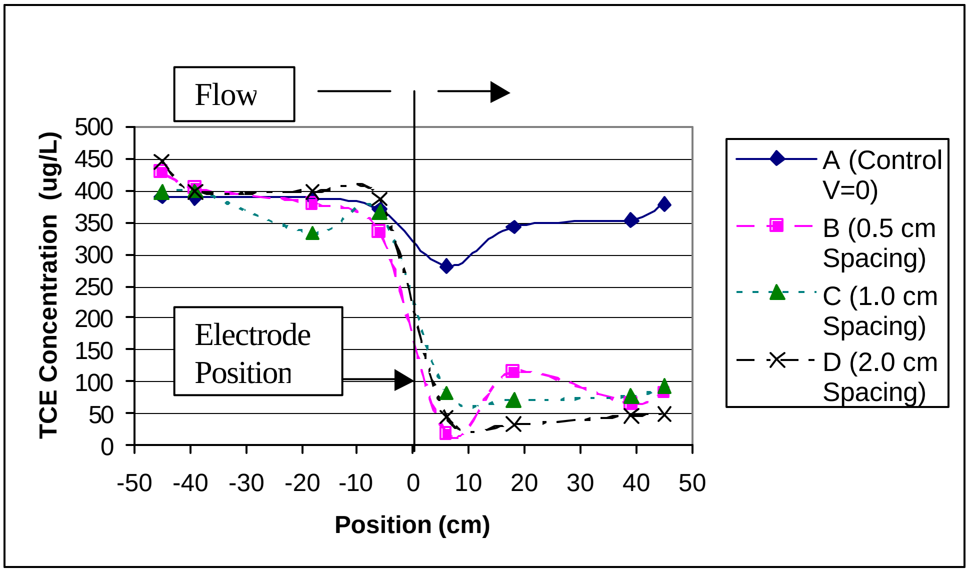


Figure 15. TCE as a function of position (20 V). Position 0 is the center of the electrode pack.

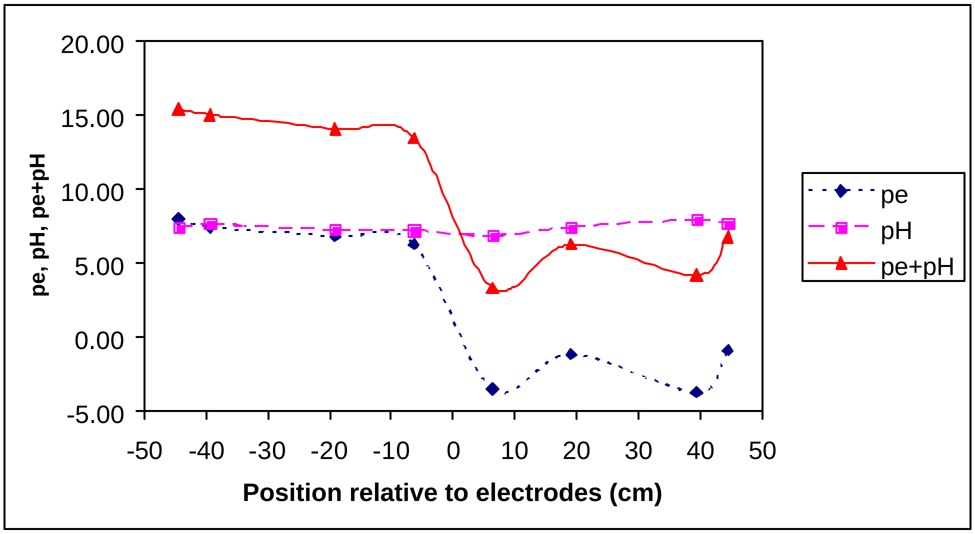


Figure 16. pe and pH as a function of position (10 V)

3.4.3 Tank Studies

Tank studies were undertaken with the primary objective of resolving construction details of the panel via construction of a small-scale model. Secondary objectives were to test the reliability of components, approach to monitoring, and performance.

The panels were constructed inside a slotted 3-inch ID PVC pipe frame. The horizontal pipe section at the bottom of the frame provides a sump for collection of sediment and scale. A hose extends into this sump for removal of these materials. The horizontal pipe section at the top of the frame is a gas collection header. A hose extending into the gas header allows flushing of fluids vertically through the panel (Figure 17).

The outside of the electrode panel is covered in an HDPE geotextile that limits intrusion of sand into the panel. The electrode panel includes three electrodes (same material as column studies) that are separated by HDPE Geonet spacers. The two panels are linked together by a sealable PVC interlock similar to that used in a sheet pile walls. Two linked panels are employed. This reflects plans to use multiple linked panels in the field demonstration. The concept of multiple linked panels arose from difficulties at the Borden site in the installation of a single 6-foot wide panel.

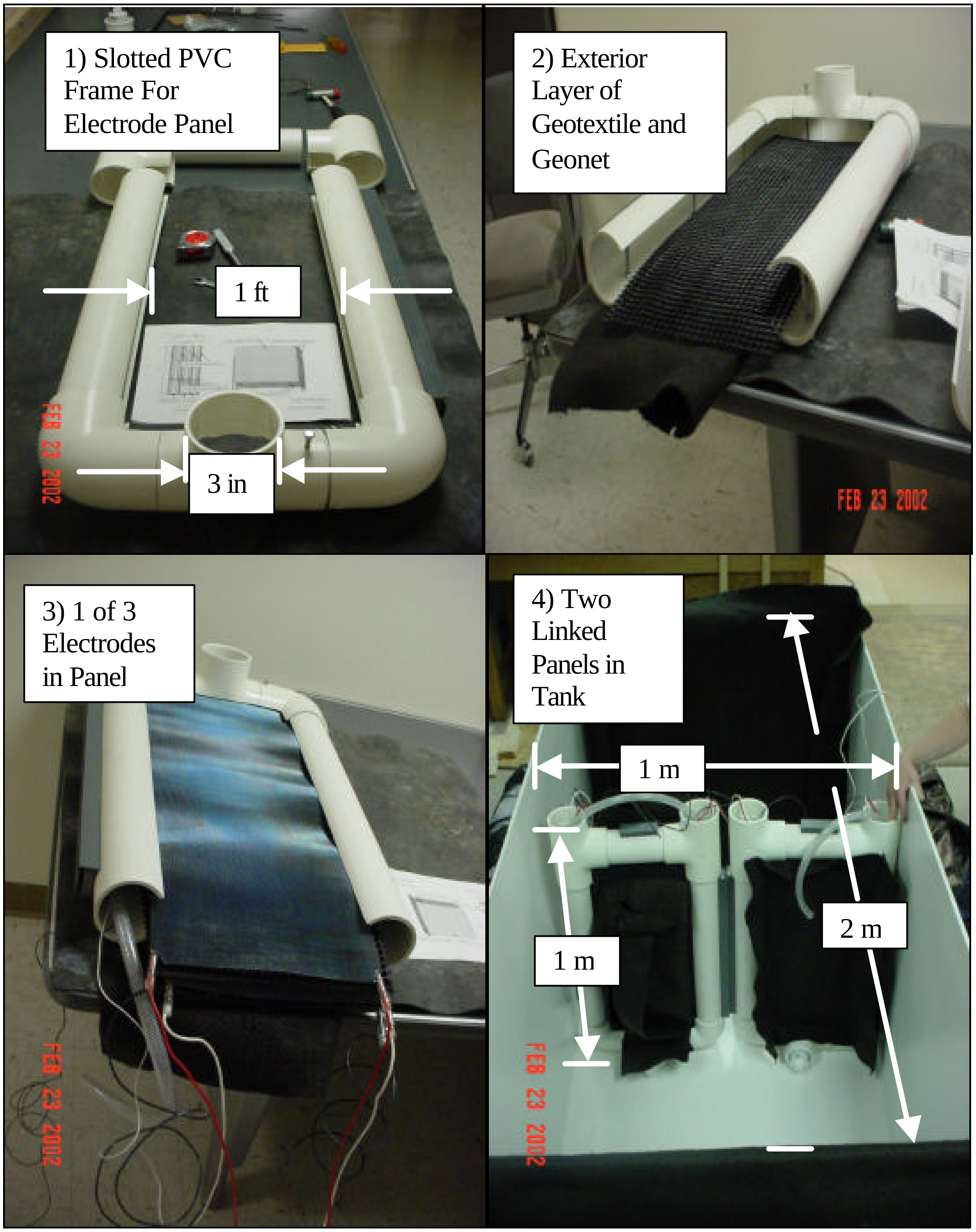
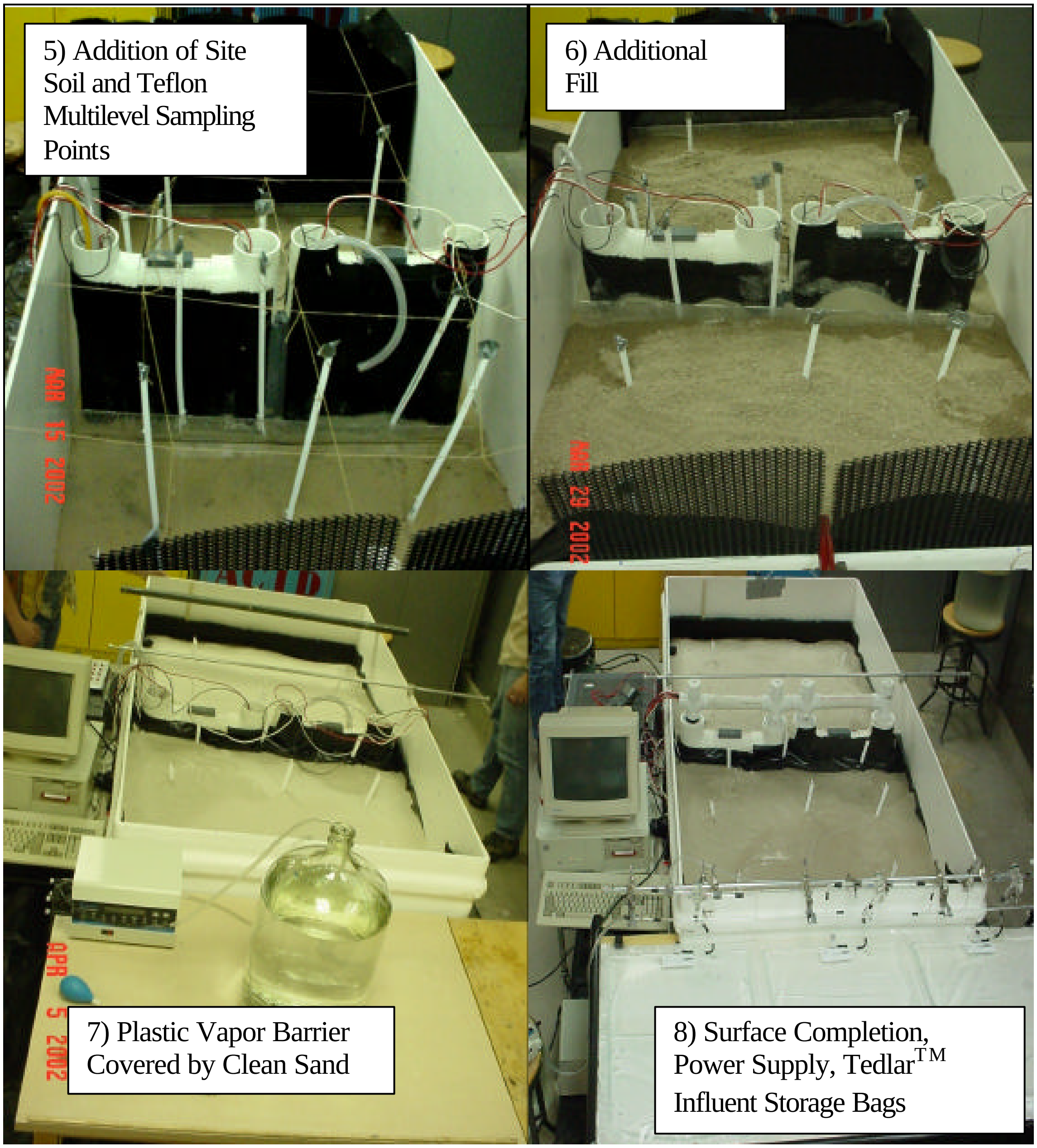


Figure 17. Development of electrode panel and installation in tank

Figure 18 illustrates filling of the tank, surface completion, and pumping systems. As a matter of practicality the soils were obtained from an off base borrow pit containing sediments similar to those encountered at F.E. Warren. Both access and frozen ground at F.E Warren limited us from acquiring tank soils from the site. The measured hydraulic conductivity of the tank sediments is essentially the same as the values measured in the field. Vertical pipes in the tank fill are Teflon sampling tubes covered with Nytex^{TM}

cloth at the *in situ* end. The Nytex^{TM} prevents sediment flow into the sample tubes. Overall, the panel design and sampling approach was based on the Borden Field Prototype.


5) Addition of Site Soil and Teflon Multilevel Sampling Points

6) Additional Fill

7) Plastic Vapor Barrier Covered by Clean Sand

8) Surface Completion, Power Supply, Tedlar^{TM} Influent Storage Bags

Figure 18. Addition of soil, multilevel sampling devices to the tank, surface completion and pumping systems

The primary result from the tank studies testing and was validation of the e^-barrier design. The field demonstration e^-barrier described in the following text is simply a scaled up version of the system developed in the tank studies.

3.5 Testing and Evaluation Plan

The following describes design, installation, operation, and monitoring of the field demonstration e^-barrier. This follows methods outlined in the Final Demonstration Plan (July 2002).

3.5.1 Demonstration Installation and Startup

3.5.1.1 e^-barrier Design

Based on 1) laboratory treatability studies (column and tank studies) and 2) the 4m^2 e^-barrier installed at Canadian Forces Base Borden, a modular e^-barrier design was developed. The design consisted of 17 individual modules (panels) each of the dimension 0.3 m x 2 m (Figure 20). The overall as-built dimension of the demonstration e^-barrier was 9.2 m x 1.9 m. The effective cross-section area is 17 m^2. Individual panels barrier modules were linked by concentric sealable interlocks (Figure 21). Each barrier module contained three Ti-mmo electrodes (ELTECH Systems, Chardon, OH), four layers of Geotextile^{TM}, and six layers of Triplanar Geonet^{TM} (Figure 19) and was framed in slotted 3" ID PVC pipe. The Geotextile^{TM} and Triplanar Geonet^{TM} are commercially available geotechnical products (TENAX Corporation, Baltimore MD). Each individual barrier module included discrete electrical connection, gas vents, and washout tubing.

Of the 17 modules, 7 included PVC centering guides and Teflon multilevel sampling bundles. The centering guides served two purposes: a) to facilitate centering the barrier within the trench box and b) to carry upgradient and downgradient monitoring points (Figure 23). The multilevel sampling bundles each consisted of 4 sampling points set at discrete depths. The deepest sample point is located immediately below the elevation of the bottom PVC pipe frame. The remaining points are located at 0.5, 1 and 1.5 meters above this point. The sampling points were constructed of 0.5 mm ID Teflon tubing screened with Nytex^{TM} mesh to prevent infiltration of formation material. Sampling bundles were placed on the upgradient and downgradient faces as well as the centering guides (upgradient 0.5 m and downgradient 0.5 m) associated with 7 panels to allow for three dimensional sampling of water quality in the vicinity of the e^-barrier.

The barrier components were fabricated at the Colorado State University Engineering Research Center. The barrier components were transported to F.E. Warren AFB immediately prior to installation and assembled on site.

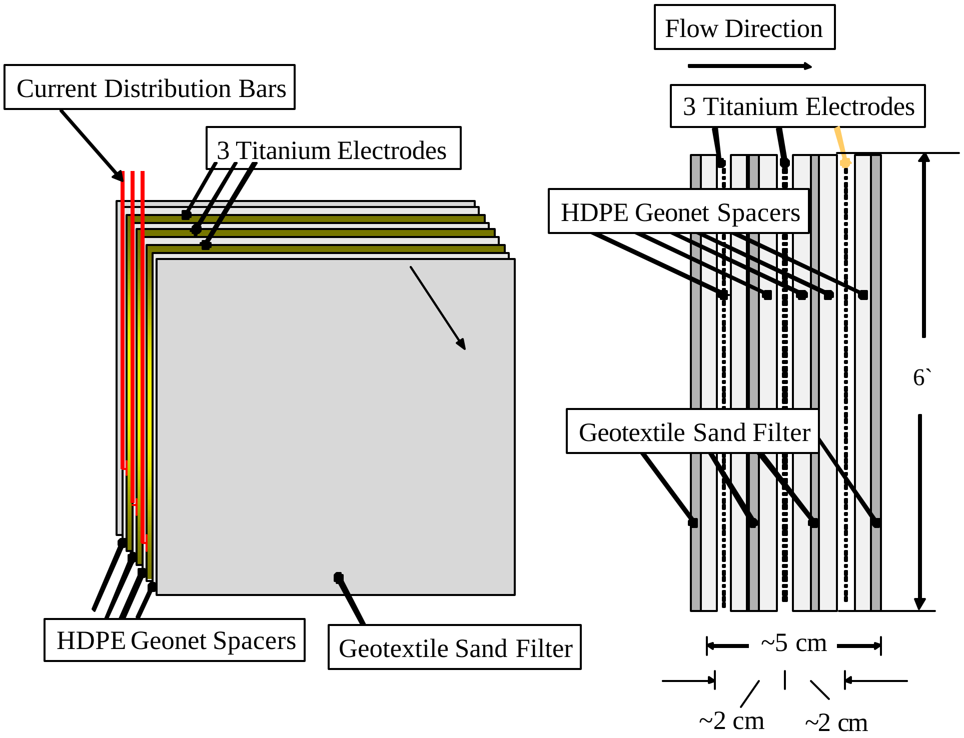


Figure 19. Composite panel detail

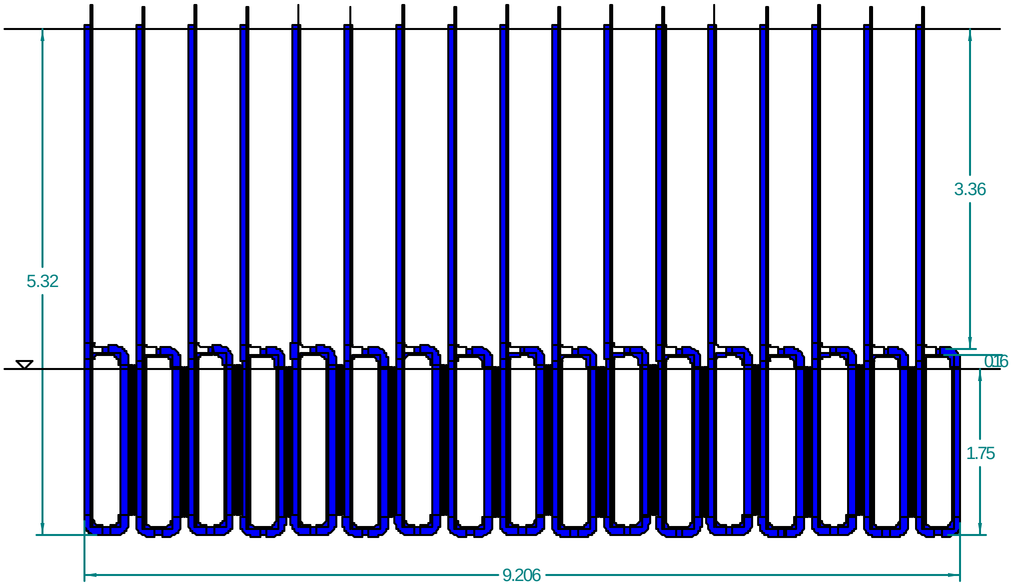


Figure 20. Demonstration e⁻barrier design indicating 17 individual modules (dimensions in meters)

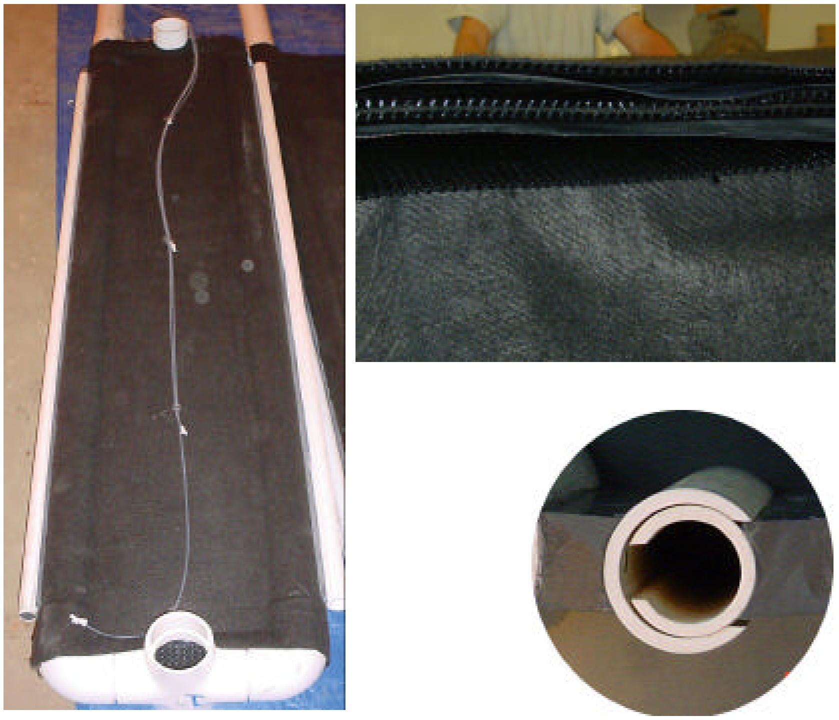


Figure 21. Demonstration e^{-}barrier components: clockwise from left: individual e^{-}barrier module (panel), e^{-}barrier material cross section, and module interlock

Figure 22. Demonstration e^{-}barrier and components prior to transport to F.E. Warren AFB

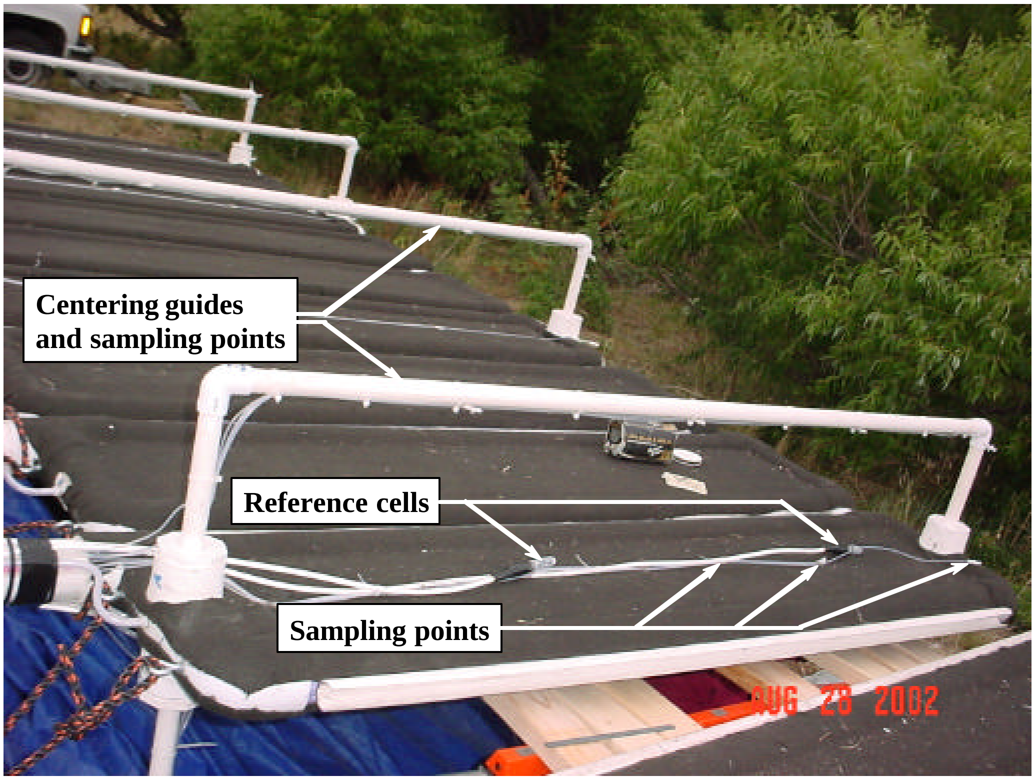


Figure 23. e$^-$barrier assembly including centering guides, sampling points and Ag/AgCl reference cells

3.5.1.2 e$^-$barrier Installation

Contractor Selection – A bid package was developed for installation of the e$^-$barrier and submitted to three pre-qualified contractors. The winning bidder was Envirocon (Golden, Colorado). The bid package is included in Appendix A. Following award of contract, a test excavation was conducted to evaluate conditions in the subsurface and appropriate techniques for barrier installation. The test excavation verified the presence of discontinuous caliche layers and potentially flowing sands. Based on the test excavation a trench box was selected as necessary shoring option for the e$^-$barrier installation.

The installation of the demonstration e$^-$barrier was conducted on August 26-27, 2002. Figure 24 and Figure 25 illustrate the initial excavation along the alignment of the temporary ESTCP monitoring wells. Coincidental with the excavation, the barrier components were assembled on site as shown in Figure 26 and Figure 27. Initially, nine of the e$^-$barrier modules were linked and placed in the trench (Figure 28 and Figure 29). Subsequently the trench box was advanced and the remaining eight panels were set.

During placement of the e$^-$barrier, backfill was added to stabilize the barrier and allow for advancement of the trench box. The backfill consisted of a well-sorted medium sand acquired from a local sand and gravel operation. The source of the backfill is the Crow

Creek alluvium. The backfill the same mineralogy encountered at the demonstration location.

Following placement of the e$^-$barrier, risers containing electrical connections, gas vents, washout tubing and multilevel sampling bundles were attached and extended (Figure 30). Additional backfill was added to approximately 0.6 m below final grade (Figure 31). Gas vents were finished within flush mounted enclosures, all piping manifolds were sealed to conduct gases to a vent pipe, and distal multi-levels sampling systems (1 and 2 m) were installed (Figure 32).

Electrical Systems - Electrodes in each individual module (panels) were connected in parallel. All wiring was placed below grade in PVC conduit. Power to the e$^-$barrier was supplied by a 30 VDC 200 amp single phase rectifier (Corrpro Companies, Medina, OH) shown in Figure 33. In December 2002, electrical service (110 VAC 60 amp) was extended to the e$^-$barrier location. This required completion of two ~60-foot horizontal borings under Missile Drive (contracted by CSU). F.E. Warren provided electrical service from a local transformer to a breaker box at the barrier. Electrical service includes a 110V 60 amp direct connection to the rectifier and a 110V 15 amp service for sampling equipment.

As built Location and Vertical Position - The demonstration e$^-$barrier was installed perpendicular to the observed direction of ground water along the alignment of the temporary wells ESTCP 1 - ESTCP 3. The e$^-$barrier was installed at an elevation of 6096.2 ft. This coincides with high watertable elevation observed in the 1-year period prior to installation. A schematic of the vertical and horizontal alignment relative to the temporary monitoring wells is given in Figure 34.

Figure 24. Initial topsoil removal prior to excavation for installation of demonstration e-barrier

Figure 25. Excavation prior to trench box installation

Figure 26. Layout of e^-barrier components prior to field assembly

Figure 27. Layout of e^-barrier components prior to field assembly

Figure 28. Lifting of nine linked e$^-$barrier modules (panels) prior to placement in trench

Figure 29. Placement of eight linked e$^-$barrier modules into the trench linking with in-place e$^-$ barrier modules

Figure 30. Backfilling of trench with imported soil. Note risers containing electrical connections, gas vests, washout tubing and multilevel sampling bundles

Figure 31. Top of risers prior to surface completion

Figure 32. Surface completion

Figure 33. Rectifier and programmable logic controller for electrode reversal (scale management)

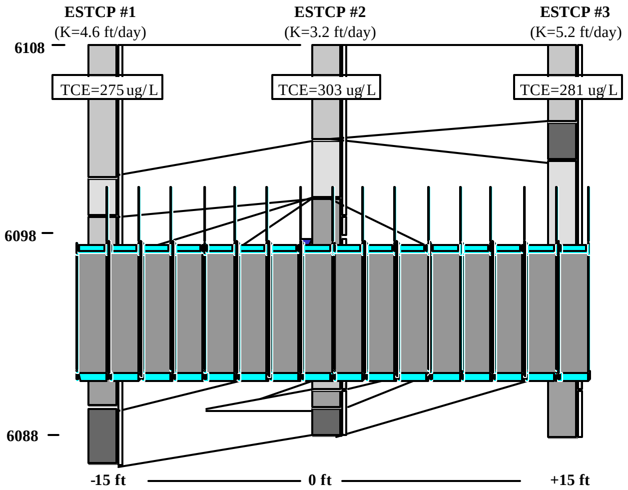


Figure 34. Location of e$^-$barrier in cross-section

3.5.1.3 Monitoring Systems

Water Quality/Water Level Monitoring Systems – Water quality monitoring is achieved using 144 multi-level groundwater sampling points located about the e$^-$barrier. Figure 35 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^{TM} screen. Samples are drawn from the sampling points using a peristaltic pump. As discussed above, multi-level sampling bundles were placed on the e$^-$barrier surfaces and 0.5 m up gradient and 0.5 m downgradient of the e$^-$barrier along seven transects. As such, these points were installed in conjunction with the barrier.

Eight additional multi-level sampling bundles were placed in the formation at the ends of the barrier and at positions 1 and 2 meters up and down gradient of the barrier. Sample tubes were attached to a ½-ID PVC pipe that also serves as a piezometer used to resolve groundwater flow direction. Elevations of the “off barrier” multilevel samplers were set to match sampling points attached to the barrier. Multi-level sampling systems at the ends of the barrier were placed prior to backfilling the trench. Multi-level samplers 1 and 2 meters up and down gradient of the barrier were installed using hollow stem auger drilling techniques. Unfortunately, a number the hollow stem auger sampling point were plugged by bentonite used to isolate the sample levels from one another. As such limited data is available from these systems. Final completion of multilevel sampling systems is illustrated in Figure 36 and Figure 37.

Electrical Monitoring Systems – Remote data acquisition is conducted using an eight-channel data recorder with wireless modem (Rohrback Cosasco Systems, Santa Fe Springs, CA). The system records applied voltage, resultant current, and electrode potential relative to the reference electrodes located on the surface of the e$^-$barrier. Data is collected on a 15-minute interval and downloaded to CSU via a wireless connection on a weekly basis.

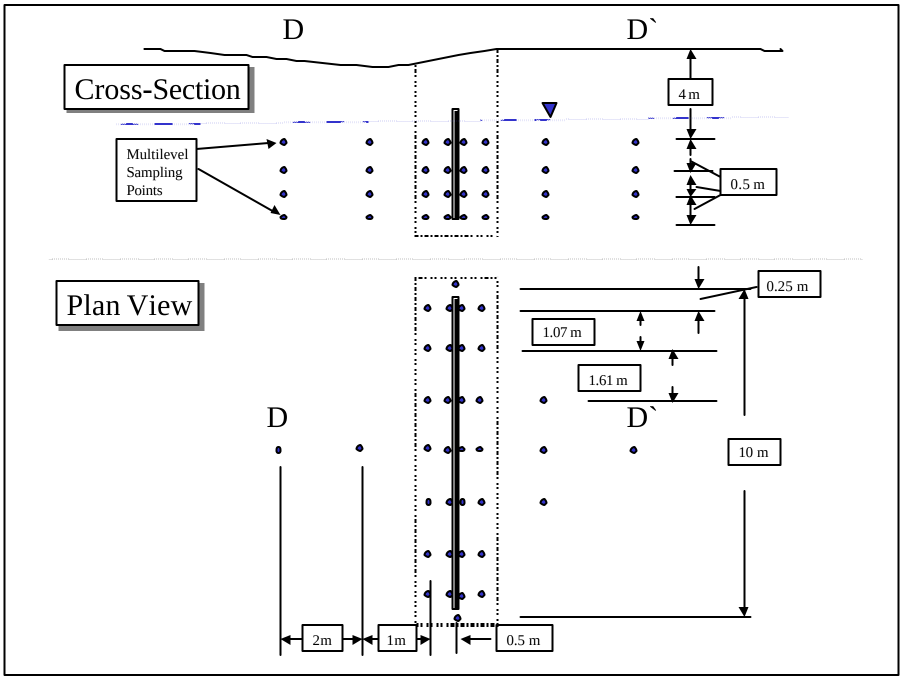


Figure 35. Network of water quality sampling points

Figure 36. Multi level sampling bundle surface completion

Figure 37. Final grade and sampling shelter

3.5.2 Period of Operation

Following installation on August 29, 2004, the e^-barrier was allowed to equilibrate with formation fluids for a period of approximately 5 months. Voltage was applied to electrodes on January 27, 2003. The demonstration has been in continuous operation since startup (~ 18 months as of 7/31/04).

3.5.3 Amount/Treatment Rate of Material to be Treated

The intent of this technology is to affect low flux boundaries within plumes. Based on formation seepage velocity of 0.37 feet per day, a formation porosity of 0.25, and a cross-sectional area of 17 m^2 the barrier treats 130 gallons of water /day. Assuming an average influent concentration of 300 µg/L, the barrier addresses ~ 140 mg of TCE /day.

3.5.4 Residuals Handling

The soil excavated from the zone of contamination during the installation of the demonstration e^-barrier was returned to the excavation. Field measurements made with a MiniRae 2000^{TM} indicated nondetect levels of VOC in the soils.

Purge water and reinstate associated with groundwater sampling is containerized and disposed of at Colorado State University in compliance with Colorado State University Environmental Health Services requirements.

CSU's Health and Safety Plan is presented in Appendix F.

3.5.5 Operating Parameters for Technology

The field demonstration was operated at three applied potential differences (E_{appl}), with one setting being duplicated. The potential differences applied to the barrier and the corresponding time periods of the demonstration are shown in Table 6.

Table 6. Applied potential differences and the corresponding time periods of the demonstration of the e^-barrier.

START DAY/END DAY	TOTAL NUMBER OF DAYS	APPLIED POTENTIAL DIFFERENCE
Pre-startup	151	0 V
0/120	120	3.1 V
121/290	169	6.5 V
291/399	108	4.9 V
400/500	100	3.1 V

3.5.6 Experimental Design

The overall experimental design is to evaluate e^-barrier performance over a range of applied potentials. At each voltage contaminant removal, electrical performance, and cost are evaluated. Comprehensive development of this topic is presented in Section 4 and in the Final Demonstration Plan (July 17 2002).

3.5.7 Sampling Plan

Chlorinated Solvents and Field Parameters – Comprehensive sampling of groundwater for TCE, TCE degradation products, and field parameters occurred initially, and at the end of each potential setting. In addition, these parameters were measured along the primary transect through the center of the barrier to resolve transient conditions at each potential setting. Samples are collected using a peristaltic pump, flow through cell, and a stainless steel sampling manifold. Approximately 100 mL is collected from the multilevel sampling points prior to collecting the VOC sample and recording the field parameters. Analytical methods are described in association with the column treatability studies (Section 3.3.2) and in Appendix B – Sampling and Analytical Plan.

Inorganic Parameters – A stated concern is that the imposed redox conditions may adversely affect inorganic water quality. Baseline conditions were evaluated prior to start up for comparison to conditions during the demonstration. In addition, inorganic parameters were measured at maximum and minimum potential settings of 6.5 and 3.1 V, respectively. Analyses are performed as described in Appendix B. Inorganic parameters are listed in Table 7.

Table 7. Inorganic parameters evaluated during the demonstration

Cations	**Anions**
Aluminum	Chloride
Calcium	Nitrate
Potassium	Nitrite
Magnesium	Phosphate
Sodium	Fluoride
Iron	Sulfate
Manganese	Carbonate
Chromium	Bicarbonate
Cadmium	
Copper	
Nickel	
Molybdenum	
Zinc	

Biological Analyses – A hypothesis of our work is that dechlorination reactions may be biologically mediated under field conditions. To assess changes in the microbial populations induced by the operation of the e^-barrier, and to obtain a first-level assessment of whether e^-barrier-induced biotransformation of TCE occurs at the site, three methods are used: (a) phospholipid fatty acid (PLFA) analysis and (b) total soil microbial DNA measurements.

Produced Gases – At an electrical potential of 6.5 volts, gases were collected from the surface vents and analyzed for VOCs (GC/TCD), fixed gases (GCMS - CO, CO_2, CH_4, N_2, O_2), and gas phase sulfides. In addition, per the health and safety plan, field meters were used to measure VOCs, hydrogen sulfide gas, carbon monoxide, and Lower Explosive Limit (LEL).

3.6 Analytical/Testing Methods

Details regarding Analytical methods are described in Appendix B.

3.7 Selection of Analytical Laboratory

Analytical work was conducted at Colorado State University Environmental Engineering Laboratory, Soil-Water-Plant Testing Laboratory, Central Instrument Facility, and Porous Media Laboratory. In addition:

- The University of Waterloo's Department of Earth Sciences laboratories were used for independent verification of VOC concentrations.

- Columbia Analytical Services Inc. and CH2M HILL Applied Science Laboratory were used for analysis of gas samples.

4. Performance Assessment

The following section presents data and results developed through the demonstration. Content follows Final Report Guidance for Cleanup and Site Characterization Projects (ESTCP, 2004).

4.1 Performance Criteria

Criteria used to evaluate the performance of the installed e^-barrier are outlined in Table 8.

Table 8. Performance Criteria

PERFORMANCE CRITERIA	DESCRIPTION	PRIMARY OR SECONDARY
TCE Mineralization	Decrease in TCE concentrations in groundwater downgradient of the barrier	Primary
Ionic Contaminant Mobility	Ionic species mobility may be increased or decreased. Mobility of other redox sensitive species may be altered.	Secondary
Hazardous Materials	Reaction intermediates (1,1-DCE, c-1,2-DCE, t-1,2-DCE, VC) may be formed and migrate out of the treatment zone.	Primary
Process Waste	Hydrogen gas – a very low volume will diffuse to the surface – Disposal: vented to the atmosphere. Oxygen gas – a very low volume will diffuse to the surface – Disposal: vented to the atmosphere. Secondary reaction products	Secondary
Factors Affecting Technology Performance	The main factor identified that may affect performance of the barrier is the presence of carbonate geology and aqueous phase carbonate species. Precipitation of carbonates has been shown to reduce the efficacy of the barrier in laboratory experiments. Active measures are available to control carbonate precipitation. Other, less critical factors are contaminant flux and the presence of other contaminants.	Primary
Reliability	Power loss to the barrier would result in process disruption but performance would quickly rebound following restoration of power.	Secondary

PERFORMANCE CRITERIA	DESCRIPTION	PRIMARY OR SECONDARY
Ease of Use	Once the barrier is installed, weekly inspections and data collection will be conducted.	Primary
Versatility	Based on ongoing laboratory research, the e^- barrier has the potential to be used to treat a wide range of contaminants (e.g. PCE, 1,1,1-TCA, BTEX, explosives, MTBE). This demonstration will provide information regarding field applicability of the e^-barrier for treatment of TCE in shallow alluvium.	Primary
Maintenance	Routine maintenance involves precipitate management activities (polarity shifts), gas sampling and disposal, connection inspection, data downloading from data logger.	Primary
Scale-Up Constraints	The barrier is limited to shallow installations. Large length barriers may require modular installation.	Secondary

4.2 Performance Confirmation Methods

The demonstration has provided the information necessary to evaluate the suitability of an e^-barrier for site-specific use. Specifically, data collected regarding efficacy, cost, and construction are used in the application evaluation. All efficacy and performance related data were collected as described in Section 3 and according to the Quality Assurance Project Plan (Appendix D). Performance criteria, expected performance, confirmation methods, results, and relevant sections of the report are tabulated in Table 9.

Table 9. Expected Performance and Performance Confirmation Methods

PERFORMANCE CRITERIA	EXPECTED PERFORMANCE METRIC (PRE DEMO)	PERFORMANCE CONFIRMATION METHOD	ACTUAL (POST DEMO)	REPORT SECTION
Primary Criteria (Quantitative)				
TCE Mineralization	Decreased groundwater TCE concentration downgradient of barrier	Sampling and analysis of water samples using all methods described above	Reduced TCE mass flux and lowered concentrations at downstream location to levels near the MCL	4.3.1

PERFORMANCE CRITERIA	EXPECTED PERFORMANCE METRIC (PRE DEMO)	PERFORMANCE CONFIRMATION METHOD	ACTUAL (POST DEMO)	REPORT SECTION
Hazardous Materials	Concentrations of reaction intermediates lower than MCL	Sampling and analysis of water samples to evaluate water quality improvements	Only c-1,2-DCE observed; levels decreased after power was applied	4.3.2
Factors Affecting Technology Performance	Carbonate precipitates minimal	E_h measurements, inspection upon decommission	Treatment efficiencies and current densities suggest this was not a significant problem over the period of operations	4.3.3
Primary Criteria (Qualitative)				
Ease of Use	Operator training limited	Experience from demonstration operation	Operations were simple, Minimal special training	4.3.4
Versatility	Suitable for a wide range of contaminants in shallow alluvium	TCE concentration measurements and field installation experience	Effective for TCE in shallow alluvium	4.3.5
Maintenance	Gas venting requirements and precipitate management inspection	Experience from demonstration and operation	Nominal level of effort required for system maintenance	4.3.6
Secondary Criteria				
Ionic Contaminant Mobility	Minor changes in pH and inorganic water quality	Sampling and analysis of water samples for inorganic species to evaluate water quality	Redox conditions were affected, but no inorganic species were mobilized	4.3.7
Process Waste	Low gas generation rates, Minimal impact of secondary reactions	Observation	Gas generated was adequately vented, Chloroform production limited potential ranges studied	4.3.8
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	4.3.9
Scale-Up Constraints	Ease of construction	Experience from demonstration installation	Modular design allows expansion, Opportunities for improvement exist	4.3.10

4.3 Data Analysis, Interpretation, and Evaluation

Detailed analysis of the performance data is presented in this section. The subsections are divided according to the criteria in Table 9. Each subsection evaluates data against the expected performance metrics using the methods corresponding to the criteria. A control plot or system was not a feasible element of the project. Alternatively, preliminary site characterization data, pre-power conditions through the system, and water quality upstream of the e^-barrier are used to resolve the effects of the e^-barrier.

4.3.1 TCE Mineralization

Contaminant removal via *in situ* degradation is a primary performance metric. Downstream TCE concentrations were expected to decrease due to treatment in the vicinity of the e^-barrier. System performance in this category was evaluated by measuring TCE concentrations and casting results in terms of flux reduction. The affects of spatial variability, temporal variability, and operating parameters are considered.

Recognizing that each sample point represents an equal area and assuming that flow is uniform through the panel, the total influent and effluent flux of constituent *i* can be estimated as:

$$M_i = \overline{C}_i Q$$

Where:

$\overline{C}_i$ = The average concentration of constituent *i* (M/L^3)
Q = Groundwater discharge through the barrier (L^3/T)

The percent flux reduction for any constituent *i* is estimated as:

$$\%F_{reduction} = \frac{M_{\text{influent}_i} - M_{\text{effluent}_i}}{M_{\text{influent}_i}} \times 100\% = \frac{\overline{C}_{\text{influent}_i} - \overline{C}_{\text{effluent}_i}}{\overline{C}_{\text{effluent}_i}} \times 100\%$$

This simplified calculation of flux does not account for flow heterogeneity about the e^-barrier. The homogeneous backfill used during installation minimizes flow heterogeneity immediately upgradient and downgradient of the e^-barrier, minimizing the error associated with for use of this simplified flux calculation.

Groundwater samples were collected from multi-level sampling points to evaluate TCE flux reduction. Aqueous concentrations measured during the demonstration were evaluated for precision, accuracy, and cross-contamination as described in the Quality Assurance Project Plan (Appendix D). Precision and accuracy were checked using relative percent difference (RPD) and percent recovery, respectively. The quality assurance results indicate:

- The average RPD for the 40 duplicate field samples collected was 9%. Five of the 40 were above the 20% limit of the QAPP acceptance criteria. The average RPD of the remainder was 5%.
- Percent recovery varied between 90% and 110%, also within the limits of the QC acceptance criteria.

- Trip, field, laboratory, and field rinsate blanks used to ascertain cross-contamination were below method quantitation limits for all samples except 5 out of 187. All blanks with a concentration greater than the quantitation limit were field rinsate blanks.
- Duplicates shared with an outside laboratory (University of Waterloo, Waterloo, Ontario, Canada) had an average RPD of 22%. Although this value was slightly outside the RPD acceptance limits, given the travel time and distance between the facilities it was an acceptable duplication of results.
- Overall percent completeness of analysis was greater than 95%.

Based on the level of completeness, the approach to sample collection and data analysis was deemed acceptable for performance evaluation.

Sampling transects perpendicular to the barrier were used to resolve TCE flux reduction at seven locations along the e^-barrier. At each distance, along each transect, the measurements from three sampling points influenced by the e^-barrier were averaged. The influent TCE concentration was calculated by averaging the TCE concentration at the locations 0.5 m upgradient of the e^-barrier. TCE flux reduction was calculated by comparing mean concentration at 0.5 meters upgradient to average concentrations at:

- the upgradient face of the e^-barrier,
- the downgradient face of the e^-barrier, and
- 0.5 m downgradient of the e^-barrier.

For clarity, the locations of these points are shown in Figure 38.

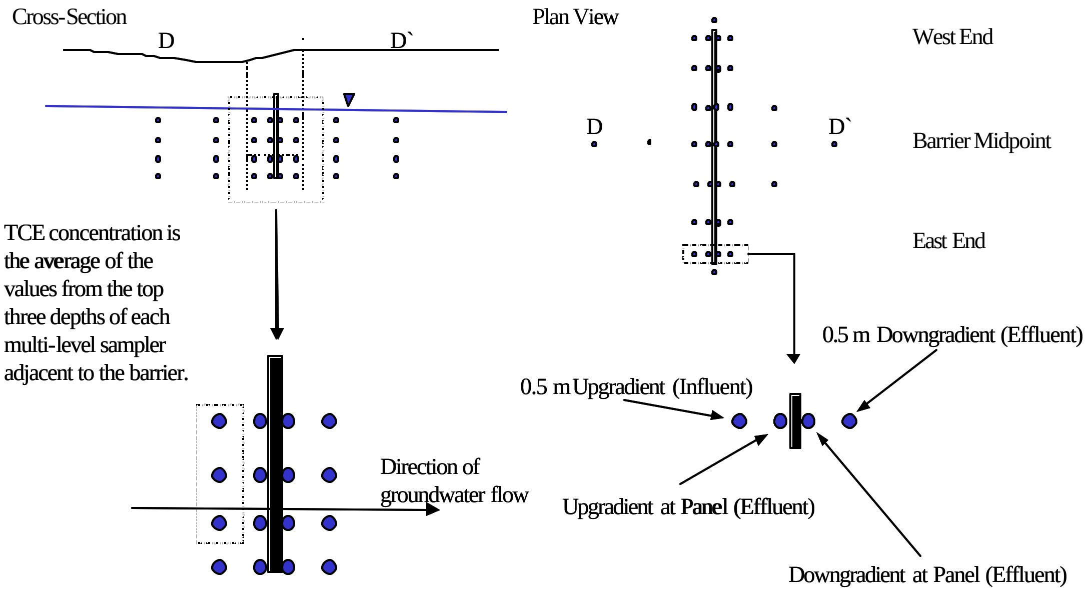


Figure 38. Monitoring points used in TCE mass flux reduction calculations

TCE flux reduction was calculated for each sampling event at the seven transects through the e^- barrier. The majority of the sampling activity occurred along the midpoint of the e^- barrier. Less frequent sampling occurred at the six off-center transects, located ±1.61 m, ± 3.22 m, and ± 4.29 m from the e^- barrier midpoint. The results are presented for each transect over time in Figure 39.

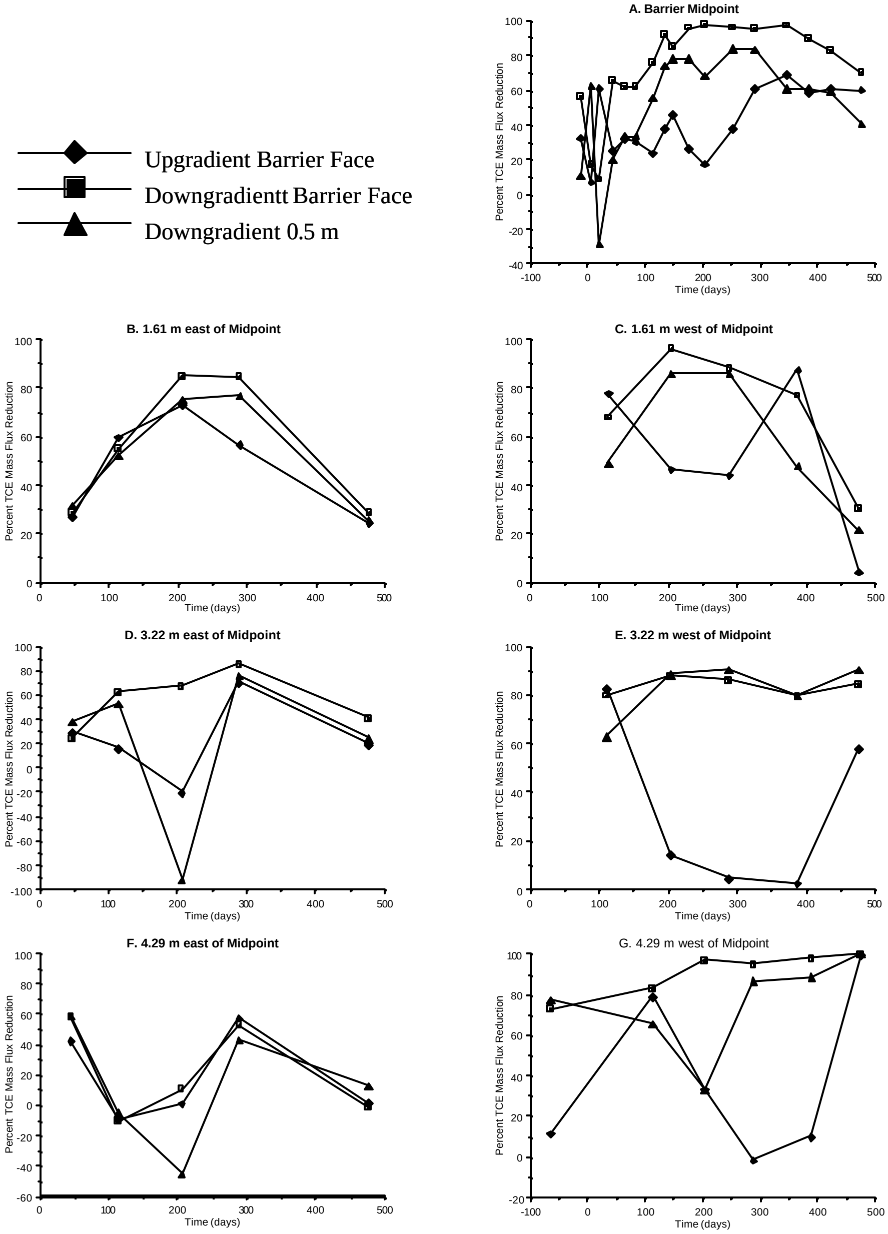


Figure 39. Percent TCE mass flux reduction at the upgradient e^- barrier face (diamonds), downgradient e^- barrier face (boxes), and 0.5 m downgradient (triangles) locations. Each location is from a perpendicular plane the stated distance from the e^- barrier midpoint. Power was applied to the e^- barrier at day 0.

Consistent with results from the pre-demonstration treatability studies, TCE flux reduction is dependent on the electrical potential difference applied to the electrodes. The field demonstration was operated at three applied potential differences (E_{appl}), with one setting being duplicated. The potential differences applied to the e^-barrier and the corresponding time periods of the demonstration are shown in Table 10.

Table 10. Applied potential differences and the corresponding time periods of the demonstration.

START DAY/END DAY	TOTAL NUMBER OF DAYS	APPLIED POTENTIAL DIFFERENCE
0/120	120	3.1 V
121/290	169	6.5 V
291/399	108	4.9 V
400/500	100	3.1 V

The relationship between E_{appl} and mass flux reduction was examined by focusing on the plane at the barrier midpoint (Figure 39 A). Observed flux reduction was greatest when $E_{appl} = 6.5$ V (day 121 - 290). During this period, flux reduction along the center transect of the e^-barrier was 95% (Figure 39 A).

The data indicates that flux reduction at 0.5 meters downgradient is less than that observed at the downgradient face of the e^-barrier. TCE flux reduction (on the center transect) at 0.5 m downgradient reaches a maximum of 80%. Lower flux reduction at 0.5 m downgradient is not rigorously understood. Potential factors include:

- Slow desorption from downgradient sediments
- Flow through joints
- Flow around, under, or over the e^-barrier

The concept of flow around or over the e^-barrier is conceptualized in Figure 40. Further consideration of non-ideal flow paths about the e^-barrier is presented in subsequent sections.

Non-ideal flow paths through the barrier are not expected to influence the measured concentrations on the downgradient face of the e^-barrier since the sampling points include groundwater collected from the interior of the e^-barrier.

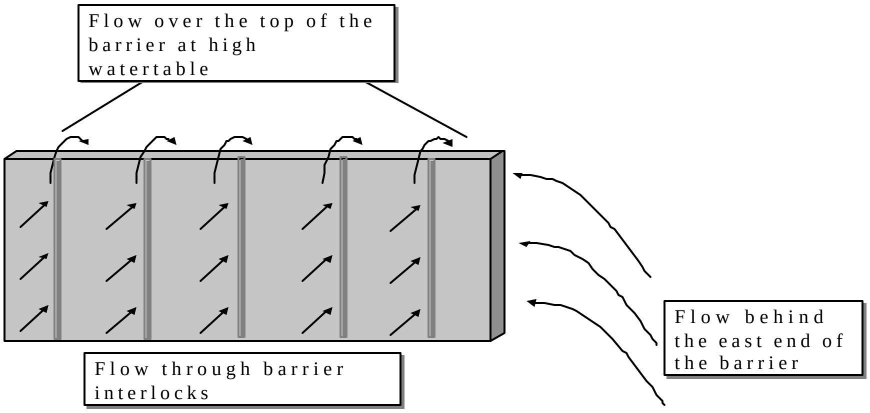


Figure 40. Potential non-ideal flow paths about the e$^-$barrier

Apparent TCE flux reduction varied along the e$^-$barrier. Comparing Graphs D and F with Graphs E and G of Figure 39 illustrate this observation. Negative flux reduction, shown in these graphs, occurred when downstream TCE concentration was larger than upstream concentration. Contaminant flux reductions at locations west of the e$^-$barrier midpoint are approximately 40% to 150% greater than those on the east side of the e$^-$barrier, regardless of the E_{appl} setting.

Examining the water table surface about the e$^-$barrier provides insight into the apparent variability of flux reduction along the e$^-$barrier. The depth to water was measured at ten locations about the e$^-$barrier over the course of the demonstration. The resulting water table surface is presented in Figure 41 at day (-11), day 291, and day 491. The surfaces were generated using a linear interpolation algorithm with extrapolation beyond the domain of data points. In general, the angle of flow through the e$^-$barrier appears to increase with time. The greatest potential for flow around the barrier appears to occur on the eastern end (3.22 m and 4.29 m east of the barrier midpoint). Consistent with the low apparent TCE flux reduction in Figure 39 D & F, water quality on the eastern end of the e$^-$barrier shows limited improvement through the demonstration.

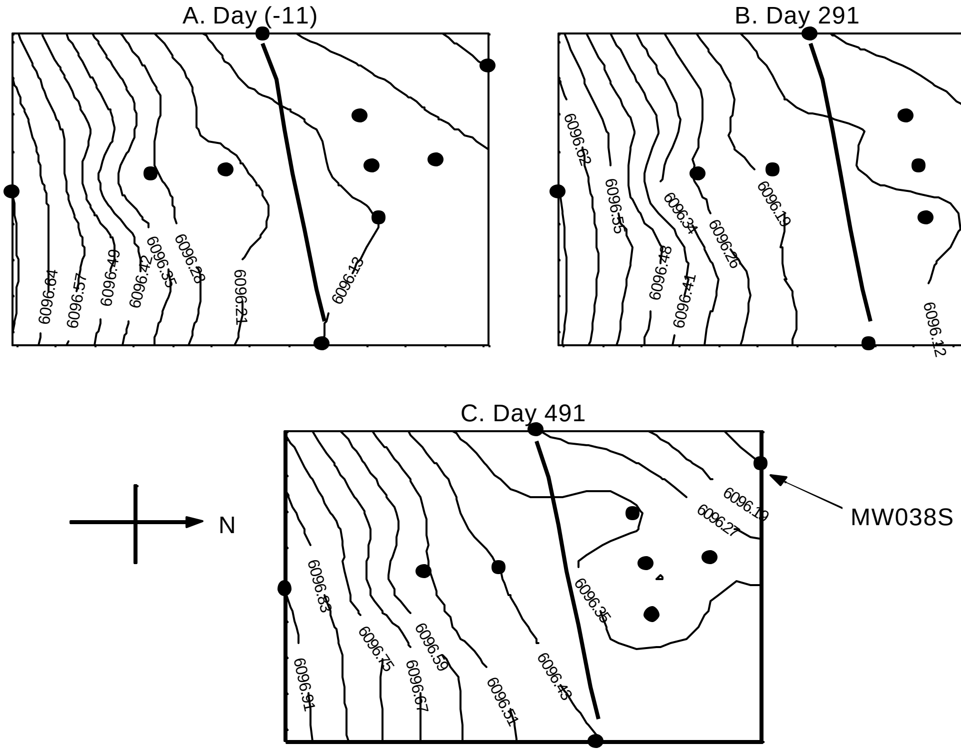


Figure 41. Water table surface at the demonstration site on A. day (-11), B. day 291, and C. day 491. Water table elevation is given in ft. The points are the locations of the depth to water measurements and the solid line is the location of the e^-barrier. Monitoring well MW038S is denoted in the Figure C.

Figure 42 presents average TCE flux reduction for the entire e^-barrier excluding data from the two eastern-most transects. Excluding the two eastern-most transects is based on results that appear to be an artifact of flow behind the e^-barrier. Figure 42 results are presented with respect to E_{appl} to illustrate the relationship between potential difference and TCE flux reduction. The spatial variability in TCE concentration prevented a meaningful statistical analysis of the data. However, inferences can be drawn based on the observed trends. As expected, TCE flux was reduced when power was applied to the system, and the reduction increased at larger E_{appl} values. The largest average reduction at the downgradient face of the e^-barrier was approximately 90% at E_{appl} = 6.5 V. Slightly lower flux reductions were calculated at the downgradient face for E_{appl} = 4.9 V. In general flux reduction observed during the second 3.1 V setting is similar or possibly lower than observed during the first. Potential reasons for lower flux reduction at the second 3.1V setting include scale accumulation on the electrode surfaces and/or altered properties of the electrodes.

There are currently two hypotheses regarding the high (approximately 50%) flux reduction observed prior to application of the first test voltage; a) adsorption of TCE to materials used in the construction of the e^-barrier, and b) catalytic reduction of TCE at the Ti-mmo surface of the electrodes. It is likely that adsorption to the HDPE geonet and geotextile is a more significant process. Additional equilibration time prior to barrier startup would have minimized this confounding variable, but the time allotted for the demonstration precluded a longer equilibration period.

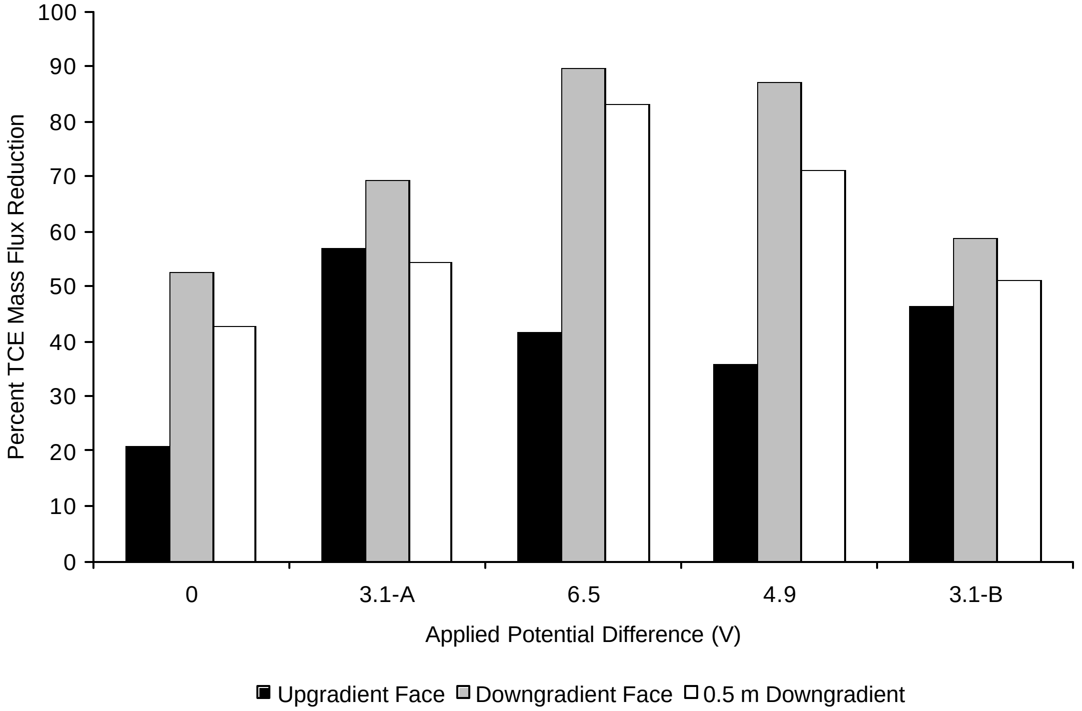


Figure 42. Barrier-wide percent TCE mass flux reduction at each E_{appl} tested during the demonstration. The settings appear in chronological order from left to right on the x-axis, such that 3.1 V-A took place before 3.1 V-B.

Further insight into performance can be gained through direct examination of TCE concentration data, presented in cross-sections parallel and perpendicular to the e^-barrier. The data is posted along with isoconcentration contours in Figure 43 and Figure 44. A full set of cross-sections is presented in Appendix E, including concentrations observed prior to energizing the e^-barrier.

The following analysis focuses on TCE concentrations measured at the end of the 6.5 V setting, which provides the best representation of the potential efficacy of the technology. Figure 43, presents contour plots perpendicular to the e^-barrier at 0.5 m upgradient, upgradient face, downgradient face and 0.5 m downgradient. Concentrations in Figure 43A depict heterogeneous TCE concentrations ranging from 3 to 371 µg/L at 0.5 m upgradient of the barrier. At the downgradient face of the barrier (Figure 43 C) concentrations are reduced by an order of magnitude to levels approaching or below the MCL for TCE. The best performance appears to be achieved on the left, or western, end of the e^-barrier.

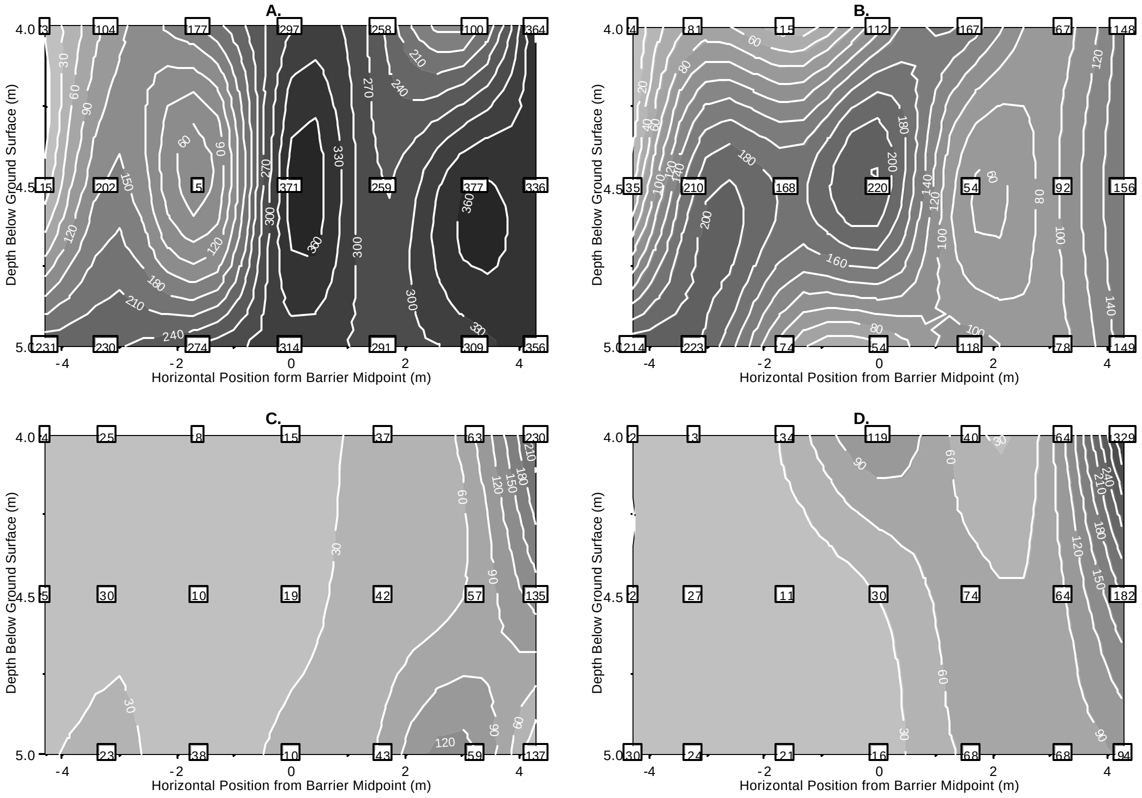


Figure 43. TCE concentration contour plots looking downgradient for E_{appl} = 6.5 V at A. 0.5 upgradient of the e^-barrier, B. upgradient face of the e^-barrier, C. downgradient face of the e^-barrier, and D. 0.5 m downgradient of the e^-barrier. Negative horizontal positions are to the west of the e^-barrier midpoint, and positive positions are to the east. All concentrations are reported in µg/L. Boxes show measured concentrations at that location.

Observation of the transect parallel to groundwater flow (i.e. a perpendicular slice through the e^- barrier) provides additional understanding of concentration reductions across the e^-barrier. A cross-section of concentration parallel to groundwater flow, at the barrier midpoint, is presented in Figure 44. TCE concentrations generally decreased from upgradient to downgradient except from the downgradient face to the 0.5 m downgradient positions.

The slightly higher concentrations observed 0.5 m downgradient of the e^-barrier were generally inconsistent with the laboratory studies and with our experience with an e^-barrier prototype tested at Canadian Forces Base Borden, Ontario, Canada. Further insight is gained by plotting average TCE concentration over time (Figure 45). In general, relative differences in TCE concentrations at the downgradient face, and 0.5 m downgradient, track over time, suggesting that desorption is not a dominant factor sustaining downgradient concentrations. If desorption was an important process, we would expect a time delayed concentration response at 0.5 m downgradient, relative to the downgradient face of the e$^-$barrier.

Other factors such as the size of the e$^-$barrier and its orientation to the natural hydraulic gradient may have influenced the apparent TCE concentration rebound at the downstream discrete and vertically integrated sampling points. Since the regional gradient is not normal to the e$^-$barrier, water quality at downstream locations was likely influenced from outside of the barrier zone of influence. This would partially explain the trends observed in Figure 45.

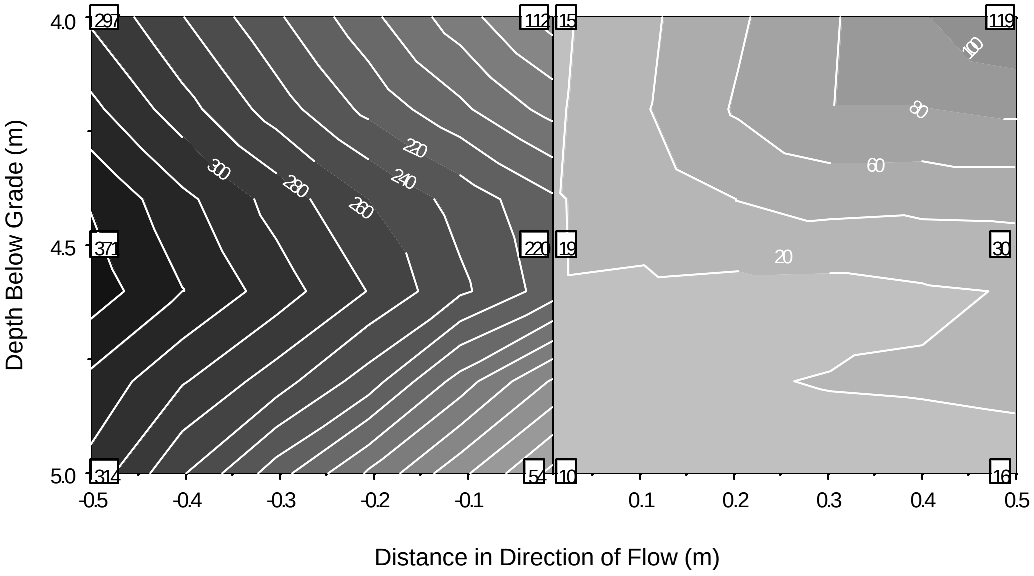


Figure 44. TCE concentration contour plot of a plane parallel to groundwater flow through the midpoint of the e$^-$barrier (on day 290, 6.5V). Positive distances are downgradient and the e$^-$barrier is located at the 0 m position. TCE concentration is reported in µg/L. Boxes show measured concentrations at that location.

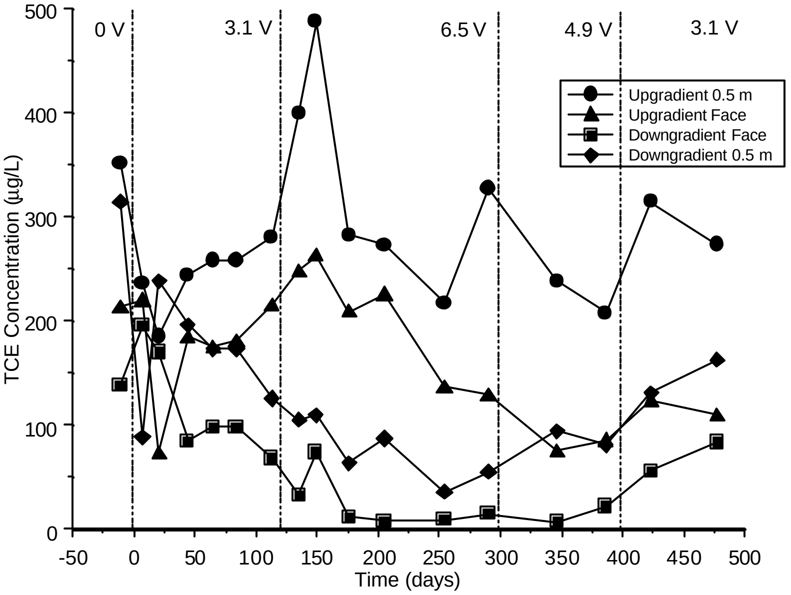


Figure 45. Average TCE concentrations along the transect parallel to groundwater flow at the e^-barrier midpoint. Values are arranged from 0.5 m upgradient of the barrier (circles), upgradient face of the barrier (triangles), downgradient face of the barrier (boxes), and 0.5 m downgradient of the barrier (diamonds). Power was applied to the e^-barrier at day 0.

Effects of the reduced TCE mass flux were realized beyond locations 0.5 m downstream of the e^- barrier during the demonstration. Concentrations measured at multi-level sampling points 2 m and 4 m downstream decreased from pre-demonstration background levels over the course of the demonstration. The largest decrease occurred at the end of 6.5 V setting, at day 290. Reduced concentrations were also measured at a pre-existing monitoring well, MW038S. After 290 days of operation, the concentration in MW038S decreased to 245 µg/L from an initial level of 300 µg/L. The data from downstream monitoring points is included in Appendix E, Figure E-6.

Estimates of the time to reach the MCL at downstream locations after E_{appl} = 6.5 V are developed using a simple advection-dispersion-retardation transport model. Building on Domenico and Schwartz (1998), the model employed is:

$$C_{TCE}(x,t) = \frac{C_{TCE,0}}{2}\,\mathrm{erfc}\left(\frac{Rx - vt}{2\sqrt{RDt}}\right) - \frac{C_{TCE,0}}{2}\,\mathrm{erfc}\left(\frac{Rx - vt`}{2\sqrt{RDt`}}\right) + C_{background}$$

Where:

C_{TCE}(x,t) = TCE concentration as a function of position (x) and time (t),
$C_{TCE,0}$ = Initial TCE concentration,
R = Retardation factor (3.7),
v = Groundwater seepage velocity,

D = Dispersion coefficient (6.5×10^{-7} m^2/sec),
t = Time to steady state through the domain of interest
t` = Time since the flux was reduced to background
$C_{background}$ = Assumed concentration at barrier
erfc = Complementary error function.

Assumptions used to model downgradient responses to the e^-barrier include:

- The problem can be sufficiently modeled in one dimension assuming a homogeneous domain
- The initial TCE concentration was 300 µg/L everywhere within the aquifer
- When E_{appl} was increased to 6.5 V, the TCE concentration at the downgradient face of the e^-barrier became 5 µg/L instantaneously
- The dispersion coefficient (6.5×10^{-7} m^2/sec) is estimated based on chloroform transport downstream of the electrode discussed in subsequent text
- The retardation factor (3.7) is based on adsorption studies conducted using excavated soils as part of an independent ongoing project with the Air Force Center for Environmental Excellence.

Observed and predicted results are presented in Figure 46. The timeframe for the model begins when E_{appl} = 6.5 V (i.e., day 121 of the demonstration is day 0 of the model). The TCE concentration profile at day 170 was chosen to compare the predicted results with values measured in the field at the end of the 6.5 V period of operation. This period occurred from day 121 to 290 of the demonstration, roughly 170 days in duration. Profiles at days 500 and 1000 are included to provide an estimate for the time required to reach the MCL at locations up to 8 m downstream of the e^-barrier. In general, the results suggest that hundreds of days will be required for the effect of the barrier to extend to MW038 located 8 m down gradient of the e^- barrier. This result reflects a limitation common to all source control remedies that reduce flux at a plane (e.g. ZVI PRBs, hydraulic barriers, and source treatments that reduce contaminant flux).

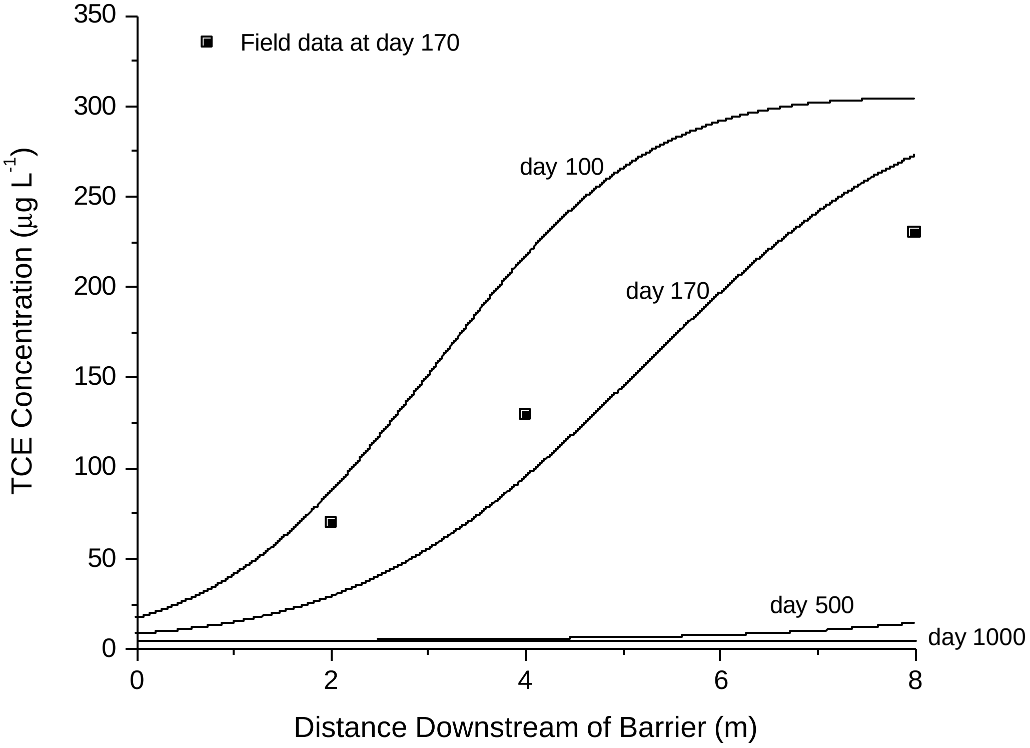


Figure 46. Modeled TCE concentration profiles downstream of the e$^-$barrier at day 100, 170, 500 and 1000 of operation at 6.5 V. Field TCE measurements at day 170 (day 290 of demonstration) after changing E_{appl} are marked as boxes.

4.3.2 Hazardous Materials

The soil excavated from the zone of contamination during the installation of the demonstration e$^-$ barrier was returned to the excavation. Field measurements made with a MiniRae 2000^{TM} indicated nondetectable levels of VOC in the excavated soils.

Purge water and rinsate associated with groundwater sampling is collected and disposed of at Colorado State University in compliance with Colorado State University Environmental Health Services requirements.

Potentially hazardous materials generated through technology operation is described in Section 4.3.8 - Process Waste.

4.3.3 Factors Affecting Technology Performance

A primary challenge to long-term e^-barrier performance is precipitation of inorganic species at the electrode surfaces. The primary concern is high-pH conditions generated at the cathode that favors precipitation of carbonate minerals (e.g. $CaCO_3$). Precipitate formation was visually identified in the pre-demonstration column and tank experiments (Figure 14). Precipitation at the electrodes is believed to affect performance by reducing the surface area available for reactions that degrade contaminants. System current density and geochemical water quality were used to investigate the effect of precipitate formation. Plans to excavate a portion of the e^-barrier for visual inspection are currently scheduled for July 2005.

Current density was used as an indicator for scale formation since this parameter is directly correlated to the electrode area available for electron transfer. A substantial decrease in current density over time can result from either a decrease in available area or a change in other parameters such as electrical conductivity of the groundwater. Current through the e^-barrier was recorded on 15-minute intervals during the demonstration. Current density was calculated from the total current using the bulk area of the electrodes. Depth to groundwater measurements were used to define the wetted area of the e^-barrier. The results of the current density normalized to wetted area are presented in Figure 47. Water table elevations at the e^-barrier endpoints and the fractional wetted cross-sectional area are given in Figure 48. Note the as-built elevation presented in Figure 48 indicates that the groundwater surface was above the top the barrier from approximately day 50 to day 150. This coincides with two anomalously large spring snowstorms and infiltration associated with subsequent snow melt. The high watertable elevation observed in the prior year was 6096.2 feet.

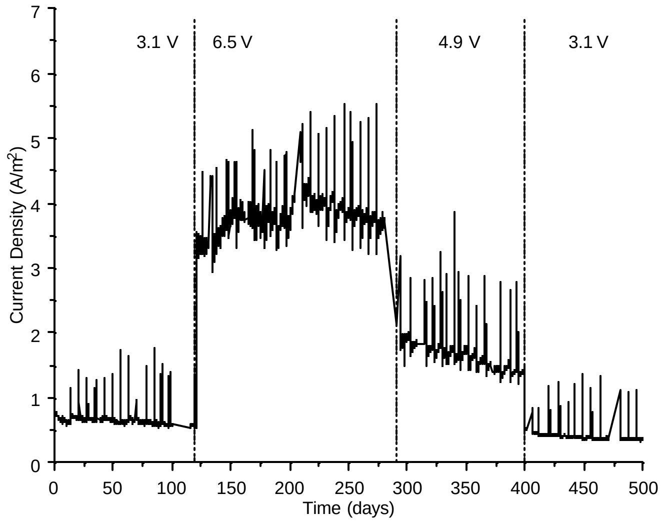


Figure 47. System current normalized to the total wetted electrode area.

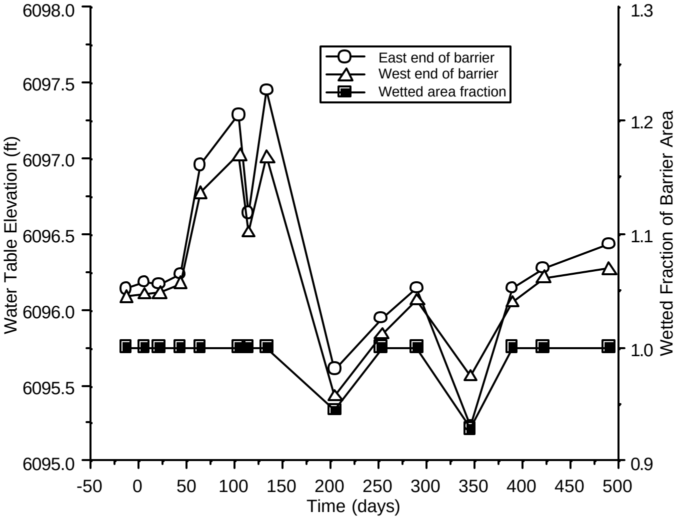


Figure 48. Water table elevation at the east and west ends of the e^{-}barrier, and the fraction of the barrier cross-sectional area below the water table.

The data shown in Figure 47 can be divided into four distinct sections (corresponding to a specific E_{appl} setting listed in Table 10). As stated above, a decline in current density over time might be attributable to precipitate accumulation at the electrode surfaces. Current density appeared to slowly decrease during certain time intervals, although the rate of decline was not consistent over time. At other intervals (e.g. day 150 to 225) current density increased by as much as 50%. Some variability was likely the result of variation in electrical conductivity of the groundwater, which affects resistance to current flow between the electrodes. Conductivity measurements averaged vertically along the transect parallel to groundwater flow through the e^{-} barrier midpoint are presented in Figure 49. The data indicates a slight increase in conductivity from day 100 to 275, followed by a slow decrease. The increase in conductivity is approximately 20 to 50 percent may account for the increase in current density observed during the same timeframe (see Figure 47). In addition, the time periods of declining conductivities correspond to declining current densities.

Periodic spikes in amperage reflect weekly 12-hour changes in the polarity of the electrodes. The standard operational mode was to operate the first and second electrodes as anode and cathode, respectively. The twelve-hour switches involved operating the second electrode as the anode and the third electrode as the cathode. Occasional periods of missing data reflect issues with the data logger and/or wireless connection (lost data). Through the ~ 18 months of operation power failures were infrequent and brief.

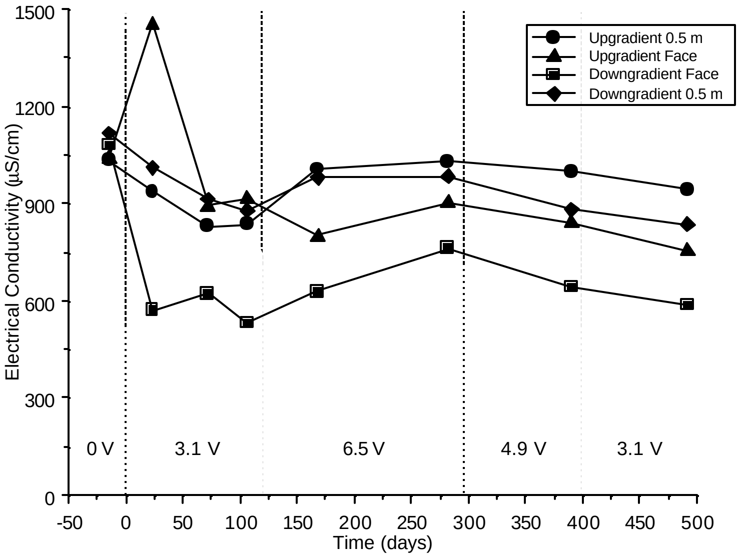


Figure 49. Electrical conductivity measured along the transect parallel to flow at the e^{-}barrier midpoint. Measurements are averaged from readings taken 0.5 m upgradient of the barrier (circles), upgradient face of the barrier (triangles), downgradient face of the barrier (boxes), and 0.5 m downgradient of the barrier (diamonds). Power was applied to the e^{-}barrier at day 0.

The oxidation-reduction potential (presented as pe) and pH of the groundwater can be used to evaluate the affect of the electrochemical processes on groundwater chemistry. In particular, the mobility of many inorganic constituents depends on the solution pe and pH. Measurements of groundwater pe and pH are presented in Figure 50. Groundwater pH generally remained below 7.5 at the locations 0.5 m from the barrier, and was lower at both the upgradient and downgradient faces. Measurements of pe at the corresponding barrier face locations were elevated relative to those 0.5 m from the barrier. These trends in both pe and pH showed that oxidized conditions were being propagated upstream and downstream of the e^{-}barrier.

The occurrence of both oxidative and reductive processes was verified by recording the electrochemical potentials of the anode and cathode relative to Ag/AgCl reference electrodes placed on the upgradient and downgradient faces of the e^-barrier. Electrode potentials, reported relative to the standard hydrogen electrode, during the demonstration are provided in Figure E-8 of Appendix E. Potential shifts of the anode to positive values and the cathode to negative values indicate that oxidizing and reducing processes are occurring at the respective electrodes. As shown in Figure E-7, electrode potentials were not spatially uniform.

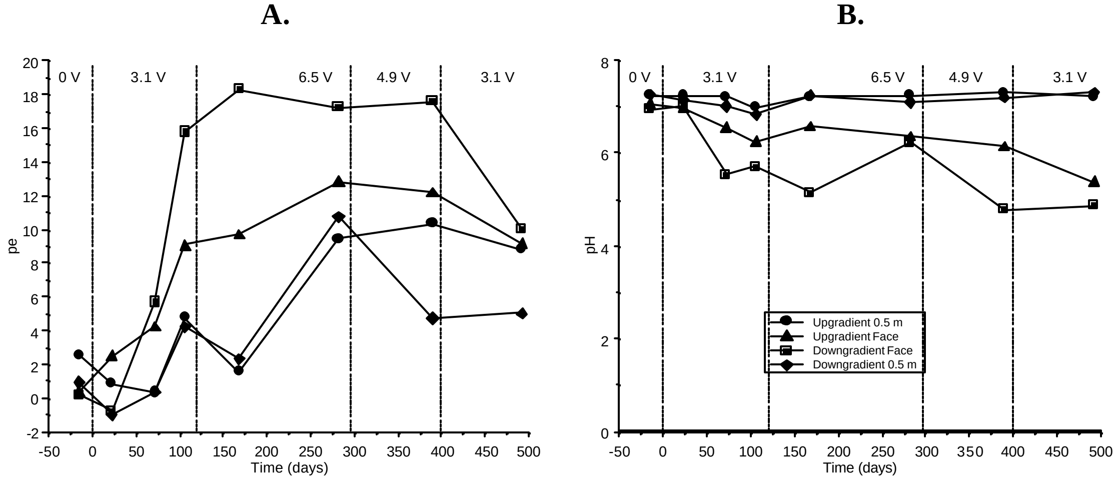


Figure 50. A. pe and B. pH measured along the transect parallel to flow at the e^-barrier midpoint. Measurements are averaged from readings taken 0.5 m upgradient of the barrier (circles), upgradient face of the barrier (triangles), downgradient face of the barrier (boxes), and 0.5 m downgradient of the barrier (diamonds). Power was applied to the e^-barrier at day 0.

The expected geochemical signal from the cathode should be reduced conditions (lowered pe and increased pH) from the reduction of water. These conditions were not observed during the demonstration. The influence of initial plume redox conditions on electrically induced shifts in pe and pH are under investigation.

Alkalinity and calcium concentrations were examined along the transect parallel to groundwater flow through the e^-barrier midpoint to evaluate mass loss associated with calcite ($CaCO_3$) precipitation. The results are shown in Figure 51. Spatial trends in alkalinity and total calcium concentrations were altered after power was applied to the e^-barrier. As seen in Figure 51, both parameters increased from upgradient to downgradient locations before E_{appl} was initially set at 3.1 V. At day 282 and 491, calcium concentrations decreased by 20 and 50 mg/L across the e^- barrier, respectively. Similarly, at day 282, alkalinity as bicarbonate decreased by almost 100 mg/L. One explanation for the decrease in parameters is calcite precipitation from high pH conditions likely generated at the cathode surface. The rate of $CaCO_3$ mass loss may not directly correlate to a precipitation rate. Other processes such as ionic migration/sequestration from the potential gradient between the electrodes may explain the full extent of the alkalinity and calcium concentration declines.

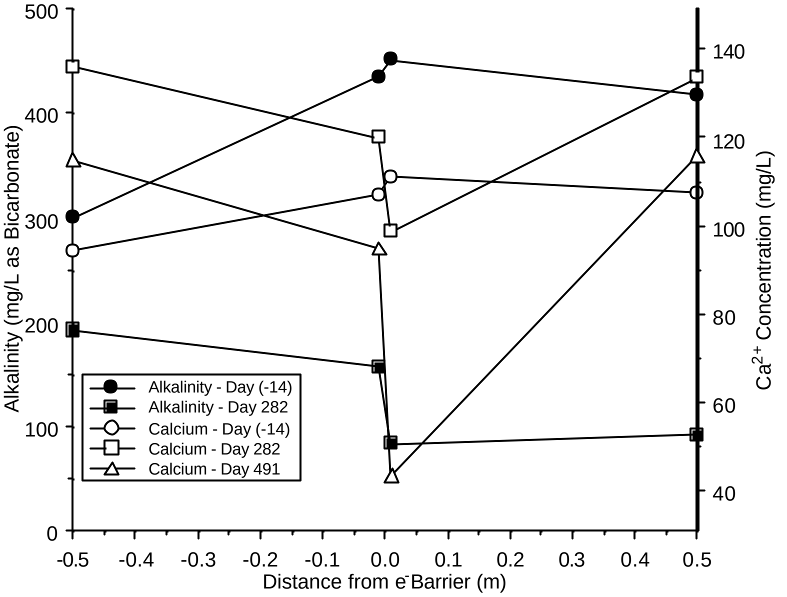


Figure 51. Alkalinity (as bicarbonate) and Ca^{2+} concentration measured along the transect parallel to groundwater flow through the e^-barrier midpoint. Measurements were taken at 14 days prior to startup (alkalinity – closed circles, Ca^{2+} - open circles), day 282 (alkalinity – closed boxes, Ca^{2+} - open boxes), and day 491 (alkalinity – N/A, Ca^{2+} - open triangles). The e^-barrier is located at 0 m and flow is from negative to positive distances.

As noted above, the strategy used to control precipitate formation during the demonstration was periodic electrode polarity reversals. The motivation behind reversing polarities was to solubilize any precipitates formed by generating low pH conditions. Utilizing the three-electrode configuration of the e^-barrier, the polarity of the cathode could be reversed while maintaining the anode-cathode sequence of the system. Remotely initiated polarity reversals were conducted once per week for twelve hours. Regularly occurring spikes in the current density data shown in Figure 47 reflect polarity reversal events. It was expected that without these measures, precipitate formation would occur to a degree that would eventually affect TCE degradation.

In summary, TCE concentrations downgradient of the e^-barrier and current density remain largely stable. During the highest E_{appl} setting (6.5 V), TCE concentrations remained close to the MCL at the downgradient face of the e^-barrier, and continued to decline within the downgradient shadow of the barrier. The observation drawn from the data is that during the lifetime of the demonstration, precipitates do not appear to have affected the performance of the e^-barrier. Weekly polarity reversals likely contributed to the sustainability of treatment. Additional data is needed to more conclusively resolve the performance of the e^-barrier beyond 18 months.

4.3.4 Ease of Use

Ease of use is evaluated based on training above and beyond that required for normal groundwater quality monitoring activities. These include groundwater sample collection and analysis, and actions to assess the physical hydrogeology of a site. Equipment specific to the e^-barrier that may require special training are operation of the rectifier and datalogging/PLC instrumentation. Additional maintenance activities focus on inorganic precipitate management and include electrode polarity reversals and panel washouts to remove the solids. Some activities may be completely automated by using the full capability of the PLC to control polarity reversals. The level of specialized training for e^-barriers is less than for more intensive approaches such as pump and treat, and slightly greater than passive approaches such as ZVI PRBs or monitored natural attenuation.

4.3.5 Versatility

The main appeal of the e^-barrier is the sequential nature of treatment, utilizing both oxidation and reduction steps. This aspect of the technology makes the e^-barrier applicable to many contaminants (including mixtures) that may not be treatable using existing technologies that involve either oxidation or reduction. Laboratory work to date suggests that treatment of dissolved energetic compounds may be the optimal niche for e^-barriers at DoD facilities.

4.3.6 Maintenance

Performance of the e^-barrier was maintained by enacting strategies to handle gas generation and inorganic precipitate formation at the electrodes. The strategies were implemented in the design of the equipment and the operating procedures of the demonstration. Each strategy demonstrated success in that excessive gas generation and scale formation at the electrodes did not appear to adversely impact TCE mass flux reduction.

Preventing precipitate buildup at the cathode surface was achieved using the three-electrode configuration of the e^-barrier to perform regular polarity reversals. Polarity reversals were implemented remotely from CSU using a wireless connection to an on-site PLC. The reversals were initiated weekly for a period of 12 hours each. This procedure could easily be automated during a full-scale operation.

Strategies used to maintain system performance of the demonstration required a low level of effort after installation of the system was complete. This differs from technologies that utilize equipment such as injection or extraction pumps, which often require intensive maintenance plans. The advantage of low-maintenance solutions can be realized in the operating costs incurred during the system lifetime.

4.3.7 Contaminant Mobility

Shifts in pH associated with altered redox conditions have the possibility of mobilizing inorganic contaminants. Groundwater quality analysis for inorganic constituents and redox conditions were conducted to determine if the concentration of these species were increasing over time. The inorganic cationic compounds evaluated were antimony, arsenic, barium, beryllium, cadmium, chromium, copper, lead, and selenium. Regulated anionic compounds evaluated were fluoride, nitrate, and nitrite. A summary of inorganic species concentrations is provided in Tables E-1, E-2, and E-3 of Appendix E.

Concentrations of all species were evaluated along the transect parallel to groundwater flow through the e^-barrier midpoint. One compound, arsenic, was detected at levels slightly above the USEPA MCL (10 µg/L) after power was applied to the system (Note: background levels of arsenic are an issue at the site under natural conditions). However, the trend in arsenic concentration declined from upstream to downstream. Arsenic concentration measured at farthest downstream location was 5 µg/L. On day 282, copper concentrations increased from the upgradient concentration to the downgradient face of the barrier (18 µg/L) well below the MCL of 1.3 mg/L. Copper levels farther downstream were lower than the downgradient face measurement. In general, no evidence supporting cationic species mobilization was found during the demonstration.

Fluoride and nitrite-N concentrations were well below USEPA MCLs at all locations. Nitrate was often below the method detection limit of 0.1 mg/L. Fluoride concentrations were reduced through the e^-barrier from approximately 0.9 mg/L to 0.35 mg/L at days 282 and 491. This may be due to fluoride reduction to F_2, similar to the mechanism that generates Cl_2 from chloride. Nitrate-N concentrations at all locations were below the USEPA MCL of 10 mg/L. Concentrations did increase through the barrier from an average of 2.5 to 5 mg/L. Levels downstream of the barrier decreased from that local high to values below 1 mg/L.

4.3.8 Process Waste

Process wastes from the e^-barrier are classified herein as compounds generated in conjunction with degradation of the target compound (TCE). This includes:

- Gases generated at the electrodes
- Intermediate products of TCE degradation
- Chloroform

The following characterizes each of these.

Gases

Gas generated from the electrolytic reduction and oxidation of water was vented to the surface through tubing attached to the top of the e^-barrier. Each of the three surface vents was attached to a subset of the 17 total e^-barrier panels. At the end of the E_{appl} = 6.5 V setting, gas samples were collected and analyzed for fixed gases, reduced compounds such as hydrogen sulfide, and chlorinated aliphatic species. Columbia Analytical Services Inc. and CH2M HILL Applied Science Laboratory conducted the analyses. The volume fraction of oxygen in the samples was 0.229 and 0.245, slightly higher than normal atmospheric oxygen volume fraction of 0.209. In addition to elevated oxygen levels, carbon dioxide volume fractions were also higher relative to ambient atmospheric levels. The increased volumetric fraction of oxygen was most likely caused by oxidation of water at the anode to form O_2 and H^+. It is hypothesized that higher levels of carbon dioxide were a result of altering redox conditions in the subsurface, converting bicarbonate to carbon dioxide. This hypothesis is supported by a decrease in bicarbonate concentration, shown in Figure 51. Reduced compounds such as hydrogen sulfide were below the detection limit of the analytical methods used. Hydrogen content was not evaluated in the vent gas. Chlorinated compounds such as TCE and chloroform were detected in the vent gas samples. Their presence was likely due to mass transfer from the aqueous to the gas phase. Data from the pre-demonstration column experiments were used to assess the impact that gas phase transfer has on VOC mass removal in e^-barriers. The results indicated that gas phase transfer was not important, contributing only small fraction to the total TCE mass removal rate.

Using a MiniRAE 2000 portable VOC monitor, hydrocarbon concentrations at grade above the e^-barrier was below action levels. In addition, the explosion hazard was evaluated using a BW GasAlertMicro meter. Constituent levels were at ambient atmospheric values in the working space above the e^-barrier, therefore no explosion hazard was evident as a result of the e^-barrier operation.

Intermediate products of TCE degradation

DCE isomers and vinyl chloride are regulated compounds that are common products of reductive degradation of TCE (Vogel et al. 1987). Production, and subsequent downgradient transport of these species would diminish the overall efficacy of the technology.

Experiments discussed in Section 3 indicate low µg/L concentrations of 1,1-DCE and c-1,2-DCE were detected in laboratory column experiments. Field samples were analyzed for DCE and VC before and after power was applied to the e^-barrier. The only degradation compound detected during the demonstration was c-1,2-DCE. All other DCE isomers and VC were not present in the field samples upstream or downstream of the e^-barrier, before or after a potential difference was applied to the system. Results of the analysis for c-1,2-DCE are shown in Figure 52 as concentration contours in cross-section through the midpoint of the e^-barrier. Two plots are presented, A) before power was applied and B) after, at day 83.

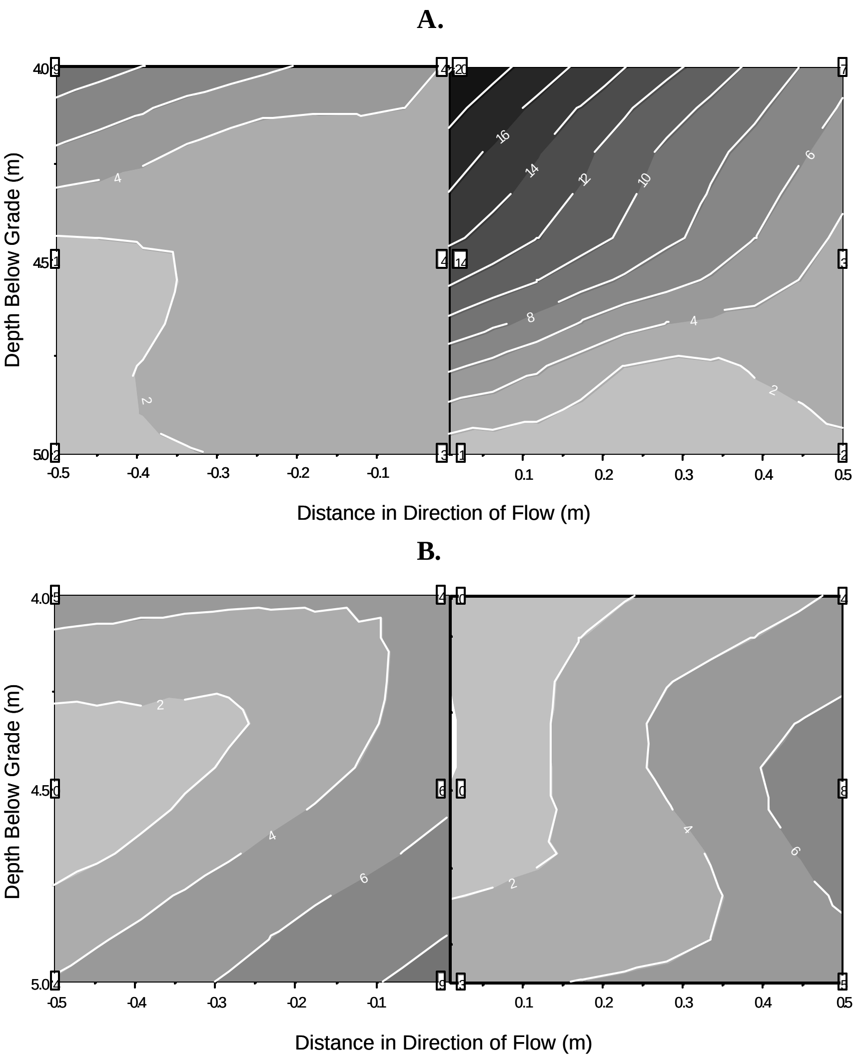


Figure 52. c-1,2-DCE concentration plots along the transect, parallel to groundwater flow, through the midpoint of the barrier at A. day –11, and B. day 83. The e^- barrier is located at 0 m, and concentrations are reported in µg/L.

Generally, higher c-1,2-DCE concentrations were measured prior to applying power to the e^- barrier. Concentrations at the downgradient face of the barrier were as high as 20 µg/L 11 days before E_{appl} was increased from 0 to 3.1 V. In addition, c-1,2-DCE concentrations increased across the open-circuit e^- barrier (Figure 52 A). Appearance of these species indicated that reductive dechlorination may have occurred at the non-polarized electrode surface. Upon application of the potential difference, thermodynamic conditions at the electrode were either sufficient to reduce TCE to ethene, or the major degradation process was shifted to an oxidative pathway. Research conducted in parallel with the field demonstration provides data to suggest that oxidative pathways can play a significant role in TCE degradation, resulting in non-chlorinated degradation products [Petersen 2003].

Water quality analysis of the groundwater downstream of the e^-barrier verified the absence of chlorinated TCE reaction intermediates migrating from the system. This aspect of the system is beneficial to the sustainability of the technology.

Chloroform

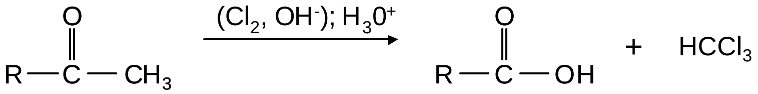
Chloroform was detected at locations downgradient of the e^-barrier approximately halfway through the $E_{appl} = 6.5$ V setting. Chloroform was not detected above method quantification limits at locations upgradient of the e^-barrier. The appearance of chloroform is attributed to chloride oxidation to chlorine, and subsequent reactions of chlorine with carbon compounds. Chloroform has not been observed in prior laboratory or field studies at significant levels.

Two factors that may have contributed to chloroform generation during the field demonstration are:

1) Conditions are far more oxic in the field demonstration than in the laboratory studies. Comparison of lab data in Figure 16 and field data (Figure 50) indicates pe values upgradient of the first electrode of 8 and 12, respectively.

2) Morris and Baum (1978), describe electrolytic chloride oxidation to chlorine, and subsequent reactions of chlorine with carbon compounds containing a methyl or ethyl ketone functional group. The reaction sequence is presented in the following set of equations. The second equation is a α-halogenation reaction of a methyl ketone to form chloroform ($HCCl_3$).

$$Cl^+ \leftrightarrow e^- + \frac{1}{2}Cl_2$$



$$R-\overset{O}{\overset{\|}{C}}-CH_3 \xrightarrow{(Cl_2,\ OH^-);\ H_30^+} R-\overset{O}{\overset{\|}{C}}-OH \quad + \quad HCCl_3$$

After the initial detection of chloroform at day 200, quantification was carried out in conjunction with analysis for TCE. Concentrations at locations along the transect parallel to ground water flow through the e^-barrier midpoint and at locations downgradient of the barrier are presented in Figure 53 and Figure 54, respectively. Chloroform levels peaked between 2 and 4 mg/L at the end of the $E_{appl} = 6.5$ V setting. Trends in chloroform concentration at monitoring points downgradient from the e^-barrier were similar to those at the barrier midpoint. After E_{appl} was changed to 4.9 V, concentrations decreased. The decrease continued as E_{appl} was lowered to 3.1 V at day 400. The changes in E_{appl} were made in response to the high concentrations of chloroform being generated.

Chloroform concentrations at locations farther than 4 m downstream from the barrier were below the method quantification limit for chloroform at the conclusion of water quality monitoring activities. At the same time, values at the downgradient face of the barrier were around 500 µg/L. The decline in chloroform through the formation may be attributable to natural attenuation processes such as biological transformation.

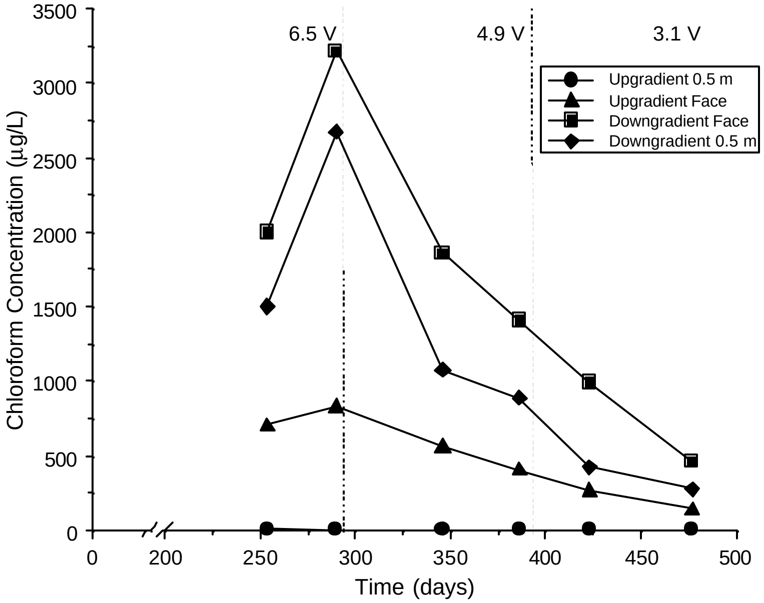


Figure 53. Average chloroform concentrations along the transect parallel to groundwater flow at the e$^-$ barrier midpoint. Values are arranged from 0.5 m upgradient of the barrier (circles), upgradient face of the barrier (triangles), downgradient face of the barrier (boxes), and 0.5 m downgradient of the barrier (diamonds). Power was applied to the e$^-$barrier at day 0.

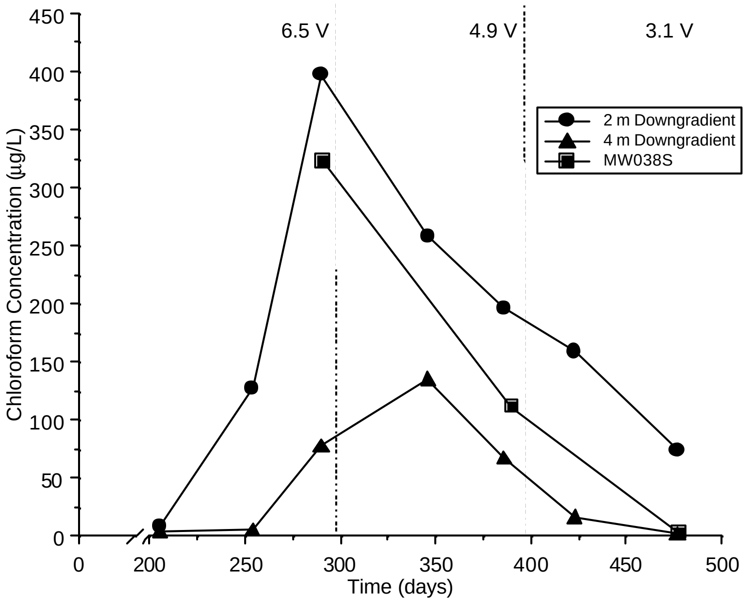


Figure 54. Chloroform concentrations at locations 2 m (circles) and 4 m (triangles) downstream of the e^-barrier midpoint. MW038S (boxes) is a preexisting monitoring well, approximately 8 m downstream of the barrier.

Chloroform was not detected at significant levels (approximately 2 orders of magnitude less than peak concentrations in the demonstration) in the pre-demonstration column experiments, or the field prototype experiment at CFB Borden. Chlorine was likely generated in each experiment due to the ubiquitous presence of the chloride ion in groundwater, available to be oxidized to chlorine. The methyl- or ethyl-ketone functional group on the organic precursor in the α-halogenation reaction can be found on humic compounds of natural organic matter in groundwater. Since chloroform did not appear to be a by-product in previous experiments with natural groundwater, other precursor sources were considered. Adhesives used to construct the e^-barrier were found to contain substantial fractions of acetone and methyl ethyl ketone, two possible organic precursors for α–halogenation to proceed under the proper conditions.

Laboratory experiments using batch e^-barrier systems were conducted to evaluate the amount of chloroform generated under different chemical compositions of the aqueous electrolyte. Three different solutions were tested. An aqueous NaCl solution, NaCl solution amended with the adhesive used to construct the e^-barrier, and groundwater collected from the demonstration site upstream of the e^-barrier. The potential difference between the electrodes was set at 10 V in each experiment. A no-power control experiment was also conducted using the NaCl solution amended with adhesives. NaCl was added to deionized water until the final conductivity of the solution was approximately equal to the field values measured at the demonstration site. Results of the experiments are shown in Figure 55.

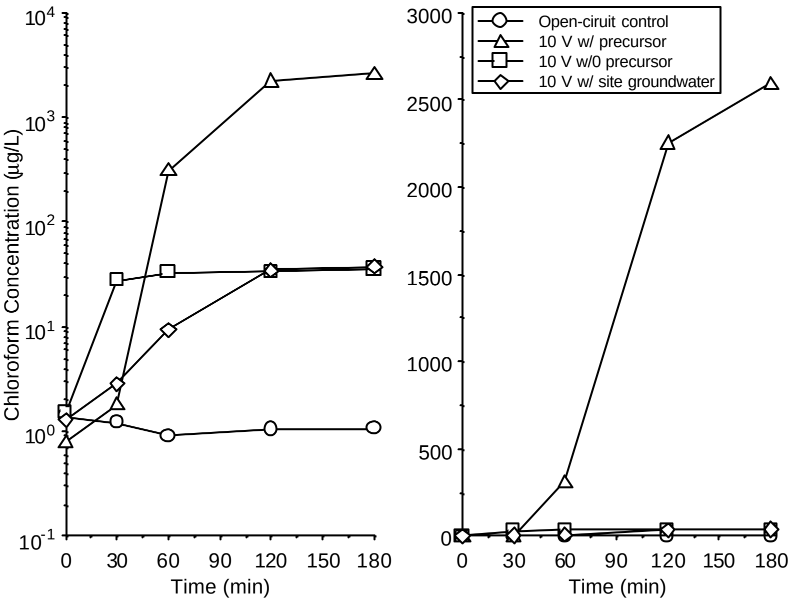


Figure 55. Chloroform concentrations from batch electrolytic experiments using a NaCl solution (boxes), NaCl with dissolved adhesive (triangles), and site groundwater (diamonds). A control experiment (circles) was conducted at E_{appl} = 0 V. Concentrations are presented on a log and linear y-axis for easy comparison.

The experiment with the adhesive amended NaCl solution contained chloroform concentrations about 2 to 3 orders of magnitude larger than the other conditions evaluated at the end of the 180 minute tests. The data supported the conclusion that chloroform was not generated due to the native groundwater conditions encountered at the demonstration site, the electrolytic conversion of TCE, or the electrode material. Instead, the evidence indicated that the materials of construction used to construct the e^-barrier frame as the likely source for organic chloroform precursors.

4.3.9 Reliability

Operation reliability of the demonstration was dictated by the electrical supply. Prolonged or consistent outages would negatively impact system performance since desired redox conditions would not be able to be maintained. Power supply to the e^-barrier during the demonstration was monitored by recording E_{appl}. The parameter was recorded and downloaded to CSU via wireless connection using the same instrumentation to record electrical current. E_{appl} was recorded on 15-minute intervals and the entire dataset is presented in Figure 56.

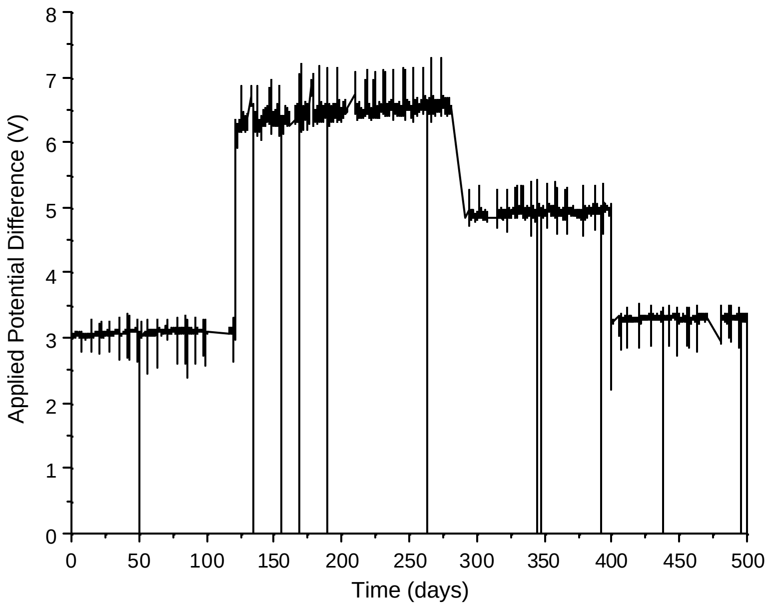


Figure 56. Applied potential difference between the anode and cathode of the e$^-$barrier during the demonstration.

Sections of the data shown in Figure 56 that drop to $E_{appl} = 0$ V indicate power supply interruptions to the system. Twelve separate instances of power interruption occurred in duration from 15 minutes to 10 hours in the first 500 days of operation. The longest outage of 10 hours occurred on 7/1/2003, day 155 of the demonstration. The relatively short and infrequent periods of power interruption did not appear to affect system performance with regard to TCE mass flux reduction.

4.3.10. Scale-Up Constraints

The demonstration e-barrier was largely modular in design. As such scale up is seen as matter of modular expansion with no major challenges. Likely the greatest constraint with e$^-$barrier scale up is depth of installation. As with all barriers (permeable or impermeable), cost increases with depth. A direct consequence is that feasibility decreases with depths. Opportunities to improve on the employed e$^-$barrier design are described in Section 5.2 under the topic of potential cost reductions.

5. 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 USEPA (1988) and cost metrics for PRBs reported in USEPA (2002).

5.1 Cost Reporting

Table 11 presents primary costs associated with design, construction, operation and maintenance of the demonstration e^-barrier. Detailed description of each item is presented in Section 3.5. With the following exceptions, all costs in Table 11 reflect actual costs 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 of 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 2 wells up and downgradient per 100 feet 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.

Table 11. Cost Tracking

COST CATEGORY	SUB CATEGORY	COMMENTS	COST	% OF 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 3ft 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 of annual sampling/reporting for 2 wells up and downgradient per 100 feet 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%

5.2 Cost Analysis

The following section addresses cost drivers, cost comparisons to similar niche technologies, and opportunities for cost reductions.

5.2.1 Cost Drivers

Building on Table 11, 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 (Table 12) 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 (see opportunities for cost reductions).

Table 12. Ranking of costs by percentage of total cost

CATEGORY	% OF TOTAL COST	COST
Barrier Installation	29.7%	$23,038
Electrodes	15.5%	$12,000
Panel Fabrication	9.0%	$6,973
Misc. Barrier Components Subtotal	5.2%	$4,033
Hydrogeologic Investigation	4.9%	$3,829
Rectifier	4.8%	$3,720
Design (5% of construction)	4.4%	$3,403
Construction Oversight (5% of construction)	4.4%	$3,403
Data Logger	4.1%	$3,180
Demobilization	3.9%	$3,000
Performance Tracking	3.1%	$2,414
Utility Conduits	2.9%	$2,275
PVC Pipe Frame	2.5%	$1,919
Drilling for Monitoring Points	2.4%	$1,882
Geonet and Geotextile	2.1%	$1,608
Reference Electrodes	0.8%	$600
Cell Phone Connection	0.2%	$175
Power	0.1%	$112
Total	100%	$77,565

5.2.2 Cost Comparison

Common metrics for evaluating permeable reactive barriers is cost per unit cross-section of plume intercepted and cost per 1000 gallons treated (EPA 2002). Costs are not normalized to the mass of contaminant removed. This reflects the fact that e^-barrier are not viewed as mean of reducing contaminant mass. Their intended niche is reducing contaminant flux.

Table 13 presents capital cost 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 14 lists capital cost and one year O&M costs for full-scale continuous ZVI PRBs reported in USEPA (2002).

Table 13. 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**
Performance Monitoring (Annual Basis) – Assumes annual sampling/reporting for 2 wells up and downgradient per 100 feet 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**
Total	**$419**

Table 14. Comparison of e^-barrier demonstration costs to full-scale ZVI PRB projects reported in USEPA (2002).

SITE	CAPITAL COST	ANNUAL O & M	DEPTH (FT)	ACTIVE AREA (FT^2)	CAPTIAL COST/ FT^2	O&M COST / FT^2
Industrial Site, SC	$400,000		29	9425	$42	
Somersworth Landfill SF Site	$2,515,000		40	32000	$79	
Cape Canveral, FL	$760,150		45	6300	$121	
Industrial Site , NY	$1,000,000		18	6600	$152	
Pease AFB, NH	$750,000	$35,000	33	4950	$152	$7.07
Watervliet Arsenal	$387,000	NA	10	1900	$204	
USCG Support Center	$835,000	$85,000	24	3648	$229	$23.30
Former Manufacturing, Fairfield, NJ	$875,000	$25,000	25	3175	$276	$7.87
Warren AFB Spill Site 7, WY	$2,350,000		15	8520	$276	
Kansas City Plant , MO	$1,300,000		39	3900	$333	
e^-barrier at F.E. Warren AFB	**$75,000**	**$2,700**	**6**	**183**	**$409.84**	**$14.75**

Table 14 indicates that the e^-barrier demonstration had a higher capital cost than all of the full-scale field applications by a factor of 1.2 to 9.7. Due to 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 also favor lower costs for e^-barriers. With this, it is concluded that e^-barriers have the potential to have similar capital cost to ZVI PRBs at other locations.

As a footnote, iron prices have doubled in 2004 due to strong global demand. In addition, iron is the primary cost component of ZVI PRBs. As such, the cost for PRBs presented in Table 14 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 metrics is used in USEPA (2002) to compare the relative cost of full-scale pump and treat systems and PRBs. Over the 500-day period 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 one year annual O&M cost for the e^-barrier are \$1620 and \$116 per 1000 gallons, respectively. Note: following USEPA 2002, the normalized capital cost is the capital cost divided by the 1-year treatment volume. Table 15 compares these costs to pump and treat cited in USEPA (2002). In general the e^-barrier demonstration cost are at the high end of costs associated with full-scale pump and treat systems.

Table 15. Comparison of e^-barrier costs to USEPA (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	\$1608	Not Available
Somersworth Landfill SF Site	\$357	\$47
Former Manufacturing, Fairfield, NJ	\$101	\$28
e^-barrier at F.E. Warren AFB	**\$1622**	**\$116**

Life Cycle Costs - Table 16 presents an estimate of life cycle costs. Primary assumptions include:

- All costs are in 2004 dollars
- All systems will have to be replaced every ten years
- Discount rates of 0, 2, 4 and 6 percent.

Note 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 stands at ~ 4 ¼ %.

Table 16. Estimated life cycle costs at 0, 2, 4 and 6% discount rates

YEAR	CAPITAL	ANNUAL O&M	NPV 0%	NPV 2%	NPV 4%	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

5.3.3 Potential Cost Reductions

The process of fabrication, installation, operation, and maintenance provides numerous insights as to opportunities for improvement that could reduce cost and/or improve efficacy. The following focuses on potential cost savings.

Economies of Scale

Installation and panel fabrication labor were all small-scale efforts that were dominated by mobilization costs. Given full-scale systems, mobilization cost would be a much smaller fraction of the total cost. In addition, many of the materials used have lower costs when purchased in large quantities (e.g. electrodes). As such, economies of scale are likely to lead to lower cost for larger (e.g. full-scale) systems.

Promising Design Modifications

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, systems automation should include automated messaging regarding operational status.

Fewer/Thinner Geonet Layers in the Barrier – In the electrode panels, each electrode is bounded on each side by a layer of 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 – Limitation of the employed panel design include:

- Expense of frame/interlock fabrication – Labor and materials associate the e^-barrier framing/interlocks was a large component of the overall cost.

- Potential leakage between panels – As fabricated it seemly possible that some flow may have gone between active portions of the barrier

- Potential for overtopping at high water levels – Portions of the plume intercepted by the barrier may have overtopped the barrier.

- Undesired reactions by products - Glues used in the framing the electrode panels appear to have been a factor in the apparent generation of chloroform at the barrier.

Mounting the electrode panel 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 washouts hoses, reference electrodes, and multilevel sampling systems. – A challenge of the installation was numerous hoses and wires that were routed to the surface from the individual panels in the barrier. Washout hose managing scale could likely be eliminated given the more rigorous four-electrode scale control strategy. Reference electrode provided data that would likely not be needed in full-scale systems. Multilevel sampling systems also provided a level of performance monitoring that is not needed in full-scale systems.

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

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. In addition 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.

Lower Cost Installation Techniques - The trench box approach to installation was selected because of the high likelihood of success and minimal chemical interferences with the demonstration. Building on the experience in recent years using biopolymer for zero valent iron 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 hold the promise of significantly lower PRB costs.

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

6. 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 USEPA regulators. This involved:
    a) Initial discussions
    b) Presentations at RAB meetings
    c) Providing work plans for review and approval
2) Utility clearances were obtained for all subsurface investigations and excavations

As no chemicals are introduced, or known adverse byproducts 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 Other Regulatory Issues

To date presentations regarding the e$^-$barrier have been made at eleven national conferences. These include:

- 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
- AFCEE – Annual Meeting 2003
- Solvents in Groundwater Research Consortium – Annual Meeting, 2003 and 2004
- Geologic 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 Army Corps of Engineers (AOE) have provided complementary funds to evaluate the use of e$^-$barriers for energetic compounds in groundwater. Promising results have led to preliminary discussions with Pueblo Chemical Depot (PCD), 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 dates include:

- 2002-2003 - Preliminary meeting and information exchange with PCD staff
- 2003 - Collection of site soils for laboratory studies from PCD
- 2004 - Completion of preliminary PCD treatability studies

  2004 – Development of a proposal to ESTCP for a field demonstration of e^-barriers for RDX at PCD.

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

Lessons Learned – This project has greatly improved our understanding of efficacy and cost of e^-barriers. Unfortunately, the issues of efficacy and cost still have relatively large uncertainties as 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.

A factor in operating future demonstrations/implementations that was unforeseen prior to this demonstration was the production of chloroform as a by-product of in situ chlorine generation. As discussed in Section 4.3.8, chlorine, generated from the oxidation of chloride in the groundwater, likely reacted with methyl- or ethyl-ketone functional groups on organic species to form chloroform. One of the most abundant sources for methyl- and ethyl-ketone functionalized organics was the acetone based adhesive used to construct the e^-barrier. Steps were taken to mitigate the production of chloroform, which are discussed in the Future Implementations subsection.

Other issues center about 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 commercially available – off-the-shelf (COTS) items. In this regard there are no significant hurtles. Patents covering the technology include Sale and Gilbert (2002) and (2004). These are not viewed as impediment to implementation of the technology.

Future Implementations – A number of promising design modifications were identified during the demonstration. Our current plan is to incorporate these into an e^-barrier demonstration at

PCD that will occur in 2005 –2006. Specific changes that hold promise for lower cost and enhanced performance include:

Addition of a fourth electrode – The demonstration barrier relied on a three electrode sequence. Future designs should consider using a four electrode sequences. Envisioned benefits include:

- Better 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, then the total flux reduction of a system of two-electrode sets would be 99%. If each set achieved 95% flux reduction then 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.

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. In addition 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.

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The field demonstration indicated that chloroform generation is a potential by-product of in situ chlorine generation at high anode reference potentials. The production of chloroform and similar disinfection-type by-products would be an obvious concern to future end-users. The strategy used to mitigate chloroform generation in the demonstration was to lower the anode reference potential by lowering the applied potential difference to the system. This action subsequently lowered chloroform by an order of magnitude during the evaluation period. A likely operation constraint for end-users in future implementations would be to limit in situ chlorine generation through the oxidation of chloride by maintaining anode reference potentials below the chlorine reduction potential of 1.36 V vs. the standard hydrogen electrode. As discussed in Section 4.3.8, the materials of construction and their chemical activity in highly oxidized or reduced environments must be considered prior to operation. A future demonstration of the technology at the PCD will utilize this design strategy by avoiding acetone-based adhesives in the construction of the e^-barrier.

Implementation Decision Tools

The field demonstration revealed several key implementation issues that are summarized in Table 17. Components of these issues are included in two decision flow-charts that are included as Figure 57 and Figure 58.

Table 17. Decision Guide

Suitable for Contaminants?

This project demonstrates TCE (and associated degradation products) depletion in groundwater in excess of 90%. Given the current status of the e$^-$barrier, TCE plumes requiring substantively higher (e.g. 99% plus) removal likely need to consider other options first.

Results from laboratory studies suggest similar or higher levels of removal can be achieved for PCE, TCA, TNT, and RDX. Furthermore, e$^-$barriers hold promise for other redox sensitive compounds in groundwater. Definitive data supporting effectiveness for other compounds is currently under development.

Suitable to Settings?

At present e$^-$barriers are limited to application in relatively shallow plumes in which continuous trenches can be opened for barrier installation. The primary applications are likely alluvial plumes with total depths less than 40-50 feet.

Similar to ZVI PRBs, conditions that constrain the installation of e$^-$barriers include permanent surface obstructions and subsurface conditions that challenge trench installation. Examples of challenging subsurface conditions include cobbles, boulders, flowing sands, and combinations of hard and soft sediments (e.g. alluvium-bedrock interfaces).

The results presented herein suggest that contaminants have moved around the ends or through interlock portions of the e$^-$barrier. Given promising design improvements and larger scale systems, these issues should not pose an impediment to full scale applications.

Cost and Performance Relative to Proven Technology?

As currently configured, e$^-$barriers for TCE have similar (or higher) costs to ZVI PRBs and Pump and Treat. Given the record of long-term performance for these technologies, it is not clear that e$^-$barriers (as currently configured) are a better option for management of shallow TCE plumes. Situations in which e-barriers may have advantages over ZVI PRBs and Pump and Treat include:

- Redox sensitive contaminants that are difficult to treat with proven technologies. Current knowledge suggests TCA, TNT, and RDX are promising candidates.
- Relative to ZVI PRBs, situations where high TDS or levels of nitrate may lead to rapid passivation of ZVI.
- Relative to Pump and Treat, situations where the long-term operations and maintenance of above ground treatment systems are inconsistent with planned land use or desired long term costs.

Operational Considerations?

Overall operation of the e$^-$barrier is quite simple. Low cost programmable logic control systems (PLCs) can be used to sustain a desired voltage setting, conduct periodic electrode polarity changes, track performance, and issue alarms as needed. The only major decisions are the applied voltage and the frequency of electrode polarity reversals. In more detail:

- Applied Voltage – Considering energy cost, electrode longevity, management of precipitates, and potential formation of undesired byproducts, lower voltages setting are preferred. The best approach for resolving the appropriate voltage is to start low (e.g. 3V) and stepwise increased voltage until the desired downgradient concentrations are achieved in the plume. As a screening value, power costs are likely to be on the order of 10 watts/m^2 given an applied potential of 4V.

- Polarity Reversal – The best available indicator of the condition of the electrodes is the current density at a fixed voltage. Decreasing current density with time suggests fouling of electrodes. The optimization of reversal reflects a balance between maintaining a positive-negative treatment sequence most of the time (for best treatment) while limiting scale formation in the first place. Minimizing initial scale formation reflects the fact that existing scale acts as crystallization points for future scale formation. Our present approach is weekly changes for 12 hours for all electrodes. If this fails to sustain current densities, more frequent and/or longer reversals should be employed

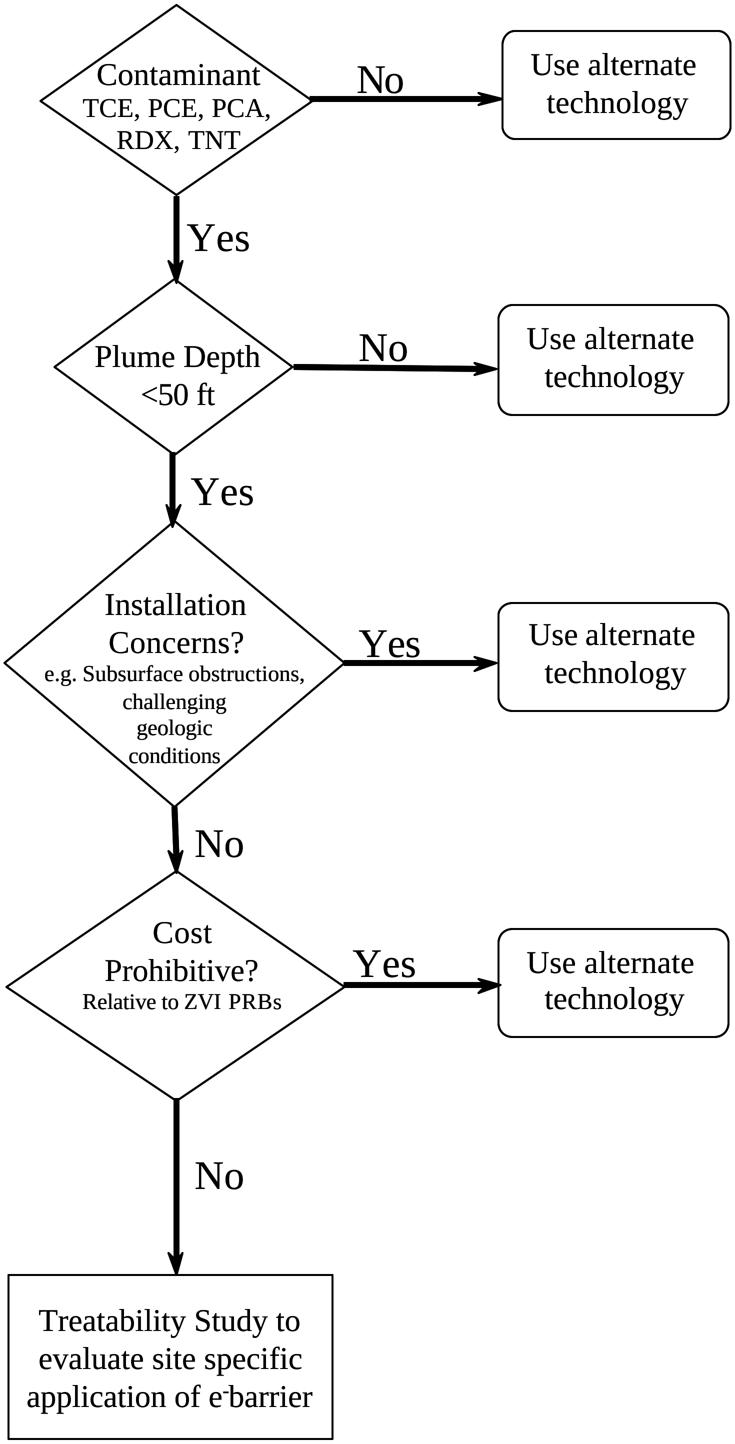

Figure 57. Decision tree to evaluate application of e-barrier technology to site specific conditions.

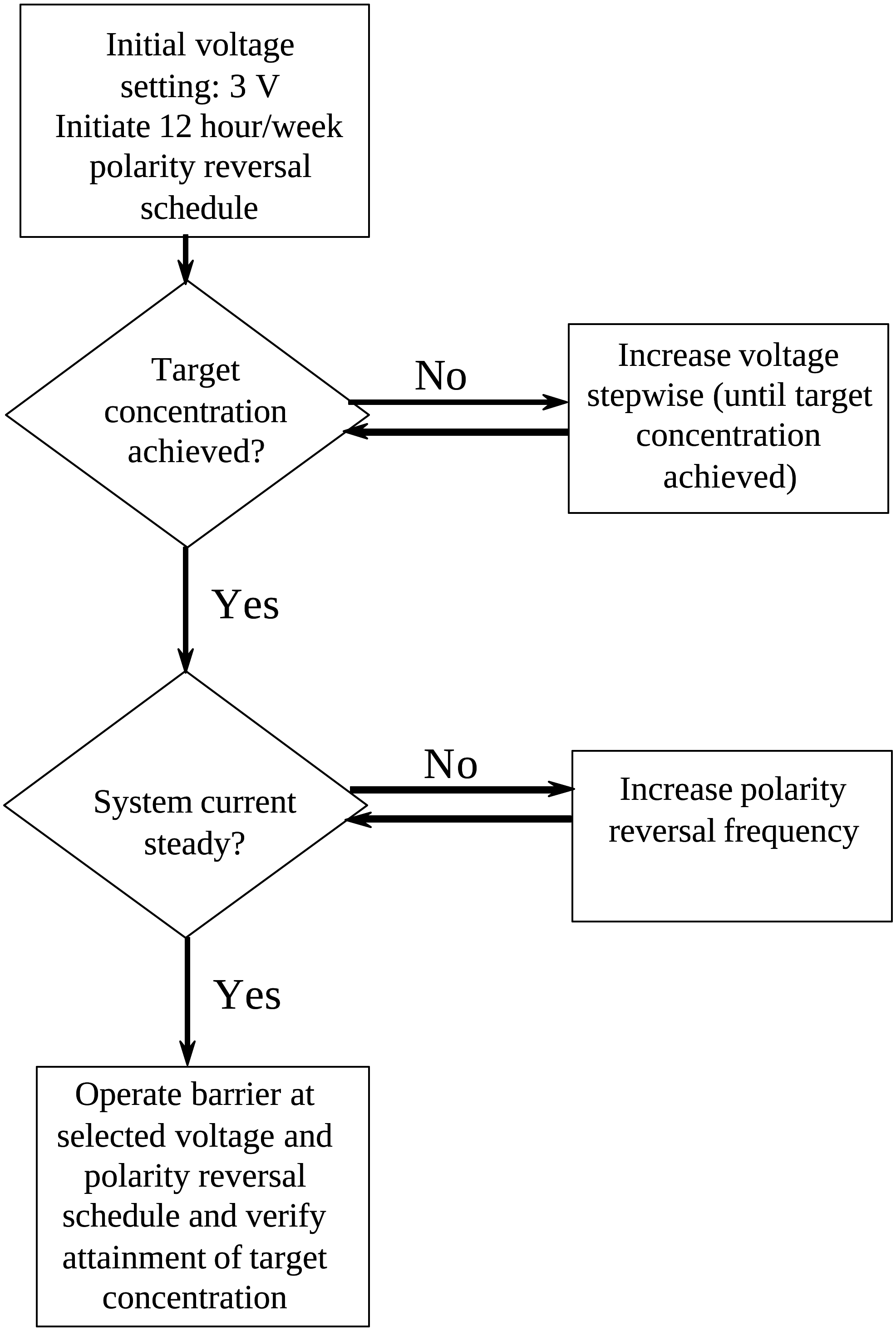

Figure 58. Decision tree for startup and operation of an e$^-$barrier

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8. Points of Contact

Point of Contact Name	Organization Name and Address	Phone/Fax/email	Role(s) on Project
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Dave Gilbert, Assistant Research Professor, CSU, Civil Engineering	Colorado State University, Engineering Research Center, Fort Collins, Colorado 80523	970-491-8880 (CSU) 970-491-8224 (Fax) gilbert@engr.colostate.edu	Assistant Principal Investigator, Lead Field Operations and Laboratory Studies
Ken Reardon. Professor, CSU Chemical and Bioresource Engineering	Colorado State University, 107 Glover , Fort Collins, Colorado 80523	970-491-6505 (CSU) 970-491-7369 (Fax) reardon@engr.colostate.edu	CSU Technical Oversight & Assistant Principal Investigator
Matt Petersen, CSU, Research Assistant Chemical and Bioresource Engineering	Colorado State University, Engineering Research Center Room B-09, Fort Collins, Colorado 80523	307-491- 8608 (CSU Porous Media Lab)	Assistance with Field Operations, Laboratory Studies, and Data Management
Dominic Leffler, CSU, Research Associate Environmental Health Services	Colorado State University, Environmental Health Services, 149E General Services Building, Fort Collins, Coloroado, 80523	970-491-4830 (w) 970-491-4808 (f) dleffler@lamar.colostate.edu	Health and Safety and Hazardous Materials
John Wright Chief Environmental Management,	300 Vesle Drive, F.E. Warren AFB, Wyoming 82005	307-773-4147 (Warren)	Chief Environmental Management, F.E. Warren AFB

F.E. Warren AFB			
Andrea Leeson	ESTCP Program Office 901 North Stuart Street, Suite 303, Arlington , Virginia 22203	703-696-2118 (w) 703-696-2114 (f)	ESTCP Program Manager
Don Ficklin	HQ AFCEE/ERT 3207 Sidney Brooks Road Brooks AFB TX 78235-5344	210-536-5290 (w) 210-536-9026 (f)	ESTCP Project Liaison
EPA	Rob Stites		Region 8 Site Manager for F.E. Warren AFB
WDEQ	Jane Cramer		WDEQ Site Manager for F.E. Warren AFB

Appendix A: Installation Bid Package

Bid Package

Trench Construction for a Demonstration Reactive Barrier

at
F.E. Warren AFB, Cheyenne, Wyoming

Response Requested by 5/15/02

Issued by Colorado State University

Contact:

Tom Sale
Civil Engineering
Colorado State University
Engineering Research Center
Fort Collins, Colorado 80523
970-491-8413

Project Description

Colorado State University (CSU) has been funded by the US Department of Defense (DoD) to develop new technology for managing groundwater contamination. The purpose of this package is to solicit bids to construct a trench approximately 3 feet wide, 32 feet long, and 18 feet deep at F.E. Warren Air Force Base, Cheyenne, Wyoming. The trench will be used to test a new reactive barrier technology. Generally, the work will involve:

1) Driving steel sheet piles to form temporary trench shoring. This can be done with or without an initial surface cut not greater than 10 feet below ground surface (bgs).
2) Excavating the material in the shoring to a depth of approximately 18 feet bgs.
3) Assistance with setting 17 interlocking treatment panels in the excavation. The panels will be provided by CSU. Approximately, they are 1.5 foot wide, 6 feet tall and weigh 70 lbs. The estimated time for setting the panels is one day.
4) Backfilling the excavation.
5) Extracting temporary trench shoring.
6) Final site grading and seeding.
7) Removing debris generated through construction.
8) Decontamination of equipment.

A complete description is provided in the following text.

The excavation will be completed into groundwater. Groundwater in the area contains approximately 300 ug/L trichlorethene (TCE). Because of this, all work must conform with Title 29 Code of Federal Regulations (CFR) 1910.120 (f). Specifically this requires 40-hour HAZWOPER training and annual refresher training.

CSU will be the prime contact for the project. Contract terms are presented in Attachment A. Tom Sale/CSU will observe the construction, coordinate setting the barrier, and assist with coordination of activities with F. E. Warren AFB.

Location

F.E. Warren is located in Cheyenne, Wyoming northwest of the intersection of Interstates 25 and 80. The primary mission of F.E. Warren AFB is maintenance of Peacekeeper missiles. The barrier will be installed near the intersections of Missile Drive and Old Glory as shown in Figure 1. Figure 2 presents a photo of the location. Figure 3 presents a plan view depiction of the barrier position and the location of permanent monitoring wells that cannot be disturbed (MW038 wells and preferably ESTCP-4).

Access to the site will require all onsite staff to obtain Contractor Badges. Badges can be acquired in approximately 1-hour given 7-day prior notification of name, address, social security number, and citizenship. Individuals who are not US citizens will receive greater scrutiny due to security concerns. All badges and vehicles will be inspected upon entry and exit from F.E. Warren AFB. Typically this has not required more than a few minutes. The contractor shall allow for up to one hour per day for inspections.

Subsurface Conditions

Personnel at F.E. Warren AFB located buried utilities in the vicinity of the excavation in October 2001 as part of a preliminary drilling activity. Based on this a buried electrical or communications line was identified at the approximate position shown in Figure 3. The October 2001 excavation permit has expired. The contractor will need to acquire a new permit for excavation at the site from the F.E. Warren AFB prior to initiating excavation.

Four temporary monitoring wells were completed at the site in October of 2001. Well logs are presented in Appendix B. Interpreted geologic cross-sections are presented in Figure 4 through 6. The excavation will be over the alignment of temporary wells ESTCP 1 through ESTCP 3 (See Figure 3). Blow counts were recorded from drives at the bottom of ESTCP 2, 3, and 4 using a standard split spoon sampler and hammer. Encountered sediments consisted of layers of silt to coarse sand that were poorly to well cemented. Groundwater has been observed at 11 to 12 feet below ground surface.

The boring logs and related information depict subsurface conditions only at the specific locations and times the explorations were performed. Subsurface conditions and water levels at other locations may differ from conditions occurring at these indicated locations. Also, the passage of time may result in a change in the conditions at these locations.

The depth and thickness of the subsurface strata indicated on the interpreted geologic cross-sections were generalized from and interpolated between test locations. Information on subsurface conditions exists only at the specific locations indicated. Subsurface conditions and water levels at other locations may differ from conditions occurring at the indicated locations. Conditions may also change over time.

Scope of Work

Health and Safety Requirements – The contractor shall provide a Health and Safety Plan that conforms to 29 Code of Federal Regulations (CFR) 1910.120 (f). For costing purposes, the contractor shall assume that all work can be performed in Level D. It is the contractor's responsibility to ensure that this is appropriate for the work that will be performed. A sample health and safety plan will be provided to the contractor upon request. Prior to starting work the contractor shall provide documentation of 40-hour HAZWOPER training and annual refresher training for all onsite staff. A kickoff Health and Safety meeting will be held with all onsite staff prior to starting the work. Topics addressed shall include execution of the work, related safety issues, and emergency procedures.

Site Access – The contractor shall provide a list of all onsite workers including their name, address, social security number, and nationality at least one week prior to starting the work. On the first day of work all onsite workers shall obtain Contractor Badges from F.E. Warren AFB. Typically this requires approximately 1-hour.

Utility Clearances – The contractor shall obtain a digging permit from FE Warren AFB. This requires submittal of a request for utilities location two weeks prior to beginning the work. Tom Sale/CSU will provide the necessary blank forms for the digging permit and contact names. The contractor shall complete the forms, meet inspectors on site, and provide additional information as required by F.E. Warren AFB.

Trench Excavation – The contractor shall use steel sheet piles to shore the trench below the watertable. It shall be assumed that sediments will collapse in the absence of shoring. The contractor shall provide all necessary bracing to support the excavation. Bracing at the top of the sheet pile shoring shall be moveable to allow for insertion of the treatment panels as described below. Sheet pile shall be driven deep enough to support the full depth of the excavation without significant horizontal deformation. The sheet pile shall also be driven deep enough to prevent bottom heave. Additives such as muds are prohibited. Below the watertable, the excavation shall be at least 1 ft wide and not more than 3-feet wide. Excavations wider than 3 feet will cause undesired disturbances. The excavation above the watertable can be an open cut (e.g. Figure 7) or may involve shoring to grade (e.g. Figure 8).

The MW-038 wells cannot be damaged. Also, there is a strong preference for not damaging well ESTCP 4. The excavation will be completed over ESTCP 1 through ESTCP 3 (Figure 3). Consequently, ESTCP 1 through ESTCP 3 will be removed during installation.

Topsoil shall be placed in a separate pile such that it can be used as cover in the final site grading. The remaining soil from above the watertable shall be placed in a separate pile. Soils removed from below the watertable shall be placed in a steel roll off box. It is anticipated that all soils will be clean enough to be used as fill at the site.

Assistance with Setting the Reactive Barrier – The reactive barrier will consist of 17 interlocking panels that are framed in 3-inch ID PVC. These will be supplied by CSU. A photo of two prototype panels (connected by an interlock) is shown in Figure 9. The primary difference with the field panel is that 1) they will be ~6 feet tall and 2) a riser pipe will be connected to one side of each panel to electrical connections and hoses to grade. The panels will be lowered one at a time into the excavation. The panels will be held together by PVC interlock that will allow one panel to be connected to the next. A picture of the interlock is shown in Figure 10. The concept of the final configuration is shown in Figure 11.

The contractor shall assume that setting the panel in the excavation will require one 8-hour day. During this time the contractor shall have available a backhoe, at least two workers, and equipments such slings and rope to assist with lowering the panels. The worker will need to assist with placing the panels into the excavation and moving top bracing to allow for insertion of the panels.

Backfill– After the panels are set, the contractor will back fill the space between the panel and the excavation wall with a 10-20 well sand that is primarily composed of quartz (e.g. Oglebay Norton, Colorado Springs, Colorado). This sand will be placed carefully such that the panels are not damaged or shifted to one side of the excavation. Sand elevation shall be gauged using a weighted tape as the sand is placed to demonstrate a uniform level for the full length of the excavation. The difference in sand elevation across the panel should never be more then 1-foot. Differences greater than 1-foot will push the panels to one side and potentially damage the panels. The sand back fill shall be brought to an elevation 2 feet above the top of the panels. The space above the sand should be backfilled with the materials excavated from below the watertable that were placed in the roll off box(s). Next materials taken from above the watertable and below the topsoil shall be used as backfill to and elevation of 1 foot below grade.

Sheet Pile Extraction – Sheet pile shoring shall be extracted using a vibratory hammer. Removal of the sheet pile shall be done carefully such that the reactive barrier panels and the 3-inch PVC riser pipes are not damaged.

Final Grading and Seed - Excavated topsoil shall be placed last as a uniform cover. The surface shall be mounded to an elevation 1-2 feet higher than the original grade to accommodate settlement. The mound shall be neatly sloped to drain. A seed (as specified by F.E. Warren AFB) shall be incorporated into the top 2 inches of the topsoil.

Removal of Debris - All debris generated during the construction including, sheet piles, abandon monitoring well casings, and used personnel protection equipment shall be removed from the site.

Decontamination of Equipment – The contractor is responsible for decontamination of all equipment brought onsite and disposal of all liquids and solid generated during decontamination of equipment.

Requested Information

Lump Sum Cost $____________________

Hourly Standby Rate (time in excess of 8 hour for assistance with setting the reactive barrier)
$__________________

Proposed date start date ______ and end date ______for work (our preference is early July).

Proposed Method for Trench Excavation
____
____
____
____

Will the field crew have 40-hour HAZWOPER training and annual refresher training?
____

Contact name and phone number for recent similar excavation
work____

Contact name and phone number for recent work requiring 40-hour HAZWOPER.
____

Please provide the above information to:

Tom Sale
Civil Engineering
Colorado State University
Engineering Research Center
Fort Collins, Colorado 80523

Questions should be directed to Tom Sale 970-491-8413 (TSale@Lamar.ColoState.Edu)

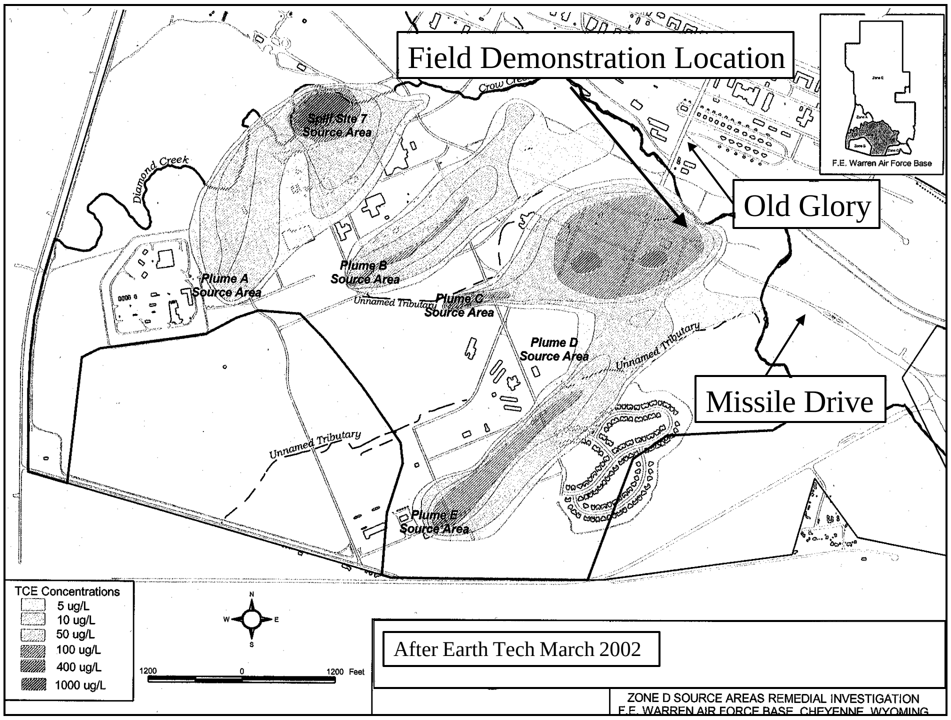


Figure 1. Site Location

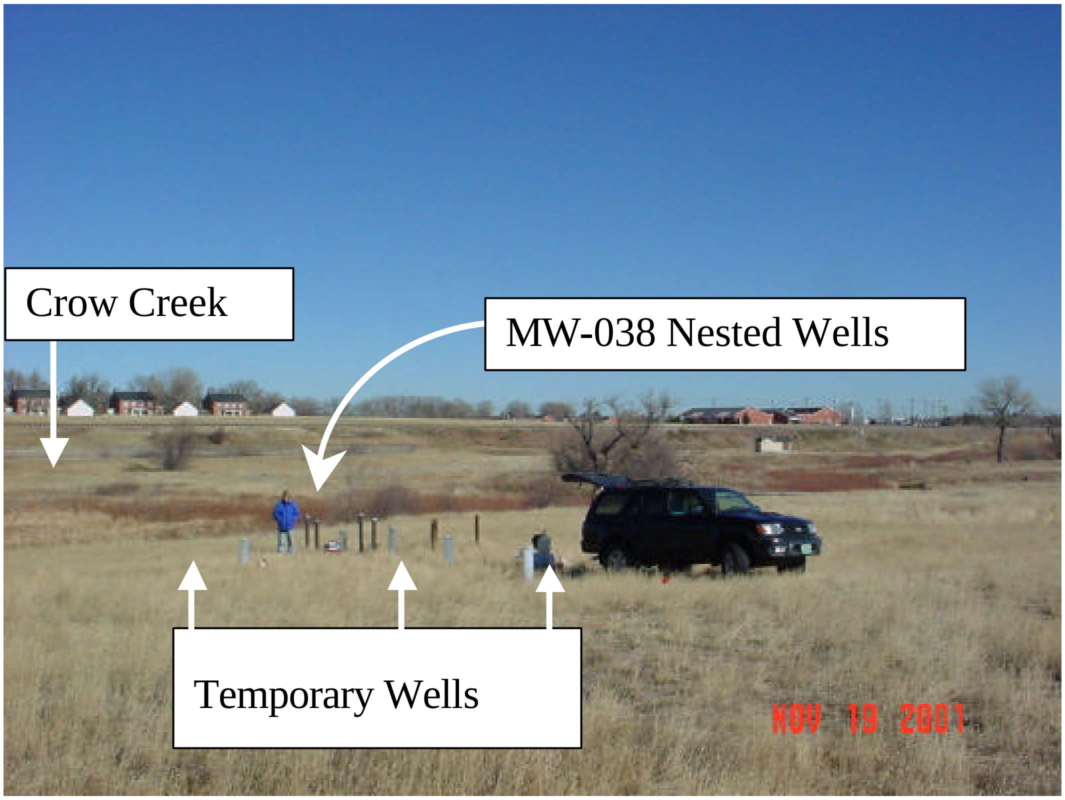


Figure 2 – Photo of MW-038 site looking northwest across Crow Creek

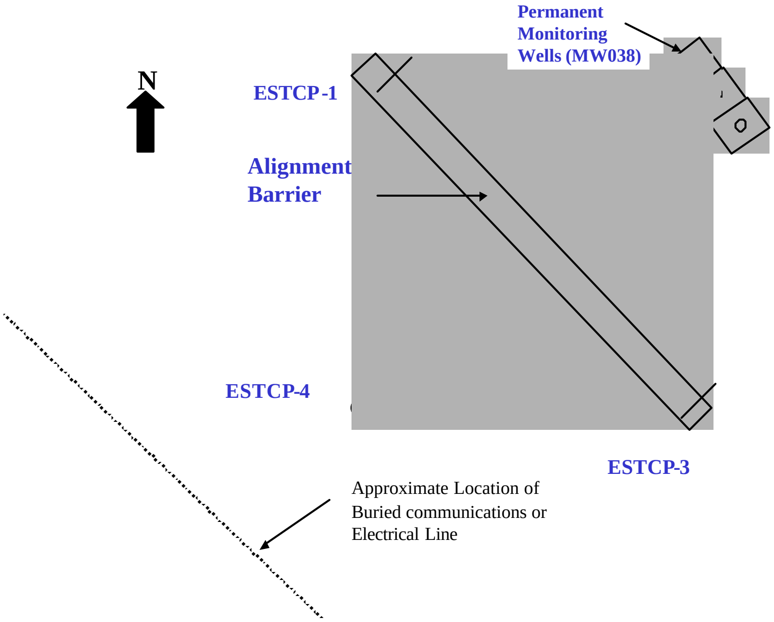


Figure 3 – Site layout – permanent wells, temporary wells, and barrier location

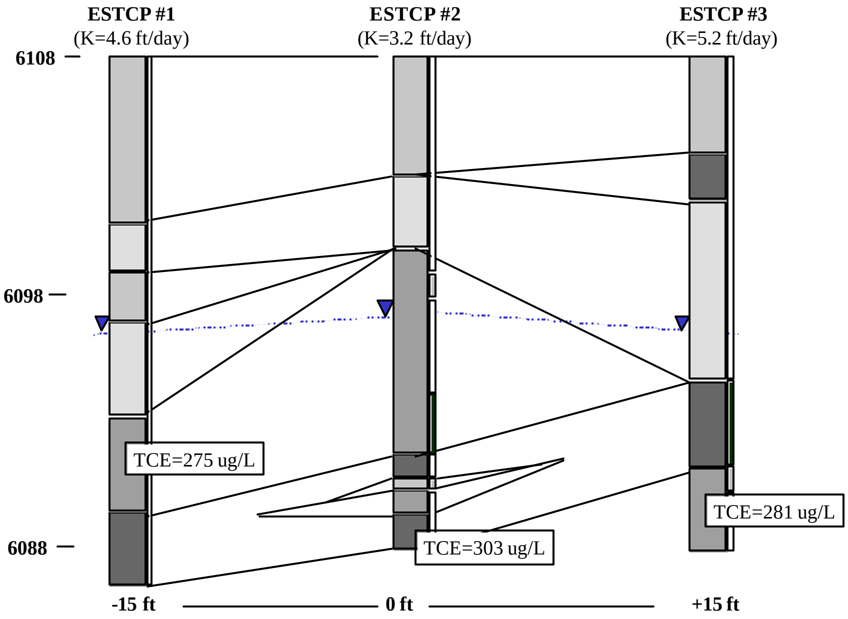


Figure 4 – Interpreted geologic cross-section along the excavation alignment

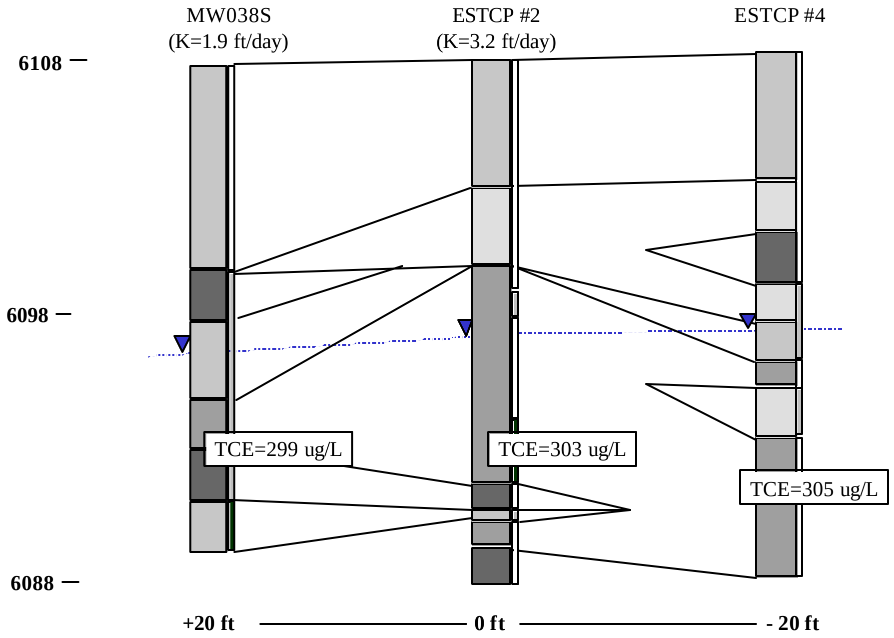


Figure 5 – Interpreted geologic cross-section perpendicular the barrier alignment

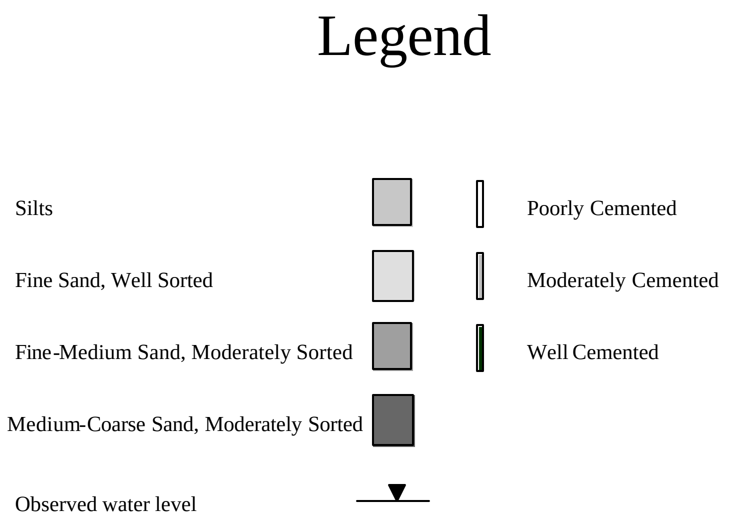


Figure 6 – Symbols used in geologic cross-sections

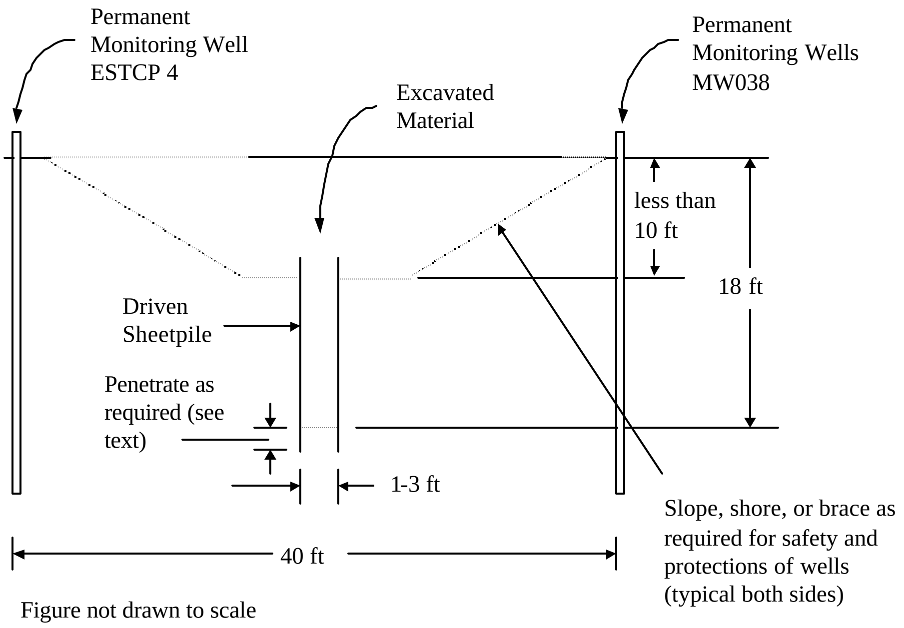


Figure 7 – Open Excavation Option

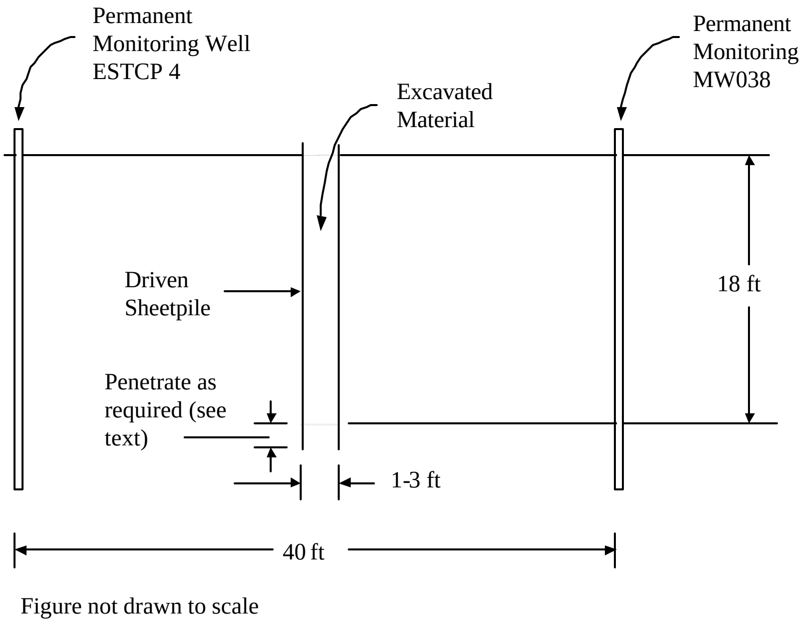


Figure 8 – Shoring to Grade Option

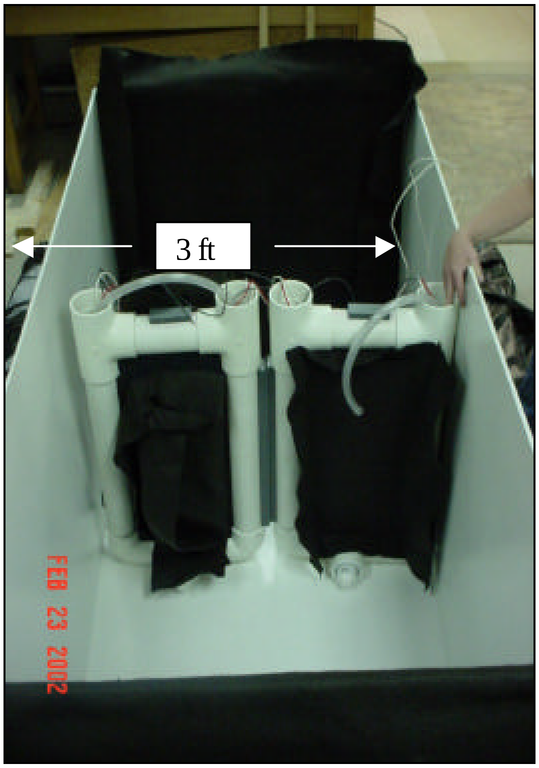


Figure 9 – Prototype Panel (Note field panels will be ~ 6 feet tall)

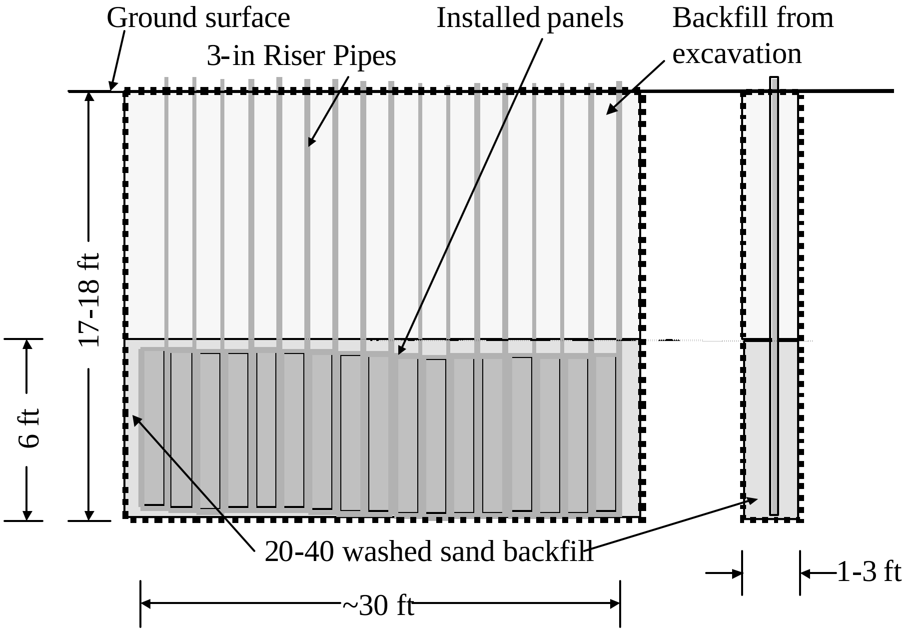


Figure 10 – Cross-sections of installation

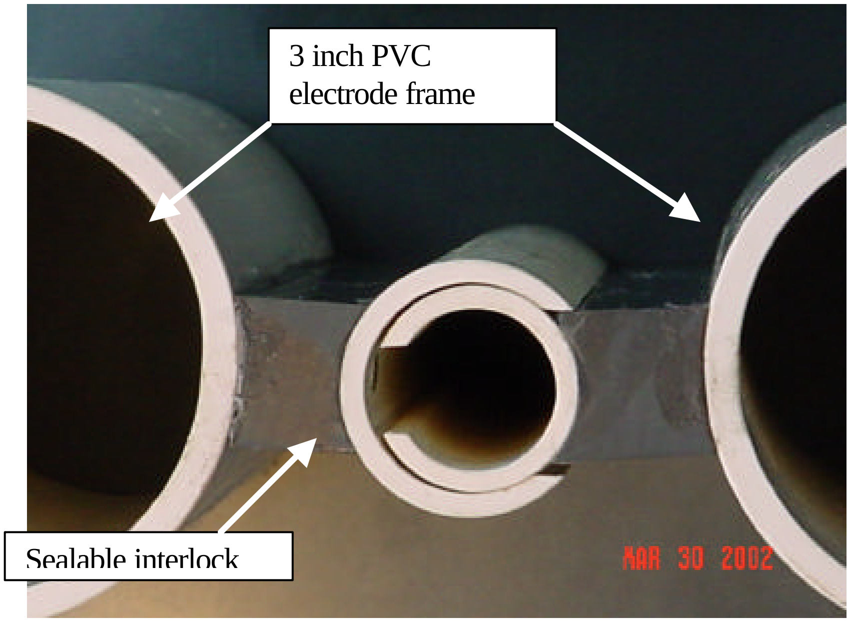


Figure 11 –Panel interlock

Colorado State University **Soil Boring**

Dept of Chemical Engineering

Project Number 532339 | **Boring No.** ESTCP # 2 | Sheet 1 of 1

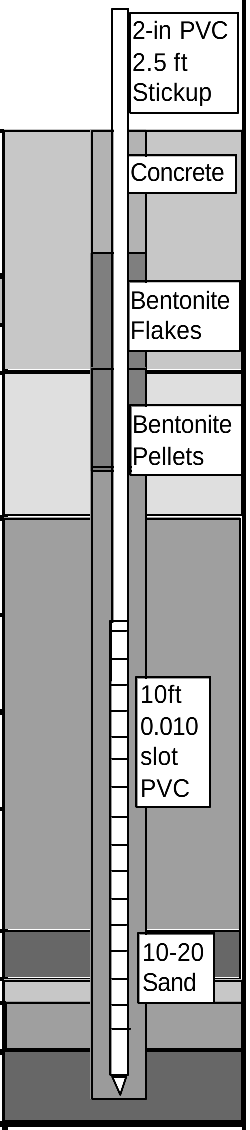
Project ESTCP e-barrier Demc | **Location** North Lobe Plume C | **Elevation**

Driller Drilling Engineers | **Drilling Equipment** Hollow Stem, Auger - Contiunuous Sampler

Water Level~10ft bgs | **Start** 10/02/01 | **Finish** 10/02/01 | **Logger** Tom Sale

Interval	**Rec.**	**Blow Counts**	**OVM** Avg	**OVM** Max	**Soil Description** - Soil, Grain size distrib, Mineralogy, Cementation, Color
3					
2					
1					
0	3 ft Barrel Sample		0.6	1.8	**Top Soil** - Well sorted silt w/fine sand (sparse pebbles), strong CO3, poorly cemented, black w/roots
1			0.5	1.1	
2					
3			-	-	
4	4 ft Barrel Sample		1	1.1	**Silt** - Moderately sorted silt w/fine sand-clay, strong CO3 minor muscovite, Poorly cemented, Black w/ white specs (CO3)
5			2.4	5.3	**Sand** - Well sorted fine sand, Quartz-hornblende-Mod CO3, Poorly cemmented, Light brown
6					
7			2.5	2.6	
8			2.2	2.4	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar muscovite-low CO3, poorly cemented light brown
9	4 ft Barrel Sample		0.2	0.3	As Above moderately cemented
10			1.5	1.7	**Sand** - Poorly sorted fine to medium sand w/silt, Quartz-Kspar muscovite-low CO3, poorly cemented light brown
11					
12			1	1.3	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar muscovite-low CO3, poorly cemented light brown
13					
14	4.5 ft Barrel Sample		0.4	0.5	As Above - Well Cemented
15					
16			0.2	0.7	
17			1	1.5	**Sand** - Moderately sorted medium to coarse sand, Quartz-Kspar muscovite-low CO3, Poorly cemented, Light pink
			0.1	0.3	**Silt** - Well sorted silt, weak CO3, moderately cemented, Brown
18			1.9	2	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar-low CO3, poorly cemented light brown
19	2 ft Split Spoon	14-20-50 Lst = 3.5"	0.8	1	**Sand** - Moderately sorted medium to coarse sand, Quartz-Kspar muscovite-low CO3, Poorly cemented, Light pink
20					
21	TD= 20.5 ft				
22					
23					

Well Completion



Colorado State University

Soil Boring

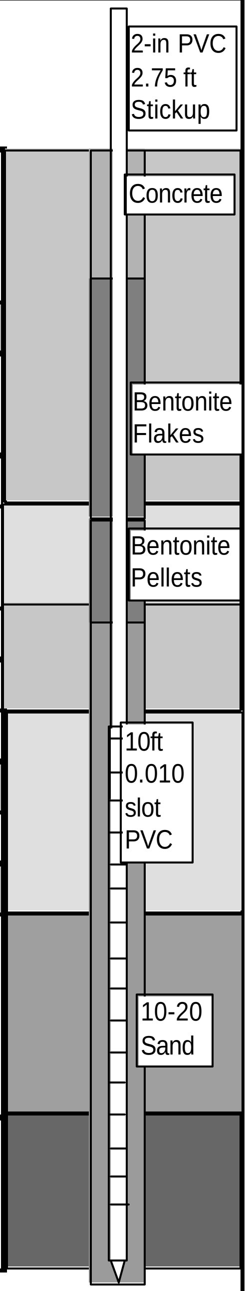
Dept of Chemical Engineering

Project Number 532339	**Boring No.** ESTCP #1	Sheet 1 of 1
Project ESTCP e-barrier Demc	**Location** North Lobe Plume C	**Elevation**
Driller Drilling Engineers	**Drilling Equipment** Hollow Stem, Auger - Contiunuous Sampler	

Water Level~10ft bgs	**Start** 10/02/01	**Finish** 10/02/01	**Logger** Tom Sale

Interval	**Rec.**	**Blow Counts**	**OVM** Avg	**OVM** Max	**Soil Description** - Soil, Grain size distrib, Mineralogy, Cementation, Color
3					
2					
1					
0	3 ft Barrel Sample		0.2	0.2	**Top Soil** - Well sorted silt w/fine sand (sparse pebbles), strong CO3, poorly cemented, black w/roots
1			0.4	0.4	
2			0.3	0.5	
3			-	-	
4	4.5 ft Barrel Sample		0.3	0.6	**Silt** - Moderately sorted silt w/fine sand-clay, strong CO3 minor muscovite, Poorly cemented, Black w/ white specs (CO3)
5			0.4	0.5	
6			0.2	0.5	**Silt** - Moderately sorted silt w/fine sand-clay, strong CO3 minor muscovite, Light tan
7			0.6	0.6	**Sand** - Poorly sorted fine to medium sand w/silt, Quartz-hornblende-kspar-moderate carbonate, poorly cememted, pink
8			1.2	2	
9	4 ft Barrel Sample		1.2	1.3	**Silt** - Well sorted silt, weak CO3, Poorly cemented, Brown
10			1.1	1.3	As above w/ muscovite
11			1.8	1.9	**Sand** - Well sorted fine sand, Quartz-Muscovite-Biotite-No CO3, Poorly cemmented, Light brown
12			-	-	
13			1.8	1.8	As above w/ moderate CO3
14	3.5 ft Barrel Sample		-	-	
15			1	1.5	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar muscovite-low CO3, poorly cemented light brown
16					
17			1	1	
18					
19	2.75 ft Barrel Sample		1.8	1.8	**Sand** - Moderately sorted medium to coarse sand, Quartz-Kspar muscovite-low CO3, Poorly cemented, Light pink
20			2.2	2.3	
21					
22	TD= 21.75 ft				
23					

Well Completion



Colorado State University

Soil Boring

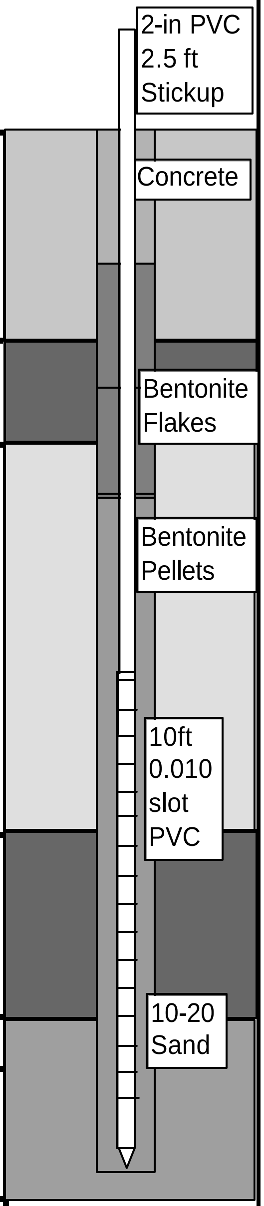
Dept of Chemical Engineering

Project Number 532339	**Boring No.** ESTCP # 3	Sheet 1 of 1
Project ESTCP e-barrier Demo	**Location** North Lobe Plume C	**Elevation**
Driller Drilling Engineers	**Drilling Equipment** Hollow Stem, Auger - Contiunuous Sampler	

Water Level~10ft bgs	**Start** 10/03/01	**Finish** 10/03/01	**Logger** Tom Sale

Interval	**Rec.**	**Blow Counts**	**OVM** Avg	**OVM** Max	**Soil Description** - Soil, Grain size distrib, Mineralogy, Cementation, Color
3					
2					
1					
0	3 ft Barrel Sample		0.2	0.3	**Top Soil** - Well sorted silt w/fine sand (sparse pebbles), strong CO3, poorly cemented, black w/roots
1			0.3	0.52	
2					
3					
4	4 ft Barrel Sample		0.4	0.4	**Sand** - Poorly sorted fine to coarse sand w/silt, Quartz-hornblende-kspar-moderate carbonate, poorly cememted, pink
5					
6			0.7	0.9	**Sand** - Well sorted fine sand, Quartz-Muscovite-Biotite-No CO3, Poorly cemmented, Light brown
7					
8			1.1	1.2	
9	4 ft Barrel Sample		1.8	2.6	
10					
11			1.4	1.5	
12			1	1.3	
13			1.1	1.4	**Sand** - Moderately sorted medium to coarse sand, Quartz-Kspar -low CO3, Well cemented, Pink
14	5 ft Barrel Sample		1.1	1.5	
15					
16			0.8	1	
17			1.3	1.5	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar muscovite-low CO3, moderately cemented, Pink
18			2.4	2.5	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar muscovite-low CO3, poorly cemented light brown
19	2 ft Split Spoon	22-30-50 Last =5"	1.3	1.4	
20					
21	TD= 20.5 ft				
22					
23					

Well Completion



Colorado State University **Soil Boring**

Dept of Chemical Engineering

Project Number 532339	**Boring No.** ESTCP # 4	Sheet 1 of 1
Project ESTCP e-barrier Demo	**Location** North Lobe Plume C	**Elevation**
Driller Drilling Engineers	**Drilling Equipment** Hollow Stem, Auger - Contiunuous Sampler	
Water Level~10ft bgs **Start** 10/02/01	**Finish** 10/02/01	**Logger** Tom Sale

Interval	**Rec.**	**Blow Counts**	**OVM** Avg	**OVM** Max	**Soil Description** - Soil, Grain size distrib, Mineralogy, Cementation, Color
3					
2					
1					
0			0	0	**Top Soil** - Well sorted silt w/fine sand (sparse pebbles), strong CO3, poorly cemented, black w/roots
1					
2	3 ft Barrel Sample				
3			0	0	**Silt** - Moderately sorted silt w/fine sand-clay, strong CO3 minor muscovite, Poorly cemented, Black w/ white specs (CO3)
4			0	1.7	**Silt** - Moderately sorted silt w/fine sand-clay, strong CO3, Light tan
5			0.2	0.4	**Sand** - Modertely sorted fine to medium sand, Quartz-hornblende-kspar-strong carbonate, poorly cememted, pink
6	5 ft Barrel Sample				
7			1.5	1.7	**Sand** - Moderately sorted medium to coarse sand, Quartz-Kspar-moderate CO3, Poorly cemented, Light pink
8					
9			1.2	1.5	**Sand** - Well sorted fine sand, Quartz-Muscovite-Biotite-moderate CO3, Moderately cemented, Light brown
10					
11	5 ft Barrel Sample		0.8	1	**Silt** - Moderately sorted silt w/fine sand, Moderate CO3, Light tan
12			1.5	1.9	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar-low CO3, poorly cemented light brown w/ interbeds of silts,
13			0.9	1	**Sand** - Well sorted fine sand, Strong CO3, Moderately cemented, Light brown
14			1.2	1.3	
15			1	1.9	**Sand** - Moderately sorted fine to medium sand, Quartz-Kspar-moderate CO3, poorly cemented, Light brown
16	2 ft Barrel Sample				
17					
18					
19	2 ft Split Spoon	18-20-38	1	1.1	
20					
21	TD= 20.5 ft				
22					
23					

Well Completion

Appendix B: Analytical Methods Supporting the Experimental Design

Table B-1- Summary of analytical methods, sample preservation methods, and holding times.

PARAMETER	METHOD	DETECTION LIMIT OR ACCURACY	SAMPLE PRESER-VATION	HOLDING TIME	NOTES
Water Levels	Electronic water level meter (e.g. Solinst ^{TM} 101).	+- 0.01 foot	None	Measure at time of sample collection	
pH	EPA Method 150.1 - Denver Instruments AP25 and glass combination electrode (Ag/AgCl reference)	+- 0.01 pH units	None	Measure at time of sample collection	
Temperature	Denver Instruments AP25 and glass combination electrode (Ag/AgCl reference)	+- 0.1 degree C	None	Measure at time of sample collection	
Eh	Denver Instruments AP25 and platinum combination electrode (Ag/AgCl reference).	+- 0.1 mV	None	Measure at time of sample collection	Correction to standard hydrogen electrode will be conducted during data analysis for Eh measurements.
Specific conductivity	Orion 130 conductivity meter and cell	+- 1 uS/cm	None	Measure at time of sample collection	
Voltage	Cordcom datalogger	+- 0.001 V	None	Instantaneous measurement	
Amperage	Cordcom datalogger	+- 0.01 mA	None	Instantaneous measurement	
Electrode potential	Cordcom datalogger	+- 0.001 V	None	Instantaneous measurement	

Table B-1 (continued) Summary of analytical methods, sample preservation methods and holding times.

TCE and degradation products products (c-1,2-DCE, t-1,2-DCE, 1,1-DCE, and Vinyl chloride	EPA Method 502.2. Analytical instrumentation consists of a Hewlett Packard 5890 Gas Chromatograph and Electron Capture Detector.	Reported detection limit of 0.02 ug/L. PQL determined through instrument calibration	40 mL glass vial screw cap with teflon face silicon septa faced to sample, bubble free, pH < 2 HCl, cooled to ~4^{o}C	14 days	No expected complications associated with the sample matrix.
Aluminum, Barium, Cadmium, Chromium, Copper, Iron, Manganese, Nickel, Zinc	EPA Method 6010 - Jarrell-Ash Inductively Coupled Plasma-Atomic Emission Spectroscopy	Reported detection limit of > 50 ug/L. PQL determined through instrument calibration	40 mL PE bottles pH less than 2, nitric acid, cooled to ~ 4^{o}C	180 days	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 Sievers Ion Chromatograph	Reported detection limit of > 0.3 mg/L. PQL determined through instrument calibration	40 mL PE cooled to ~ 4^{o}C	28 days for F^-, Cl^-, SO_4^{-2} 48 hours for NO_3^-, NO_2^-, PO_4^{-3}	
Alkalinity	EPA Method 310.1 Titration to a pH of 4.5	1 mg/L	40 mL PE cooled to ~ 4^{o}C	14 days	
Evolved Gas	Fixed Gases Standard Methods 2770C GC/TCD Chlorinated VOCs USEPA TO-14 GC/MS	0.5 percent 1000 ppbv	1L Tedlar bags	48 hrs 48 hrs	Commercial analysis

Reference

Keith, L.H. 1996. Compilation of EPA's sampling and analysis methods. 2nd ed.CRC Press, Inc.

Findlay, R.H. and F.C. Dobbs. 1993. Quantitative description of microbial communities using lipid analysis, p. 271-280. *In* P. F. Kemp, B. F. Sherr, E. B. Sherr, and J. J. Cole (ed.), Handbook of Methods in Aquatic Microbial Ecology. Lewis Publishers.

Appendix C: Analytical Methods Supporting the Sampling Plan

See Appendix B

Appendix D: Quality Assurance Project Plan (QAPP)

A. PROJECT MANAGEMENT

A1 TITLE AND APPROVAL SHEET

Plan Title: Demonstration Plan for Electrically Induced Redox Barriers for Treatment of Groundwater

Organization: Colorado State University
Department of Civil Engineering
Engineering Research Center
Fort Collins, Colorado 80523
USA

Principal Investigator:

Dr. Tom Sale
Research Scientist
Department of Civil Engineering
Colorado State University
Fort Collins, Colorado 80523

A2 Table of Contents

A3 Distribution List

Point of Contact Name	Organization Name and Address	Phone/Fax/email	Role(s) on Project
Andrea Leeson	ESTCP Program Office 901 North Stuart Street, Suite 303, Arlington , Virginia 22203	703-696-2118 (w)	ESTCP Program Manager for Cleanup
Erica Becvar	Technology Transfer Division HQ AFCEE/ERT 3207 North Road Brooks AFB TX 78235-5363	210-536-4314 (w) 210-536-4330 (f)	ESTCP Project Liaison
John Wright Chief Environmental Management, F.E. Warren AFB	300 Vesle Drive, F.E. Warren AFB, Wyoming 82005	307-773-4147 (Warren)	Chief Environmental Management, F.E. Warren AFB
EPA	Rob Stites		Region 8 Site Manager for F.E. Warren AFB
WDEQ	Jane Cramer		WDEQ Site Manager for F.E. Waren AFB

A4 Project/Task Organization

A4.1 Background

The project organizational chart identifying task managers and individuals responsible for performing the project is included in Figure E1. Dr. Tom Sale will act as the primary project coordinator for Colorado State University. Dr. Ken Reardon will act as the project technical advisor and QA officer. Contact information for project team members are included in Section 8 of the Work Plan.

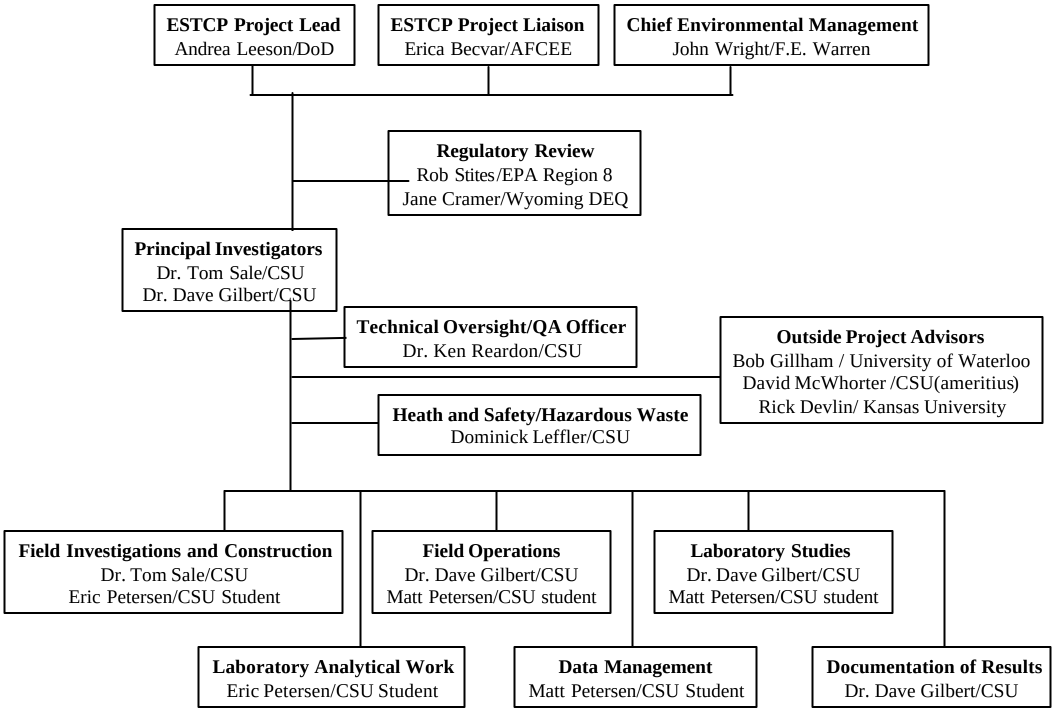


Figure E-1. Project Organization Chart

A.5 Problem Definition/Background

See Sections 1 and 2 of the Demonstration Plan for Electrically Induced Redox Barriers for Treatment of Groundwater

A6 Project/Task Description and Schedule

See Section 3 of the Demonstration Plan for Electrically Induced Redox Barriers for Treatment of Groundwater

A7 Quality Objectives and Criteria for Measurement Data

A7.1 Background

See Sections See Sections 4 and 5 of the Demonstration Activities Work Plan

A7.2 Quality Objectives

Quality objectives are essential for ensuring that data collected are sufficient to meet the intended goals of the project. Quality objectives are pre-established goals or “bench-marks” used to monitor and assess the progress of the project and the quality of the work performed. It is essential that quality objectives be defined prior to initiation of the project work. This will ensure that activities performed in support of the project yield data sufficient to meet the project objectives.

Quality objectives are broken into two categories: Data Quality Objectives (DQOs) and Quality Assurance Objectives (QAOs). DQOs are associated with the overall objective of the project as it relates to data collection. QAOs define the limits of acceptance for the project-generated data as they relate to data quality.

DQOs: the data collected through the program described here has two intended uses:

- Pre-demonstration data is intended to optimize the design and operation of the demonstration barrier

- Demonstration data is intended to provide information on the efficacy, cost and constructability such that end users can evaluate the suitability of the e^-barrier for specific application

The specific objectives of the pre-demonstration studies are to:

1. Verify performance under site conditions,
2. Test materials of construction,
3. Optimize design (e.g. electrode spacing), and
4. Evaluate operational strategies (e.g. applied voltage and scale management)

The specific objectives of the demonstration phase are to:

- Collect the data necessary to evaluate treatment efficacy for TCE in groundwater
- Acquire the information needed to characterize cost and implementability

Precision, Accuracy, Representativeness, Completeness, and Comparability

The basis for assessing precision, accuracy, representativeness, completeness, and comparability is discussed in the following section.

Precision

Precision measures the reproducibility of measurements. It is strictly defined as the degree of mutual agreement among independent measurements as the result of repeated application of the same process under similar conditions. Analytical precision is the measurement of the variability associated with duplicate or replicate analyses. For purposes of this project, we will laboratory control samples to determine the analytical precision. For this analysis, control samples will be compared between batches. If duplicate samples are within the precision criteria (Table E.1) between batches, precision will be considered to be within limits. Total precision is the measurement of variability associated with the entire sampling and analysis process. It is determined by analysis of duplicate or replicate field samples and measures the variability introduced by both field and laboratory operations. In the data collection phase of this demonstration project, field duplicate samples and matrix duplicate spiked samples will be analyzed to assess total precision. Results will be calculated as relative percent difference (RPD):

$$RPD = \left[\frac{(x_1 - x_2)}{\left(\frac{x_1 + x_2}{2} \right)} \right] \times 100$$

where: x_1, x_2 are the duplicate analysis

For replicate analyses, relative standard deviation (RSD) will be calculated as:

$$RSD = \frac{s}{\bar{x}} \times 100$$

Precision limits for samples taken as part of this project are given in Table E.1

Accuracy

Accuracy is a statistical measurement of correctness and includes components of random error (variability due to imprecision) and systematic error. It therefore reflects the total error associated with a measurement. A measurement is accurate when the value reported does not differ from the true value or known concentration of a spike or standard. Analytical accuracy is measured by comparing the percent recovery of analytes spiked into a laboratory control sample to a control limit. Percent recovery will be calculated by:

$$percent\ recovery = \frac{(value\ of\ spiked\ sample - value\ of\ unspiked\ sample)}{value\ of\ added\ spike} \times 100$$

Representativeness

Representativeness of samples collected during this demonstration will be achieved through the use of standard field sampling and analysis procedures discussed in Section B of the QAPP. Representativeness of samples is also achieved through program monitoring design included in the Demonstration Design (Section 3 of the Demonstration Activities Work Plan).

Completeness

Completeness of results is a measure of the number of valid results compared to the total number of results. For purposes of this demonstration, any sample not meeting the QC requirements outlined in Section B will not be considered valid. The following will be used for calculation of completeness:

$$\%\ completeness = \frac{number\ of\ valid\ results}{number\ of\ possible\ results}$$

Comparability

Comparability is the confidence with which one data set can be compared to another data set, the objective being to produce data with the greatest degree of comparability. For purposes of this Demonstration, comparability is achieved by using standard methods for sampling and analysis, reporting of data in standard units, normalizing results to standard conditions and using standard and comprehensive reporting formats.

Determination of Method Detection Limits

Method detection limits are the minimum concentration that can be measured and reported with a 99% confidence that the analyte concentration is greater than zero. Method detection limits will be estimated for each analytical instrument used during the demonstration by reporting the concentration value that corresponds to an instrument signal to noise ratio in the range of 2.5 to 5.

Selection of quantitation limits

The quantitation limits for a specific sampling effort are dictated by the intended use of the data. For the pre-demonstration phase of the project, the quantitation level must be low enough so that the results of the analyses are sufficiently accurate to provide design and operational information to feed the demonstration phase of the project. For the demonstration phase of the project, the quantitation level must be low enough so that the results of the analyses are sufficiently accurate to ascertain barrier performance.

The quantitation levels in this QAPP were used to select appropriate analytical methods for the laboratory and field sampling included in the work plan (Section 3).

For purposes of the demonstration phase, estimation of the quantitation limit will be conducted for each instrument following Devlin, 1996 (A method to assess analytical uncertainties over large ranges with reference to volatile organics in groundwater. Journal of Groundwater Monitoring and Remediation 16:179-185).

Instrument Calibration

Analytical instruments will be calibrated in accordance with the analytical methods. All results reported will be within the calibration range. The lowest standard used to develop the calibration curve will be at or below the quantitation limit. Calibration of each instrument will be checked at a minimum of 10 samples run. The calibration check will be a standard analyte at or below the middle of the calibration curve. Failure of a calibration check to fall within 90% of the initial calibration curve will result in recalibration of the instrument and reanalysis of samples run after the most recent acceptable calibration check. Records of calibration, calibration checks and standard preparation will be maintained.

A8 Special Training Requirements/Certification

A8.1 Background

This section describes training associated with laboratory work, field work, and reporting.

A8.2 Training

Laboratory
- CSU Hazardous Materials Handling (4 hours)
- CSU Laboratory Safety (4 hours)
- Porous Media Laboratory Measurement Methods (2-40 hours depending on activities)

Field
- Logging – Geologist Registered in the State of Wyoming
- Porous Media Laboratory Field Measurement Methods (4 hours)
- Site Orientation Training (4 hours)
- American Red Cross First Aid (4 hours)
- Non-intrusive field work in low exposure areas (24 hours of relevant training per 29 CFR1910.120 (e) (2) and (e) (3).
- Intrusive field work - 40-hour HAZWOPER per 29 CFR1910.120 (e) (2) and (e) (3).

Reporting

- All final report will be reviewed by individuals with Ph.D. degrees

A8.3 Certification

Written documentation of the above.

A9 Documentation and Records

All records will be in either written or electronic formats. Written records (e.g. measurements, chain of custody records) will be stored and filed in a secure location. Where appropriate, written records will be transferred to a Microsoft Access^{TM} database. Electronic records (databases, amperage logs, output from analytical instruments) will be stored on a secure personal computer and will be backed up as significant amounts of new data are added.

Table E.1. QC Acceptance Criteria

Analyte	**Accuracy (percent recovery)**	**Precision (RPD)**
TCE	75-141	≤20
1,1-DCE	53-147	≤20
Cis 1,2-DCE	75-120	≤20
Trans-1,2-DCE	75-130	≤20
Vinyl Chloride	47-142	≤20
Cations (ICP)	80-120	≤20
Anions (IC)	85-115	≤20

B MEASUREMENT/DATA ACQUISITION

B1 SAMPLING PROCESS DESIGN (EXPERIMENTAL DESIGN)

See Section 3 of the Pre-Demonstration Activities Work Plan and Appendix B (Analytical Methods).

B2 SAMPLING METHODS REQUIREMENTS

B2.1 Background

Sampling will consist of:

- Collecting aqueous samples from columns and tanks in the laboratory,
- Obtaining aqueous samples from sampling points in the field
- Collecting soil samples in the field
- Measuring amperage and voltage of the e^-barrier in the laboratory and the field

Methods of analysis are presented in Appendix B.

B2.2 Sample Collection, Preparation, and Decontamination Procedures

Aqueous samples from column and tank laboratory experiments – pH, Eh, conductivity and temperature measurements will be made using a low volume flow cell connected directly to a glass sampling port in the column or tank experiment. Five mL of aqueous sample will be drawn through the sample port and flow cell using a peristaltic pump or glass syringe before recording pH, Eh, conductivity and temperature measurements. Experience indicates that a representative measurement can be obtained with this volume. Withdrawal of more than 5 mL of sample volume tends to adversely disturb flow and thermodynamic conditions in the column. Cleaning of the flow-through cell and measurement electrodes will be conducted using a deionized water rinse (triplicate).

Samples for analysis of TCE and associated degradation products in water will be acquired by drawing samples from glass sampling ports directly into 3 mL glass vials with Teflon septa. Samples will be drawn into the vial using either a peristaltic pump or a glass syringe. A minimum of 6 mL will be flushed through the sample bottle prior to collecting the sample. Samples will be placed in a sample-only refrigerator at 4^oC. To minimize the potential for cross contamination, dedicated Viton and glass fittings will be used to collect samples.

Obtaining aqueous samples from sampling points in the field – Aqueous samples will be acquired from sampling points using a variable speed peristaltic pump. Measurements of pH, Eh, conductivity and temperature and samples for TCE and associated degradation products will be acquired directly from the suction line. A low volume flow-through cell will be used measure pH, Eh, temperature, and conductivity. Samples for analysis of TCE and associated degradation products in water will be acquired by drawing samples from the suction line directly into 3 mL glass vials with Teflon lined septa. A minimum of 6 mL will be flushed through the sample bottle prior to collecting the sample. Samples will be placed in a sample-only cooler packed with ice.

Equipment decontamination/cleaning will be conducted following each well sampling. Cleaning will consist of rinsing the sample tubing with reagent grade methanol followed by deionized water.

> ***Collecting soil samples in the field -*** *Soil samples will be collected in 40 mL glass vials with teflon lined caps containing 20 mL of reagent grade methanol. Soil samples will be placed in a sample-only cooler packed with ice.*

B2.3 Identify Support Facilities for Sampling Methods

Colorado State University Environmental Engineering Laboratory – Gas chromatography, Ion chromatography
Colorado State University Soil, Water, and Plant Testing Laboratory – ICP
Colorado State University Porous Media Laboratory – Field staging, laboratory studies

B2.4 Describe Sampling/Measurement System Failure Response and Corrective Action Process

Given anomalous results from QA/QC procedures, an investigation will be initiated to either identify sources of error or confirm results. For purposes of this project a reevaluation of the results will be initiated if any of the following occurs:

1. duplicate analysis not meeting the QC criteria for precision (See Table E.1),
2. spike recovery not meeting the QC criteria for accuracy (See Table E.1)
3. field or trip blank indicating detectable TCE or associated degradation product

The investigation/corrective action process will consist of one or more of the following:

1. data verification
2. analytical instrumentation check
3. verification of instrument calibration (record check)
4. reanalysis of sample(s) in question
5. resampling

B2.5 Describe Sampling Equipment, Preservation, and Holding Time Requirements

See Appendix B

B3 SAMPLE HANDLING AND CUSTODY REQUIREMENTS

B3.1 Background

Colorado State University personnel will collect all water and soil samples described in this document. Since project personnel will conduct analysis at Colorado State University, transfer of sample custody will be limited.

B3.2 Sample Custody Procedures

Samples collected at Warren will be stored in coolers under the direct control of personnel from Colorado State University. A Chain of Custody (COC) form will be completed following sample collection and will be used to track the samples from the field to the laboratory through sample disposal. Samples will remain in secure locations at all times during the sampling, transport and analysis phases of the data collection effort.

COC forms will include the following information:

- Sample identification
- Date and time of sample collection
- Analytical method required
- Sample matrix
- Preservative (if necessary)
- Holding time
- Signature blocks for transfer of custody
- Any comments to identify special conditions or requests

B4 ANALYTICAL METHODS REQUIREMENTS

See Appendix B

B5 QUALITY CONTROL REQUIREMENTS

The following section describes the measures that will ensure the representativeness, completeness, comparability, accuracy, and precision of the data collected as part of this project. To the extent possible, EPA Methods will be followed to ensure comparability, accuracy and precision of the data. Specific EPA Methods or Guidance are outlined in Appendix B and the following section.

Quality Assurance/Quality Control (QA/QC) measures that will be conducted to ensure data quality include analysis of:

1) blind duplicates
2) matrix spikes
3) field blanks
4) trip blanks
5) replicates (both sample and analysis)
6) analysis of split samples by outside laboratory
7) laboratory control samples (replicates and spike)
8) laboratory blanks

QA/QC samples will consist of a minimum of 10% of the total samples collected, or at least 1 per sampling event. In addition, 20% split analysis will be conducted in the laboratory. Samples will be analyzed in groups of no more than 20 samples per lot. Samples in each lot will be similar in type and matrix (e.g. groundwater samples collected during a single round of field sampling). During the analysis of each lot of environmental samples, at least one laboratory control sample, one laboratory blank, and one calibration check will be included. Additionally, blind duplicates or matrix spikes will be included at a minimum 10% frequency. Field blanks and trip blanks will be included as part of each field sampling event. Analysis of split samples by the University of Waterloo will be conducted at least once during the demonstration. Note that split analysis (by the University of Waterloo) on samples collected as part of the pre-demonstration activities yielded results with a RPD of less than 10%.

B6 INSTRUMENT/EQUIPMENT TESTING, INSPECTION, AND MAINTENANCE REQUIREMENTS

All equipment will be inspected at least weekly and maintained per manufacturer recommendations. The gas chromatograph will undergo preventative inspection yearly.

B7 INSTRUMENT CALIBRATION AND FREQUENCY

Laboratory calibration of the gas chromatograph (Hewlett Packard Model 5890) will be conducted prior to analysis as described in USEPA Method 8000B (Determinative Chromatographic Separations). Calibration standards will be prepared as described in USEPA Method 5000 (Sample Preparation for Volatile Organic Compounds). Calibration of the instrument will be checked following each 10 samples analyzed. Recalibration will be conducted if necessary as described above (Section A7.2). Internal standards will be used in accordance with method requirements.

Field calibration of the pH and conductivity sensors will be conducted prior to sampling and checked following each sample. Recalibration will be conducted if necessary. Field calibration records will be maintained at part of the data collection process.

Calibration of the pH sensor will be conducted using commercially available pH buffer solutions (pH 4.0, 7.0, 10.0). Electrode slope values of less than 90% of ideal and greater than 110% of ideal will be considered outside the acceptable limit. Electrodes that will not calibrate to within this limit will be reconditions per the manufacturer recommendations. Subsequent calibration checks will be conducted following each sample by measurement of one of the calibration solutions. Note that the Denver Instruments AP25 pH meter for use in pH measurements includes automatic temperature compensation.

Calibration of the conductivity sensor will be conducted using 0.01 M KCl solution (1413 uS/cm at 20^{o}C). Electrodes that will not calibrate will be reconditioned per manufacturer specifications or replaced. Note that the Orion Model 130A-conductivity meter includes automatic temperature compensation.

Eh electrodes will be calibrated in the laboratory using a saturated quinhydrone solution as described in ASTM Practice D1498-00 (Standard Practice for Oxidation-Reduction Potential of Water) and checked prior to each field-sampling event (using a saturated quinhydrone solution). Electrodes that will not calibrate will be reconditioned per manufacturer specifications or replaced.

B8 INSPECTION/ACCEPTANCE REQUIREMENTS FOR SUPPLIES AND CONSUMABLES

All materials received will be inspected prior to acceptance to assure that they are in first hand condition.

B9 DATA ACQUISITION REQUIREMENTS (NON-DIRECT MEASUREMENTS)

Not applicable

B10 DATA MANAGEMENT

All records will be in either written or electronic formats. Written records (e.g. measurements, chain of custody records) will be stored in labeled three ring binders. Where appropriate written records will be transferred to a Microsoft Access^{TM} database. Electronic records (e.g. databases, amperage logs, output from analytical instruments) will stored data on a personal computer and will be backup as significant amounts of new data area added. All field data collection forms, calibration records, laboratory data forms will be developed prior to July 2002.

C ASSESSMENT/OVERSIGHT

C1 ASSESSMENTS AND RESPONSE ACTIONS

As the Principal Investigator, Dr. Sale will be responsible for the overall quality of the project. He will be assisted by the project Co- Principal Investigator, Dr. Ken Reardon.

C2 REPORTS TO MANAGEMENT

Following ESTCP guidelines, project status and results to date will be communicated through quarterly progress reports, presentations at the annual management meeting, and presentations at the annual symposium. Final documentation will include:

Draft and Final Technical Reports – Relevant aspects of the project will be documented. The goal of the final report will be to rigorously document our research including information needed to evaluate the applicability, cost, and implementation of the technology. The audience for the final report will be individuals wanting to evaluate the applicability, cost, and design of the technology for a given site.

Draft and Final Cost and Performance Reports – A concise (e.g. 40-pages) summary of cost and performance will be developed. The audience for this document will be individuals wanting a concise overview of the technology.

D DATA VALIDATION AND USABILITY

D1 DATA REVIEW, VALIDATION, AND VERIFICATION REQUIREMENTS

Data are potentially subject to sampling and data reduction errors. Quality Assurance Objectives (QAOs) are established to control the sources of errors and quantify the errors whenever possible.

The analysts or the field person generating the data collected for this project will review one hundred percent of the data collected. The acceptance limits and any data qualifiers that should be appended to the data will be included in the fields or analytical report. Quality Assurance reports will be generated including results of duplicate analysis, matrix spike recovery, analysis of blanks, split analysis and outside laboratory analysis on an ongoing basis. The QA reports will also include any corrective actions taken, if necessary. A summary QA report will be included in the Draft and Final Technical Reports.

Appendix E: Supplementary Performance Data

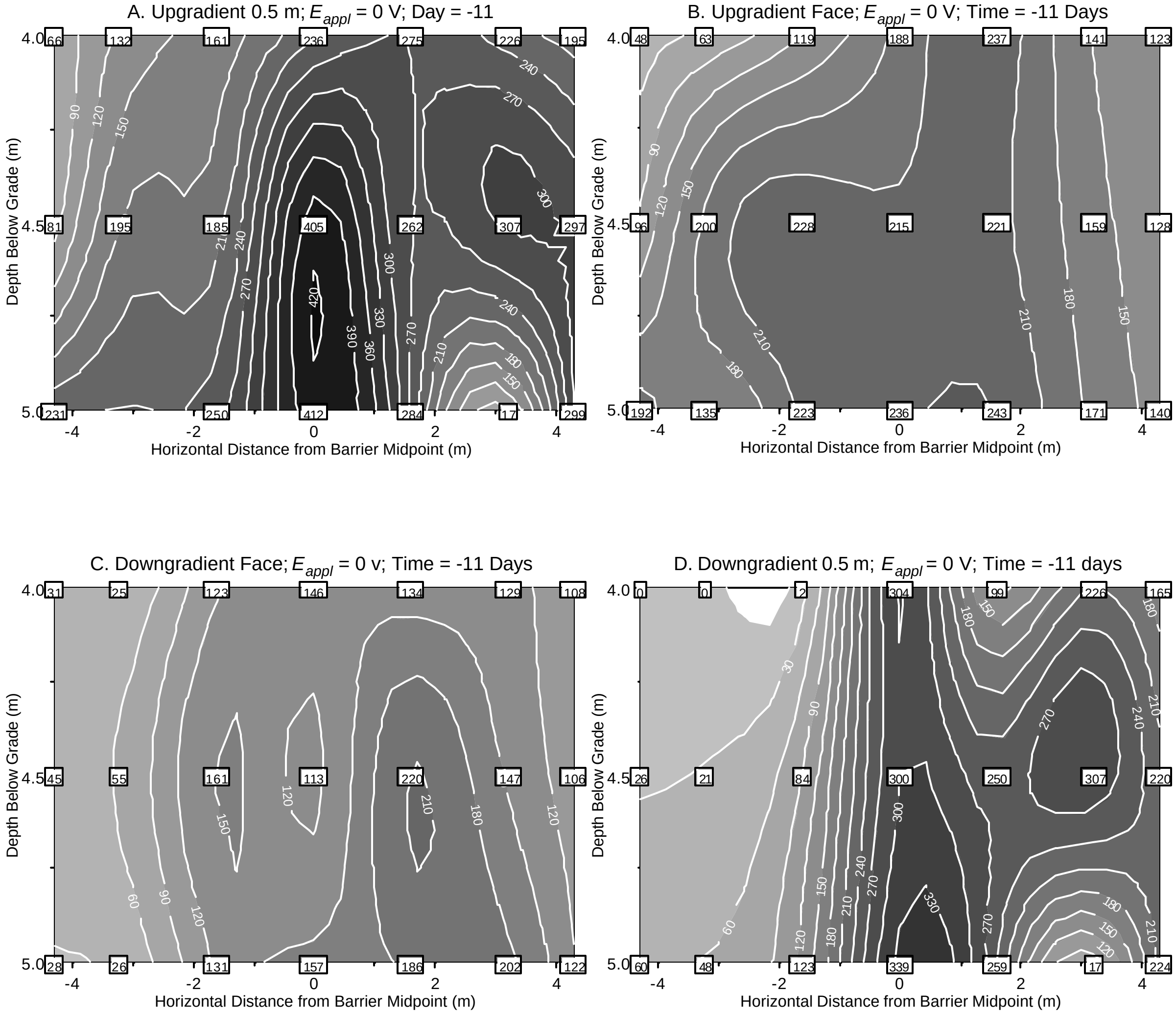


Figure E-1 - TCE concentration contour maps looking downgradient for *Eappl* = 0 V on day -11 at A. 0.5 upgradient of barrier, B. upgradient face of barrier, C. downgradient face of barrier, and D. 0.5 m downgradient of barrier. Negative horizontal positions are to the west of the barrier midpoint, and positive positions are to the east. All concentrations are reported in mg/L. Boxes show measured concentrations at that location.

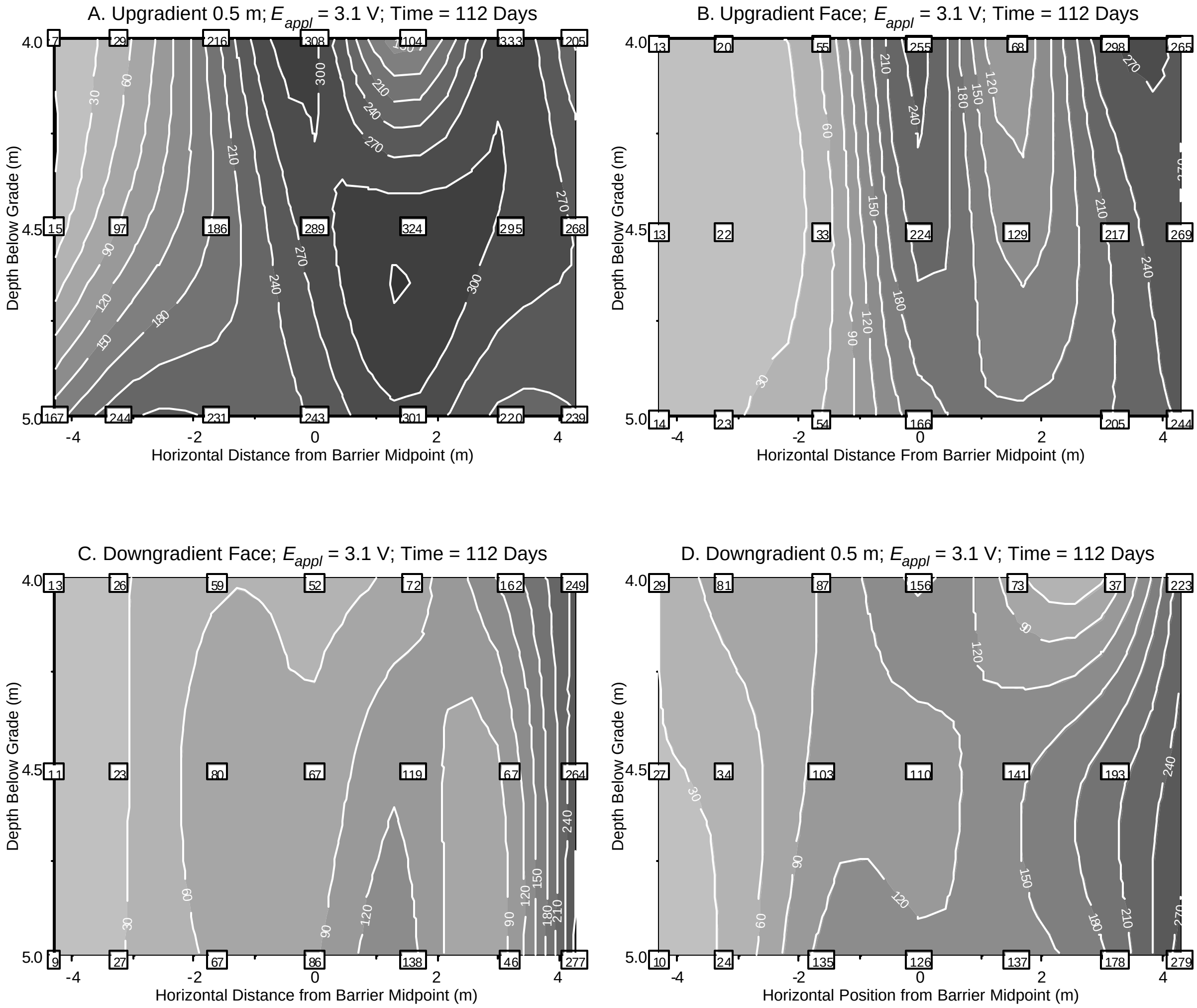
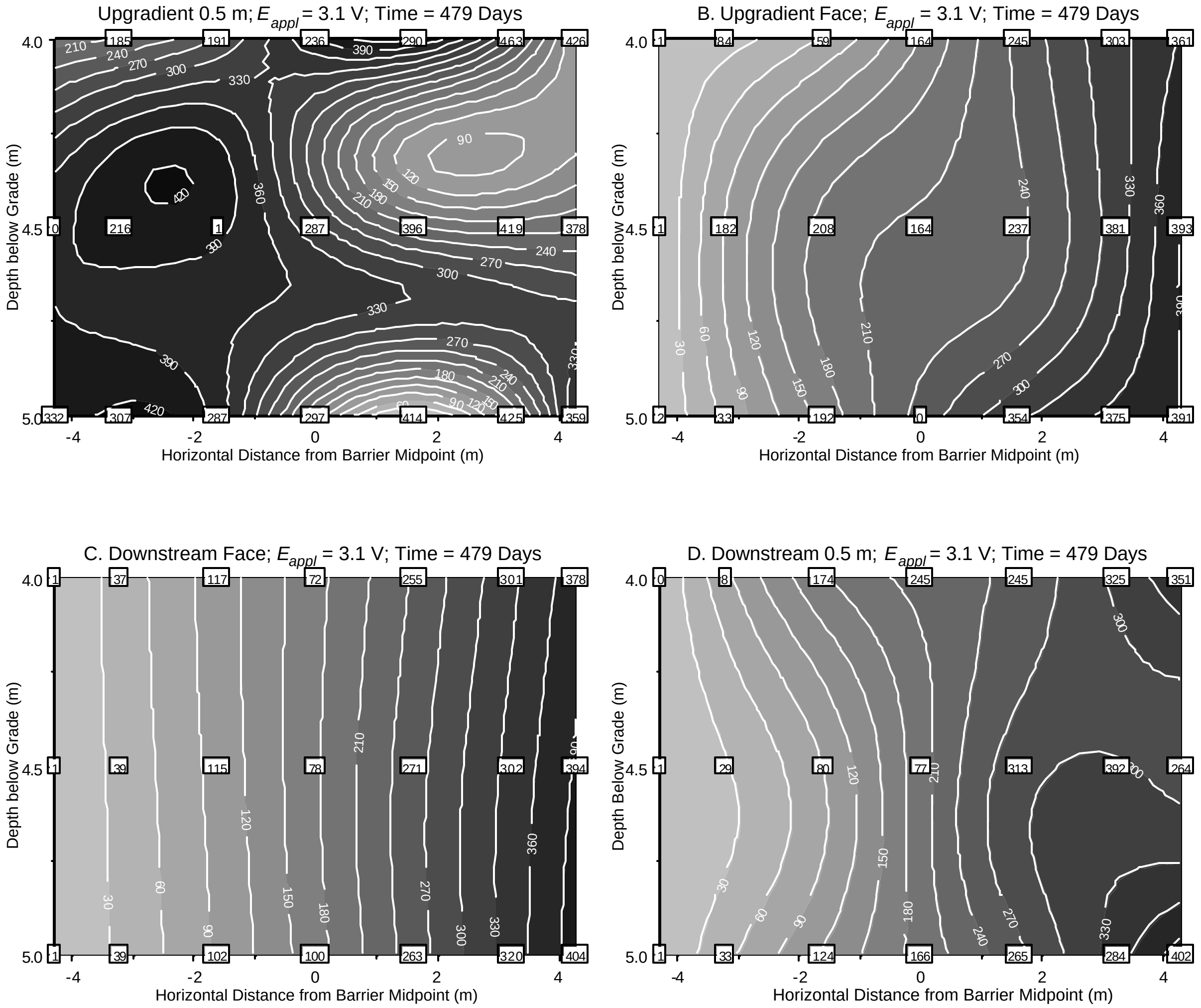


Figure E-2 - TCE concentration contour maps looking downgradient for *Eappl* = 3.1 V on day 112 at A. 0.5 upgradient of barrier, B. upgradient face of barrier, C. downgradient face of barrier, and D. 0.5 m downgradient of barrier. Negative horizontal positions are to the west of the barrier midpoint, and positive positions are to the east. All concentrations are reported in mg/L. Boxes show measured concentrations at that location.



Upgradient 0.5 m; E_{appl} = 3.1 V; Time = 479 Days

B. Upgradient Face; E_{appl} = 3.1 V; Time = 479 Days

C. Downstream Face; E_{appl} = 3.1 V; Time = 479 Days

D. Downstream 0.5 m; E_{appl} = 3.1 V; Time = 479 Days

Figure E-3 - TCE concentration contour maps looking downgradient for *Eappl* = 3.1 V on day 479 at A. 0.5 upgradient of barrier, B. upgradient face of barrier, C. downgradient face of barrier, and D. 0.5 m downgradient of barrier. Negative horizontal positions are to the west of the barrier midpoint, and positive positions are to the east. All concentrations are reported in mg/L. Boxes show measured concentrations at that location.

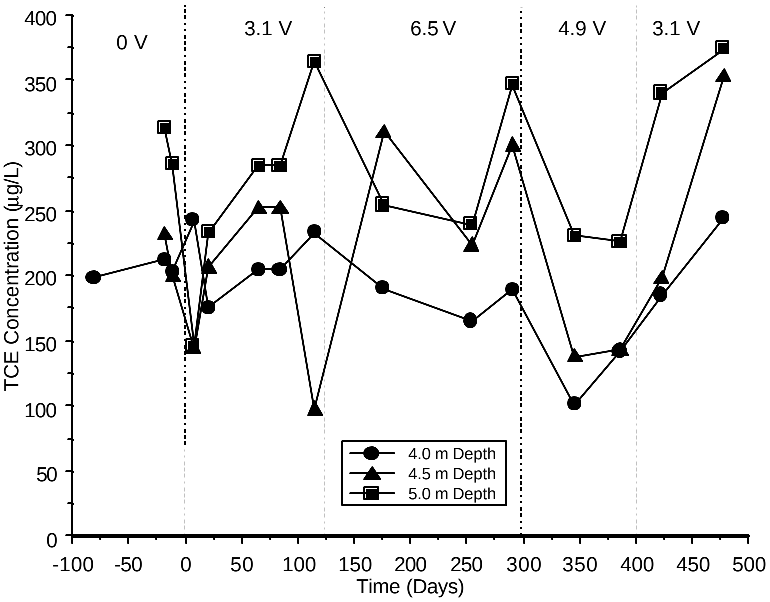


Figure E-4 – TCE concentration from multi-point sampler 2 m upstream of the e-barrier midpoint. Concentrations were measured at 4.0 m (circles), 4.5 m (triangles), and 5.0 m (boxes) below the surface. Power was applied to the e-barrier at day 0.

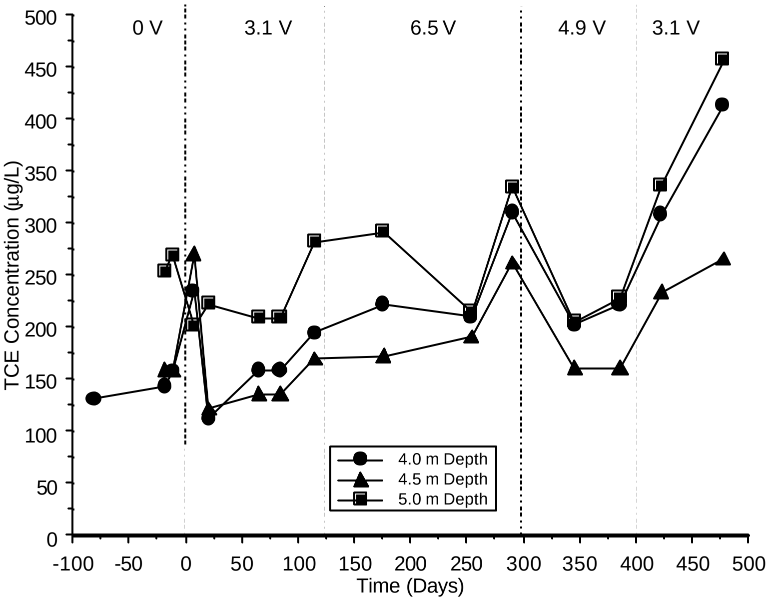


Figure E-5 – TCE concentration from multi-point sampler 4 m upstream of the e-barrier midpoint. Concentrations were measured at 4.0 m (circles), 4.5 m (triangles), and 5.0 m (boxes) below the surface. Power was applied to the e-barrier at day 0.

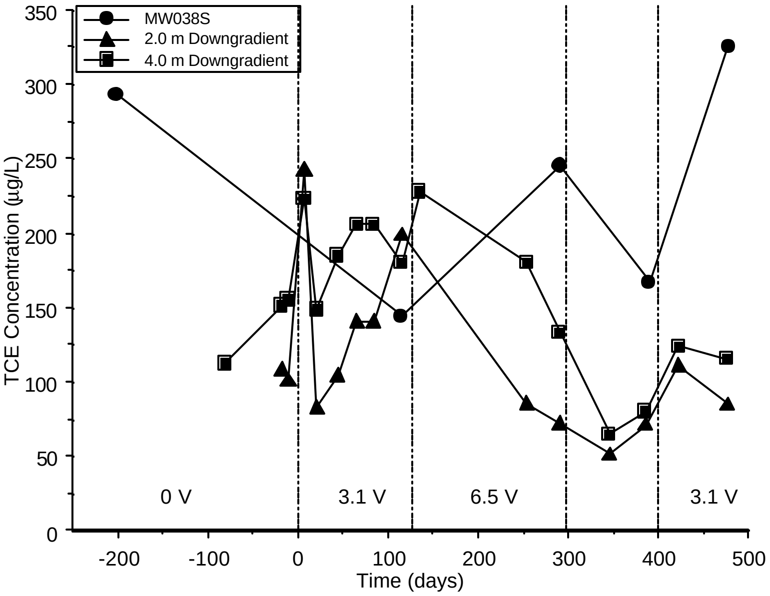


Figure E-6 – TCE concentrations at monitoring points downstream of the e-barrier. The points are 2.0 m downstream (triangles), 4.0 m downstream (squares), and at monitoring well MW038S (circles). Power was applied at day 0, *Eappl* values are marked in their corresponding time period.

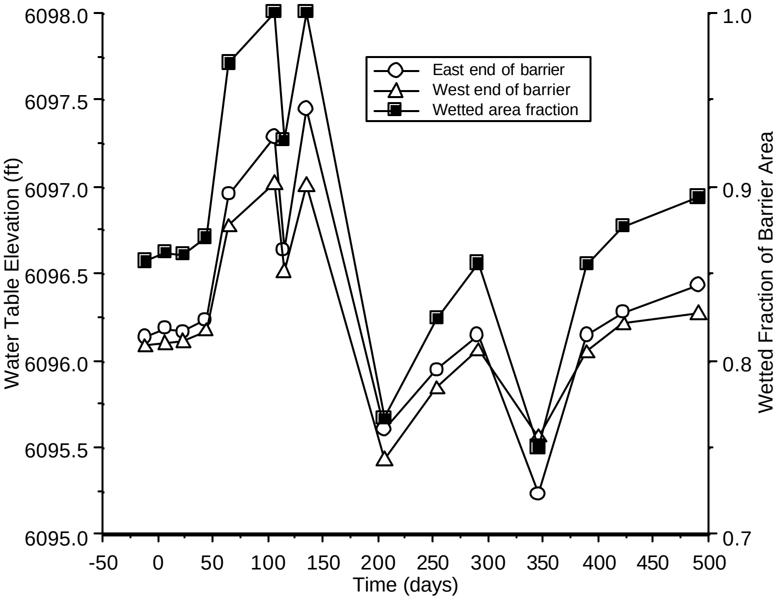


Figure E-7 – Water table elevation at the east and west ends of the e⁻barrier, and the fraction of the barrier cross-sectional area below the water table.

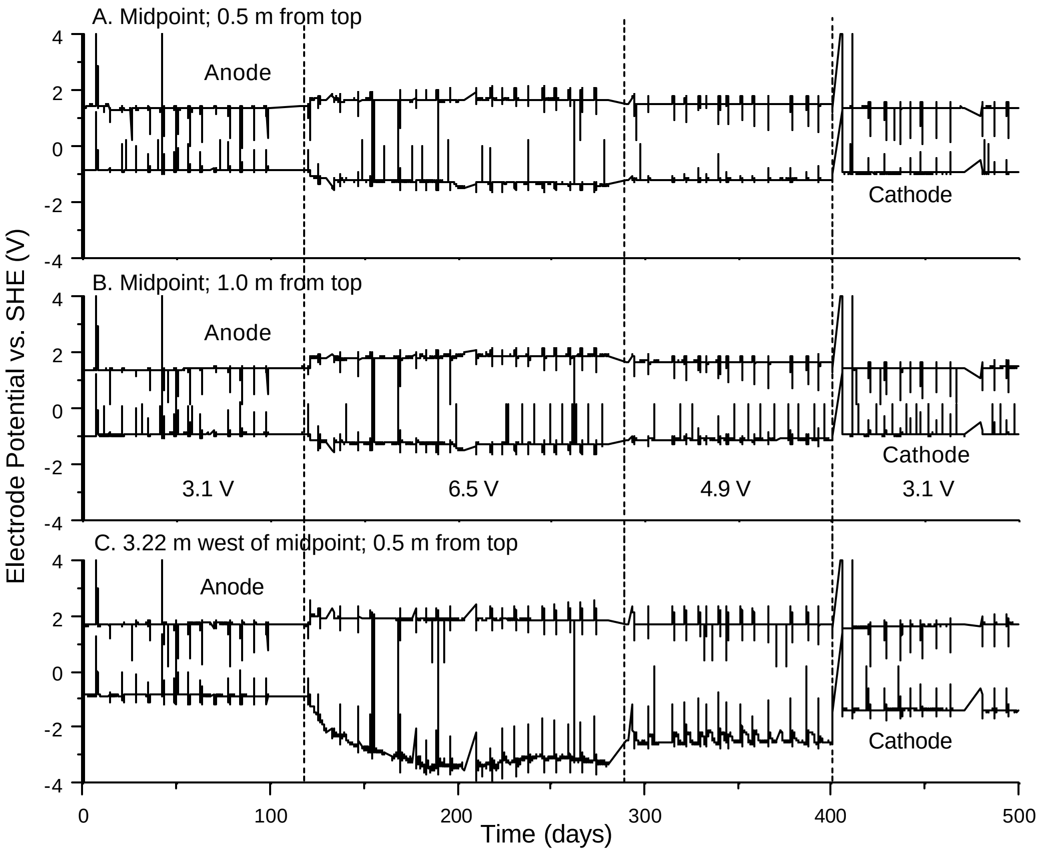


Figure E-8 – Electrode potentials relative to the standard hydrogen electrode (SHE). The reference electrodes were located at the e$^-$barrier midpoint 0.5 m from the top of the barrier (A), 1 m from the top of the barrier (B), and 3.22 m west of the barrier 0.5 m from the top of the barrier (C).

Table E-1 – Average concentrations in mg/L of inorganic species along the transect, parallel to groundwater flow, through the e$^-$barrier midpoint. Samples were collected 14 days prior to startup except where noted.

	E_{appl} = 0 V				
	Upstream 0.5 m	Upstream face	Downstream face	Downstream 0.5 m	MW038S
Anions					
Chloride	79.6*	79.6*	79.6*	79.6*	51.0
Flouride	N/A	N/A	N/A	N/A	N/A
Bromide	N/A	N/A	N/A	N/A	N/A
Nitrite	ND	ND	ND	ND	ND
Nitrate	33.2*	33.2*	33.2*	33.2*	29
Sulfate	63.4*	63.4*	63.4*	63.4*	42
Phosphate	ND	ND	ND	ND	ND
Alkalinity (as $CaCO_3$)	299.3	434.3	450.7	416.7	224.0
Cations					
Calcium	94.2	107.0	110.9	107.4	133.0
Potassium	54.8	28.6	38.9	34.2	4.0
Magnesium	18.2	21.6	21.4	21.9	21.0
Sodium	33.3	32.6	32.5	37.1	50.0
Antimony	0.01	0.01	0.01	0.02	N/A
Arsenic	N/A	N/A	N/A	N/A	N/A
Barium	0.44	0.57	0.55	0.62	N/A
Beryllium	ND	ND	ND	ND	N/A
Cadmium	ND	ND	ND	ND	N/A
Chromium	ND	ND	ND	ND	N/A
Copper	0.01	ND	0.01	0.01	N/A
Lead	0.01	ND	ND	0.02	N/A
Selenium	N/A	N/A	N/A	N/A	N/A

N/A = Not Available
ND = Not Detected
* = Average from preliminary monitoring wells ESTCP 1 – 4

Table E-2 – Average concentrations in mg/L of inorganic species along the transect, parallel to groundwater flow, through the e$^-$barrier midpoint. Samples were collected 282 days after.

	E_{appl} = 6.5 V				
	Upstream 0.5 m	Upstream face	Downstream face	Downstream 0.5 m	MW038S
Anions					
Chloride	153.3	160.0	170.0	170.0	200
Flouride	0.6	1.1	0.3	0.6	0.41
Bromide	0.3	0.2	0.2	0.2	0.23
Nitrite	ND	ND	ND	ND	ND
Nitrate	1.8	1.0	3.4	0.3	4.1
Sulfate	55.7	50.7	66.5	63.0	53
Phosphate	ND	ND	ND	ND	ND
Alkalinity (as $CaCO_3$)	191.7	156.7	83.3	91.9	200
Cations					
Calcium	136.0	119.9	98.6	133.6	140.9
Potassium	4.7	4.1	4.6	5.6	2.8
Magnesium	23.3	6.3	6.0	14.6	22.8
Sodium	23.5	18.3	19.6	17.8	19.1
Antimony	ND	ND	ND	ND	ND
Arsenic	ND	ND	ND	ND	ND
Barium	0.79	0.50	0.32	0.81	0.50
Beryllium	ND	ND	ND	ND	ND
Cadmium	ND	ND	ND	ND	ND
Chromium	ND	ND	ND	ND	ND
Copper	ND	ND	ND	ND	ND
Lead	ND	ND	ND	ND	ND
Selenium	ND	ND	ND	ND	ND

N/A = Not Available
ND = Not Detected

Table E-3 – Average concentrations in mg/L of inorganic species along the transect, parallel to groundwater flow, through the e^-barrier midpoint. Samples were collected 491 days after.

	E_{appl} = 3.1 V				
	Upstream 0.5 m	Upstream face	Downstream face	Downstream 0.5 m	MW038S
Anions					
Chloride	95.5	120.0	80.3	75.7	140.0
Flouride	0.3	0.9	0.4	0.5	0.2
Bromide	0.3	0.2	0.2	0.3	0.34
Nitrite	ND	ND	ND	ND	ND
Nitrate	4.1	3.8	6.8	5.2	5.2
Sulfate	58.0	69.5	62.7	60.7	55.0
Phosphate	ND	ND	ND	ND	ND
Alkalinity (as $CaCO_3$)	N/A	N/A	N/A	N/A	N/A
Cations					
Calcium	114.8	94.6	43.2	115.6	135.2
Potassium	5.7	4.3	4.7	5.3	4.8
Magnesium	17.6	6.0	8.4	10.0	19.5
Sodium	41.4	42.8	34.3	41.2	28.0
Antimony	ND	ND	ND	ND	ND
Arsenic	0.018	0.017	0.014	0.005	0.01
Barium	0.59	0.20	0.11	0.40	ND
Beryllium	ND	ND	ND	ND	ND
Cadmium	ND	ND	ND	ND	ND
Chromium	ND	ND	0.014	ND	ND
Copper	0.01	0.01	0.02	0.01	0.01
Lead	ND	ND	ND	ND	ND
Selenium	ND	ND	ND	ND	ND

N/A = Not Available
ND = Not Detected

Appendix F – Health and Safety Plan

ESTCP – Field Demonstration – Electrically Induced Redox Barriers

To be conducted at
F.E. Warren Air Force Base
Cheyenne, Wyoming

Prepared for: **ESTCP**

and

F. E. Warren Air Force Base
Cheyenne, Wyoming

Prepared by:

Colorado State University
Department of Chemical and Bioresource Engineering
And Environmental Health and Safety

July 2002

HEALTH AND SAFETY PLAN

ESTCP – Field Demonstration – Electrically Induced Redox Barriers

F.E. Warren Air Force Base
Cheyenne, Wyoming

REVIEWED AND APPROVED BY:

Tom Sale, Principal Investigator/Site Health and Safety Officer

Date

Dominic Leffler,
CSU Environmental Health Services

Date

LIST OF ABBREVIATIONS AND ACRONYMS

°F	degrees Fahrenheit
ACGIH	American Conference of Governmental Industrial Hygienists
AFCEE	Air Force Center for Environmental Excellence
AIHA	American Hygiene Association
bpm	beats per minute
BTEX	benzene, toluene, ethyl benzene and total xylenes
CNS	central nervous system
CPC	chemically protective clothing
CFR	Code of Federal Regulations
dBA	weighted decibels A
EPA	U.S. Environmental Protection Agency
FEW	F.E. Warren Air Force Base
FPTA1	Fire Protection Training Area 1
H&SP	Health and Safety Professional
HASP	Health and Safety Plan
HAZWOPER	Hazardous Waste Operations and Emergency Response
IDLH	immediately dangerous to life or health
LEL	lower explosive limit
MSDS	Material Safety Data Sheet
NIOSH	National Institute of Safety and Health
OSHA	Occupational Safety and Health Administration
OVM	organic vapor monitor
PEL	permissible exposure limit
PID	photoionization detector
PM	Project Manager
PPE	personal protective equipment
ppm	parts per million
RI/FS	Remedial Investigation/Feasibility Study
SCBA	self-contained breathing apparatus
SSO	Site Safety Officer
TCE	trichloroethene
TLV	threshold limit value
URS	URS Consultants, Inc.
UXO	unexploded ordnance
VOC	volatile organic compound
WBGT	wet bulb globe temperature

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INTRODUCTION

Colorado State University (CSU) has been selected by the Environmental Security Testing and Certfication Program (DoD) to conduct a field demonstration of an electrically induced redox barrier (e^-barrier) at F. E. Warren AFB, Cheyenne, Wyoming. This Health and Safety Plan (HASP) has been prepared to address drilling, groundwater sampling, e-barrier construction operations and facility decommissioning. The provisions of this are mandatory for all CSU staff and/or subcontractor on-site personnel engaged in work related to the e-barrier demonstration.

It is the policy of CSU to provide a safe and healthful work environment for all its employees. CSU considers no phase of operations or administration to be of greater importance than prevention of injury and illness. Safety takes precedence over expediency or shortcuts. CSU also requires that all visitors to areas under its control abide by these procedures. During the work operations, CSU will retain primary on-site authority for management and enforcement of safety-related activities and requirements as specified in this *HASP.* In case of a conflict between this plan and federal, state, or local regulations, the most stringent shall apply.

Regulatory Applicability

This HASP addresses all health and safety plan elements as presented in Title 29 Code of Federal Regulations (CFR), Part 1910.120 (b)(4). The applicable elements include those items which are identified as part of the scope of work (Section 3).

References

This HASP has been developed using applicable CSU policy, U.S. Department of Labor Occupational Safety and Health Administration (OSHA), and U.S. Environmental Protection Agency (EPA) regulations.

HEALTH AND SAFETY RESPONSIBILITIES

Demonstration activities including monitoring well installation, subsurface soil sampling, groundwater sampling, barrier installation, barrier operations, and decommissioning will entail field operations will be involving CSU and/or subcontractor personnel. This section describes the responsibilities and lines of authority and communication, which will be established at the work site with regard to health and safety.

All Personnel

Each person is responsible for his/her own health and safety, for completing tasks in a safe manner, and for reporting any unsafe acts or conditions to his/her supervisor and/or the Site Supervisor. All personnel are responsible for continuous adherence to these health and safety procedures during the performance of their work. No person may work in a manner that conflicts with the letter or intent of safety and environmental precautions expressed in these procedures. After due warnings, CSU will dismiss from the site any person who violates safety procedures. CSU employees are subject to progressive discipline and may be terminated for blatant or continued violations. All on-site personnel will be trained in accordance with 29 CFR 1910.120 and this document.

Project Manager

The Principal Investigator (PI), Dr. Tom Sale, PG, has overall management authority for ensuring that all project activities are completed in accordance with requirements set forth in this plan. The PI will confer with the designated Health and Safety Professional (H&SP) on all matters affecting health and safety. Other health and safety-related duties of the PI include:

1. *Reading and becoming familiar with this* HASP*,*

2. *Selection of subcontractor organizations capable of safely performing required work activities,*

3. *Ensuring that personnel assigned to field activities meet appropriate health and safety qualifications and possess sufficient experience and knowledge to safely perform required duties, and*

4. *Providing day-to-day management of site work activities.*

Health And Safety Professional

The designated Health and Safety Professional (H&SP), Dominic Leffler, is the member of the CSU Environmental Health Services Department responsible for overseeing all aspects of the site safety program and preparing any site-specific safety guidance documents or addenda to this plan. The designated H&SP does not report to the PI, but is separately accountable to CSU senior management for site health and safety. The H&SP will act as the sole contact with all regulatory agencies on matters of health and safety. The H&SPs other responsibilities include:

1. General health and safety program administration,
2. Conducting project health and safety audits as warranted,
3. Developing site-specific employee/community emergency response plans, as required, based on expected hazards,
4. Determining the level of personal protection required,
5. Updating equipment or procedures based on information obtained during site operations,
6. Establishing air-monitoring parameters based on expected contaminants, and
7. Implementing employee exposure assessment notification.

Site Supervisor

If the designated site supervisor is unable to be on-site at a certain time, then several different individuals will be capable of assuming the site supervisor's role at any time. However, at any one time a single CSU employee will be designated as Site Supervisor and will exercise direct responsibility for implementation of the HASP during these work operations. This responsibility includes communicating site requirements to all personnel, observing that field personnel and/or subcontractors enforce all provisions of this HASP, and consulting with the H&SP regarding changes to the HASP. Other responsibilities include:
Reading and becoming familiar with the HASP,
Enforcing the HASP and other safety regulations, and
Maintaining the presence of at least one qualified first-aid provider on-site at all times.

The individual designated as Site Supervisor shall meet the training requirements specified in 29 CFR 1910.120 (e)(4).

Site Safety Officer

Dr. Sale or designated alternate will serve as the Site Safety Officer (SSO) at the work site during all activities. The SSO is responsible for performing the routine duties for health and safety and coordinating any necessary assistance from the designated H&SP. The SSO will administer this *HASP* and any supplemental safety and health guidance. Additional SSO responsibilities include:

1. *Reading and becoming familiar with this* HASP *and enforcing its procedures and other applicable safety requirements;*

2. *Conducting periodic safety reviews of the project site and project documentation;*

3. *Performing regular and frequent site inspections to identify hazards and observe employees at work;*

4. *Stopping work, as required, to maintain personal and environmental health and safety;*

5. *Determining emergency evacuation routes, establishing and posting local emergency telephone numbers, and arranging emergency transportation;*

6. *Ensuring that all site personnel and visitors have received the proper training and medical monitoring before entering any controlled work areas;*

7. *Establishing any necessary controlled work areas (as designated in the* HASP *or other health and safety documentation);*

8. *Presenting any tailgate safety meetings and maintaining appropriate training documentation and attendance records;*

9. *Discussing potential health and safety hazards with the designated H&SP and the PM;*

10. *Implementing air monitoring according to directives in this* HASP;

11. *Implementing any changes in health and safety procedures as directed by the PM and/or approved addenda to this* HASP;

12. *Implementing air monitoring according to directives in the* HASP *or other health and safety documentation and forwarding all employee exposure monitoring information to the H&SP to enable exposure notification and;*

13. *Maintaining decontamination procedures which meet established criteria.*

Any individual designated as SSO shall meet the training requirements specified in 29 CFR 1910.120 (e)(4), and shall be approved by the H&SP.

Subcontractors

Each CSU subcontractor is responsible for assigning specific work tasks to its employees and for ensuring that its personnel are properly trained and participate in health and safety programs which fulfill the requirements specified in this HASP (e.g., hearing conservation). Each subcontractor's management will provide qualified employees and allocate sufficient time, materials and equipment to safely complete its assigned tasks. In particular, each subcontractor is responsible for equipping its personnel with any required personal protective equipment (PPE).

CSU considers each subcontractor to be an expert in all aspects of the work operations for which it is tasked to provide, and each subcontractor is responsible for compliance with those regulatory requirements that pertain to those services. Each subcontractor is expected to perform its operations in accordance with its own unique safety policies and procedures to ensure that hazards associated with the performance of the work activities are properly controlled. Copies of any required safety documentation for a subcontractor's work activities will be provided to CSU for review prior to the start of on-site activities, if required. Operators of heavy equipment will be required to supply copies of the Heavy Equipment Certification form as required in Appendix A. If a subcontractor’s procedures or requirements conflict with requirements specified in this HASP, the more stringent guidance will be adopted.

Hazards not listed in this HASP but known to any subcontractor, or known to be associated with a subcontractor's services, must be identified and addressed to the CSU Site Supervisor prior to beginning work operations. The Site Supervisor or authorized representative has the authority to halt any subcontractor operations and to remove any subcontractor or subcontractor employee from the site for failure to comply with established health and safety procedures or for operating in an unsafe manner.

Appendix B provides CSU’s general subcontractor safety rules, which will be observed by all subcontractor organizations.

On-site Personnel And Visitors

All personnel working for CSU or its subcontractors are required to read and acknowledge their understanding of this *HASP*. All visitors to controlled areas of the site must also read and acknowledge their understanding of this *HASP*. All personnel are expected to abide by its requirements and cooperate with site supervision to ensure a safe and healthful work site. Personnel must immediately report any of the following to the Site Supervisor or SSO:

- Accidents and injuries, no matter how minor;
- Unexpected or uncontrolled releases of any hazardous substances;
- Any symptoms of exposure to a hazardous substance;
- Any unsafe or malfunctioning equipment; and
- Any changes in site conditions, which may affect the health or safety of project personnel.

Project Information

The e-barrier field demonstration will be conducted at F.E. Warren AFB (FEW), Cheyenne, Wyoming. Historical maintenance and other activities at FEW resulted in inadvertent releases of TCE and fuel hydrocarbons to a shallow alluvial aquifer.

3.1 Site Conditions/Status

The field demonstration will be located in a plume containing dissolved phase trichoroethene (TCE) at concentrations less than 1 mg/L. The demonstration will be located to minimize interference with ongoing site activities include site investigations and remediations. All work will be conducted in areas that are well characterized through prior RI/FS activities

3.2 Scope of work

The e^-barrier demonstration will involve the following field activities:

- Site visits to identify promising locations for the field demonstration
- Installation of monitoring wells at the identified demonstration location to confirm the location selected for the field demonstration.
- Collection of groundwater samples from the demonstration location to establish a water quality base line.
- Conducting treatability studies using down hole electrolytic reactors (sand columns with paired electrodes operated at low voltage [e.g. 5V])
- Installation of an insitu e^-barrier below the watertable. The length will be approximately 30-feet. The saturated height will be approximately 6 feet.
- Operation of the e^-barrier for a period of approximately 12-months. This will include routine measurements of amperage and voltage in a low voltage, low amperage system.
- Routine collection of groundwater samples including field measurements of pH, Eh, Temp, and conductivity.
- Decommissioning of the e^-barrier and associated monitoring well network.

General Health and Safety Operating Procedures

All CSU and subcontractor personnel performing work at FEW will comply with the requirements of 29 CFR 1910.120. Consistent with 29 CFR 1910.120 two types of site worker are recognized. The first is workers participating in intrusive work such as excavation of a trench for the e-barrier and construction of the e-barrier and worker with supervisory roles (Level 1). The second is workers conducting specific task such as groundwater sampling in areas that are fully characterized indicating that exposures are under permissible exposure limits (Level 2). Accordingly, the following requirements will apply for all personnel performing any controlled-area work operations.

MEDICAL SCREENING AND HEALTH SURVEILLANCE

All Level 1 CSU and subcontractor personnel will have completed a HAZWOPER physical exam which conforms to the requirements of 29 CFR 1910.120 (f). Based on exam results Level 1 personnel will be medically authorized to perform HAZWOPER activities by an occupational physician. Level 2 personnel will be required to have a recent physical providing evidence of their current health. This is consistent with occasional work in areas which have been monitored and fully characterized indicating that exposures are under permissible exposure limits.

TRAINING REQUIREMENTS

All personnel on-site will meet the following training requirements.

General Training Requirements

All Level 1 field personnel will have completed the necessary HAZWOPER training requirements as specified which conforms to the provisions established in 29 CFR 1910.120 (e)(2) and (e)(3) [40-hour], 29 CFR 1910.120 (e)(8) [annual refresher training], and 29 CFR 1910.120 (e)(4) [supervisor training]. All Level 2 personnel will have completed the necessary HAZWOPER training requirements as specified which conforms to the provisions established in 29 CFR 1910.120 (e)(2) and (e)(3) [24-hour] and 29 CFR 1910.120 (e)(8) [annual refresher training]

Initial Orientation Training

Prior to the start of on-site activities, all CSU and subcontractor personnel will attend a site safety/orientation briefing, to be conducted by the SSO. This training will address all elements of the site health and safety program. Training will also include instruction in:

1. Toxic and physical hazards associated with identified environmental contaminants of concern;
2. Anticipated exposure hazards (as determined based on analysis of work operations and site contaminant concentrations);
3. Requirements and rationale used in the selection of safety equipment;

4. On-site monitoring procedures;
5. Decontamination procedures;
6. Care and use of selected PPE; and
7. Emergency notification and response procedures.

The training content and a list of all attendees will be documented and maintained with the project files. Worker personnel initially assigned to the site after work operations have commenced will be provided with orientation training by the SSO that addressed the above requirements. All visitors to the site (personnel not assigned to work on-site) will be provided with an abbreviated version of this training, along with specific orientation as to the hazards present on-site at the time of the visit and any applicable safety requirements (escorts, etc.).

Tailgate Safety Briefings

A tailgate safety briefing will be conducted at the start of each workday. The SSO will conduct the tailgate safety briefings and will review and discuss the health and safety issues associated with the days planned work activities, problems encountered, and modifications to existing procedures. Documentation of the tailgate safety briefings will be accomplished by using the Tailgate Safety Briefing Sign-in Log; a copy is included in Appendix C. The SSO will maintain copies of all tailgate safety briefing sign-in logs in the project files. All field personnel associated with each day's project activities are required to attend these meetings.

Hazard Communication Training

Section 5.2 provides information concerning environmental contaminants that could be expected to be encountered during the planned work operations. In addition, any organization wishing to bring any hazardous material onto any CSU controlled work site must first provide a copy of the item's Material Safety Data Sheet (MSDS) to the SSO for approval and filing. The SSO will maintain copies of all MSDSs on-site. All personnel will be briefed on the hazards of any chemical product they use and will be aware of and have access to all MSDSs.

GENERAL SITE SAFETY RULES

The following general requirements apply to all on-site activities (including work occurring outside controlled work areas).

Smoking, Eating, and Drinking

Smoking, eating and drinking will not be permitted except in designated areas of the site. Field workers will perform proper decontamination procedures when leaving an Exclusion Zone prior to eating or drinking. Consumption of alcoholic beverages is prohibited anywhere on FEW.

Site Awareness

Field crewmembers will be familiar with the physical characteristics and requirements of the work site, including ongoing activities of other personnel at the FEW site which may affect the work area. Personnel will also be aware of:

Emergency procedures and evacuation assembly points, and

Location of protective and emergency equipment and relevant first-aid procedures.

The number of personnel and equipment in work areas should be minimized, consistent with site operations.

Buddy System

Except as designated by the SSO, all on-site personnel will operate using the two-person concept (buddy system). All personnel will operate in teams of two or more (single person entry into any controlled work area is prohibited), whose members will maintain visual contact with each other at all times. Team members must observe each other and be alert for signs of heat stress or toxic exposure.

Housekeeping

During site activities work areas will be continuously policed for identification of excess trash and unnecessary debris. Excess debris and trash will be collected and stored in an appropriate container (e.g., plastic trash bags, garbage can, roll-off bin) prior to disposal. At no time will debris or trash be intermingled with waste PPE or contaminated materials. Anyone observed throwing contaminated material or PPE away with municipal wastes will be removed from the site.

Personal Hygiene

At a minimum, adequate supplies of personal hygiene supplies will be available for use by site personnel. Personal hygiene items will include the following:

Water Supply

A water supply meeting the following requirements will be utilized:

Potable Water. An adequate supply of potable water will be available for field personnel consumption. Potable water can be provided in the form of water bottles, canteens, water coolers, or drinking fountains. Where drinking fountains are not available, individual-use cups will be provided together with adequate disposal containers. Potable water containers will be properly identified to distinguish them from non-potable water sources.

Non-Potable Water. Non-potable water may be used for handwashing and cleaning activities. Non-potable water will not be used for drinking purposes.

Toilet Facilities

A toilet facility will be provided for use by personnel. If access is available, existing site toilet facilities will meet this requirement.

Washing Facilities

Employees will be provided washing facilities (e.g., buckets with water and Alconox) at each work location. The use of water and hand soap (or similar substance) will be used by each employee upon exiting any controlled work area, prior to breaks and at the end of daily work activities.

Drum Handling

Where containers with a capacity greater than 10 gallons are used for containerizing chemical products or waste materials, handling of the containers will be accomplished in accordance with the following:

When not in use, drums/containers will be covered with a tight fitting lid.

At the conclusion of each work shift all drums and containers will be placed in the designated waste storage area. This area will be properly marked and secured.

Mechanical or powered drum-handling equipment will be used to move drums and containers. Manual handling of the drums leads to musculo-skeletal injuries and will be avoided to the extent possible.

LIGHTING

At a minimum, all portions of each work location will be sufficiently lit so that all surfaces are illuminated at 10 foot-candles or greater. Since work activities are expected to be conducted exclusively outdoors and during daylight hours, the use of supplemental lighting is not anticipated.

HEAT AND COLD STRESS

Heat Stress

Heat stress can be a significant field site hazard, especially for workers wearing protective clothing. Depending on the ambient conditions and the work being performed, heat stress can occur very rapidly, within as little as 15 minutes. Site personnel will be instructed in the identification of a heat stress victim, the first-aid treatment procedures for the victim, and the prevention of heat stress casualties.

Workers should be encouraged to immediately report any difficulties or heat-related problems that they may experience or observe in fellow workers. Supervisors should use such information to alter the work-break schedule to accommodate such problems. During breaks, workers should be encouraged to drink plenty of water or other liquids to replace lost fluids and to help cool off. Should any worker exhibit signs of severe heat distress, such as profuse sweating, extreme confusion and irritability, or pale, clammy skin, that worker should be relieved of all duties at once and made to rest in a cool location and drink plenty of water. Anyone exhibiting symptoms of heat stroke (red, dry skin or unconsciousness) should be taken immediately to the nearest medical facility, taking steps to cool the person during transportation (clothing removal, wet the skin, air conditioning, etc.). Severe heat stress (heat stroke) is a life-threatening condition that must be treated by competent medical authority.

Heat Stress Monitoring

The prevention of heat-stress-related accidents or illnesses is best performed through continuous observation of employees and routine heat stress awareness training activities. Heat stress monitoring can be accomplished using one of the techniques discussed below.

Any results obtained from monitoring techniques should be used as guidance only. To properly mitigate the effects of heat stress, it is necessary to establish a work routine that incorporates adequate rest periods to allow workers to remove protective clothing, drink fluids (vital when extreme sweating is occurring), rest and recover. The frequency and length of such work breaks must be determined by the individual work location supervisor based upon factors such as the ambient temperature and sunshine, the amount of physical labor being performed, the physical condition of the workers, and protective clothing being used. While heat stress measurement techniques provide guidance in optimizing this routine, breaks must always be sufficient to prevent workers from manifesting symptoms of heat stress regardless of monitoring results.

Evaluations of heat stress to determine appropriate work/rest cycles will be performed whenever fieldwork activities are occurring at ambient temperatures greater than 70 degrees Fahrenheit (°F). The Basic Instrument Measurements Method shown below must be used for personnel using Level D protective equipment only. Where any type of chemically protective clothing (CPC) is in use, the Modified Instrument Measurements Method will be used together with the Direct Observation method to provide guidance in appropriate work/rest cycles.

Basic Instrument Measurements Method:

This method will only be used to monitor heat stress where workers are not using chemically protective clothing. The Wet Bulb Globe Temperature (WBGT) value will be determined using a WBGT meter (Reuter-Stokes 214 DL or equivalent), and compared with the values shown in Table 4-1 to determine appropriate work/rest cycles.

Table 0-1 WBGT Values for Level D Work/Rest Cycles

Work-Rest Regiment	**WBGT**		
	Light Work (°F)	**Moderate Work (°F)**	**Heavy Work (°F)**
Continuous Work	86	80	77
75% Work – 25% Rest	87	82	78
50% Work – 50% Rest	89	85	82
25% Work – 75% Rest	90	88	86

NOTE: Re-printed from American Conference of Governmental Industrial Hygenists (ACGIH) (1999) *Threshold Limit Values for Chemical Substances and Physical Agents*

Modified Instrument Measurements Method:

This method will be used whenever personnel use chemically protective clothing. The WBGT value will be determined as above. The measured value will then be compared with the values shown in Table 4-2 to determine the appropriate work/rest cycle.

Table 0-2 WBGT Values for CPC Work/Rest Cycles

Work-Rest Regiment	**WBGT**		
	Light Work (°F)	**Moderate Work (°F)**	**Heavy Work (°F)**
Continuous Work	75	69	66
75% Work – 25% Rest	76	71	67
50% Work – 50% Rest	78	74	71

NOTE: Modified from ACGIH (1999) *Threshold Limit Values for Chemical Substances and Physical Agents*

Direct Observation:

This method can be used as a substitute for the Modified Instrument Measurements Method and can be used whenever personnel use chemically protective clothing. At the start of the workday each worker's baseline pulse rate will be determined in beats per minute (bpm). Worker pulse rates will then be measured at the beginning and end of each break period. As recommended by the American Conference of Governmental Industrial Hygienists (ACGIH), each worker's maximum heart rate at the start of any break should be less than [180 minus worker's age] bpm. If this value is exceeded for any worker, the duration of the following work period will be decreased by at least 10 minutes. At the end of each work period all workers' heart rates must have returned to within +10% of the baseline pulse rate. If any worker's pulse rate exceeds this value, the break period will be extended for at least 5 minutes, at the end of which pulse rates will be re-measured and the end-of-break criterion again applied.

Heat-Related Illnesses

The following guidance can be used in the identification and treatment of heat-related illness.

Mild Heat Strain. The mildest form of heat-related illness. Victims exhibit irritability, lethargy, and significant sweating. The victim may complain of headache or nausea. This is the initial stage of overheating, and prompt action at this point may prevent more severe heat-related illness from occurring.
First Aid: Provide the victim with a work break during which he/she may relax, remove any excess protective clothing and drink cool fluids. If an air-conditioned spot is available, this is an ideal break location. Once the victim shows improvement, he/she may resume working; however, the work pace should be moderated to prevent recurrence of the symptoms.
Heat Exhaustion. Usually begins with muscular weakness, dizziness, nausea, and a staggering gait. The victim exhibits an extremely high body temperature (> 102°F). The bowels may move involuntarily. The victim is very pale, with clammy skin, and he or she may perspire profusely. The pulse is weak and fast, breathing is shallow. He or she may faint unless he or she lies down.

First Aid: Immediately remove the victim from the work area to a shady or cool area with good air circulation (avoid drafts or sudden chilling). Remove all protective outerwear. Call a physician. Treat the victim for shock. (Make the victim lie down, raise his or her feet 6-12 inches, and keep him or her cool by loosening all clothing). If the victim is conscious, it may be helpful to give him or her sips of water. Transport victim to a medical facility as soon as possible.

Heat Stroke. This is the most serious of heat illness and represents the collapse of the body's cooling mechanisms. As a result, body temperatures often rise to between 105°-110°F. As the victim progresses toward heat stroke symptoms such as headache, dizziness and nausea can be noted, and the skin is observed to be dry, red, and hot. Sudden collapse and loss of consciousness follow quickly and death is imminent if exposure continues. Heat stroke can occur suddenly.

First Aid: Immediately evacuate the victim to a cool and shady area. Remove all protective outerwear and all personal clothing. Lay the victim on his or her back with the head and shoulders slightly elevated. Apply cold wet towels, ice bags, etc. to the head, armpits, and thighs. Sponge off the bare skin with cool water or rubbing alcohol, if available, or even place the victim in a tub of cool water. The main objective is to cool without chilling the victim. Give no stimulants or hot drinks. Since heat stroke is a severe medical condition requiring professional medical attention, emergency medical help should be summoned immediately to provide on-site treatment of the victim and proper transport to a medical facility.

Cold Stress

Because of the location of FEW, cold stress can be a significant hazard when performing outdoor activities. Cold weather conditions may exist from early autumn and last well into spring. Cold injury (frostbite and hypothermia) may impair a person's ability to work. Low temperatures and wind chill factors should be considered. This section provides information on cold stress and procedures for preventing and dealing with cold stress. Adverse cold climatic conditions are important considerations in planning and conducting site operations. Ambient temperature effects can include physical discomfort, reduced efficiency, personal injury, and an increased probability of accident.

Cold Stress Effects

Persons working outdoors in temperatures at or below freezing may be frostbitten. Extreme cold for a short time may cause severe injury to the skin or result in profound generalized cooling, causing death. Areas of the body that have a high surface-area-to-volume ratio, such as fingers, toes, and ears, are the most susceptible.

Local injury resulting from cold is included in the generic term "frostbite". There are several degrees of damage. Frostbite of the extremities can be categorized into:

Frost nip or initial frostbite: characterized by suddenly blanching or whitening of skin.

Superficial frostbite: skin has a waxy or white appearance and is firm to the touch, but tissue beneath is resilient.

Deep frostbite: tissues are cold, pale, and solid; extremely serious injury.

Exposure Limits and Cold Stress Monitoring

Typical exposure limits for work in cold are presented in Table 4-3 as a guide for establishing work schedules. Air temperature data and worker exposure times shall be monitored when the ambient temperature is 45°F or below.

Control Measures

Dead air space between the warm body and clothing and the outside air is essential. Clothing is worn to keep body warmth in and cold out. Usually, no one type of clothing is best for all weather conditions. Denim is relatively loose-woven and not only allows water to penetrate but permits wind to blow away the body heat that should remain trapped between the body and clothing worn. Duck or goose down is good for stopping wind, but is of little use when wet. Plastic or closely woven nylon is good protection from wind and rain but offers little insulation against cold.

Many layers of relatively light clothing with an outer shell of windproof material maintain body temperature much better than a single heavy outer garment worn over ordinary indoor clothing. The more air cells each of these clothing layers has, the more efficiently it insulates against body heat loss. Make sure that clothing allows some venting of perspiration because wet skin will freeze more rapidly than dry skin. Use all feasible means to keep as dry as possible. Make full use of windbreaks and avoid exposing skin to the direct effects of wind. The need to wear layers of special clothing may make the wearer very clumsy in performing many routine work procedures. Increased body dimensions must also be considered if tight spaces are encountered.

Frostnip: Frostnip is not a freezing injury, and rewarming should be attempted at the site. Immersion in warm water (100-110oF) is preferred. An alternative method of rewarming is to provide direct contact with the employee’s own skin or another person’s skin.
Frostbite: Thawing of the injured area should never be attempted if there is a likelihood that refreezing may occur. Keeping the extremity frozen, even for hours, is preferable to thawing followed by refreezing. Therefore, the injured area should be protected and the victim should receive medical attention immediately.

Table 4-3 Maximum Daily Limits for Exposure at Low Temperatures

Temperature Range		**Maximum Daily Exposure**
Celsius (degrees)	Fahrenheit (degrees)	
0 to –18	30 to 0	No limit, providing the person is properly clothed.
-18 to –34	0 to –30	Total work time, 4 hours. Alternate one hour in and one hour out of the low-temperature area.
-34 to –57	-30 to –70	Two periods of 30 minutes each, at least 4 hours apart. Total low-temperature work time allowed: one hour. (Note that some difference exists among individuals. One report recommends 15-minute period, but not over four periods per 8-hour work shift. Another limits periods to 1 hour out of every 4 hours, with a low chill factor, i.e., no wind. A third says that continuous operation for 3 hours at -53 has been experienced without ill effects.)
-57 to -73	-70 to –100	Maximum permissible work time: 5 minutes during an 8-hour working day. At these extreme temperatures, completely enclosed headgear equipped with a breathing tube running under the clothing and down the leg to preheat the air is recommended.

Source: NSC Data Sheet 465, Cold Room Testing of Gasoline and Diesel Engines

Accident or Incident Reports

All accidents and incidents that occur on-site during any field activity will be promptly reported to the SSO and the Site Supervisor.

If any CSU employee is injured and requires medical treatment, Dominic Leffler, CSU Environmental Health and Safety (970-491-4830), will be notified. The PI will initiate a written report, using the Supervisor's Report of Incident form (found in Appendix C). The PIM will complete the first three sections of this form within 24 hours of the incident.

If any employee of a subcontractor is injured, documentation of the incident will be accomplished in accordance with the subcontractor's procedures; however, copies of all documentation (which at a minimum must include OSHA Form 101 or equivalent) must be provided to the SSO within 24 hours after the accident has occurred.

Visitor Clearances

Visitors will not be allowed within any controlled work area unless they comply with the health and safety requirements of this HASP and can demonstrate an acceptable need for entry into the work area. All visitors desiring to enter any controlled work area must be briefed on the hazards associated with the site activities being performed and acknowledge receipt of this briefing by signing the appropriate tailgate safety briefing form.

If the site visitor requires entry to any Exclusion Zone but does not comply with the above requirements, all work activities within the Exclusion Zone must be suspended and monitoring using direct reading instruments must indicate that no airborne contaminant concentrations are present which exceed the established background levels. Until these requirements have been met, entry will not be permitted.

Contractor Safety

In addition to the requirements of this Health and Safety Plan, subcontractors of CSU will observe the rules outlined in the "General Safety Rules for Contractors" which are located in Appendix B of this document. Compliance with these rules will be observed by subcontractors during all phases of site activities.

HAZARD ASSESSMENT

The work activities to be performed at FEW will consist of the following activities:
Installation of an insitu e-barrier below the watertable. The length will be approximately 30-feet. The saturated height will be approximately 6 feet.
Operation of the e-barrier for a period of approximately 12-18 months. This will include routine measurements of amperage and voltage in a low voltage, low amperage system.
Routine collection of groundwater samples including field measurements of pH, Eh, Temp, and conductivity.
Decommissioning of the e-barrier and associated monitoring well network.

The potential hazards include, but are not limited to:
Exposures to environmental contaminants such as waste solvents,
Excavation safety,
Operation of heavy earth-working equipment,
Hazardous noise produced by earth-working equipment,

Task hazard Analysis

Where work activities are identified which are not addressed in this HASP, appropriate safety documentation and procedures will be implemented. Prior to initiation of work activities the subcontractor organization tasked with performance of the work will submit a work procedure document which presents appropriate safety procedures applicable to the specific work activities to be undertaken. Submitted safety procedures will be reviewed by the H&SP for adequacy and compliance with applicable regulatory requirements and the requirements presented in this HASP. Work will not be initiated until this review is completed and any identified deficiencies corrected to the satisfaction of the H&SP.

The H&SP may issue an exemption to this requirement based on the nature of the work activities to be undertaken.

CHEMICAL HAZARDS

The information presented below is intended to inform site personnel about the expected hazards associated with known or suspected environmental contaminants. Environmental contaminants in the investigation area include a variety of chlorinated solvents, represented primarily by trichloroethene (TCE) Hazards associated with the use of commercially available hazardous materials are addressed as part of worker hazard communication requirements.

Exposure to site contaminants can occur through two direct routes (inhalation and skin contact) and one indirect route (ingestion).

Inhalation Exposure. Airborne concentrations of organic vapors in mists and metals in dust can approach occupationally significant levels in confined areas. Mitigation of this hazard will be achieved by allowing proper ventilation of the area, and monitoring with specified direct reading instrumentation will be conducted to verify that no airborne hazard exists.

Skin Contact. Although the concentrations of the noted site contaminants are low to moderate, prolonged skin contact can produce limited skin irritation. However, the concentrations assure that significant whole body exposure through skin absorption is unlikely. Handling of samples, purge water, and investigation-derived wastes present the potential for skin contact with contaminated materials. Use of chemical-resistant gloves and other clothing (e.g., aprons) will provide adequate protection.

Ingestion. Eating, drinking, and smoking can allow ingestion of small amounts of site contaminants to occur where these activities take place without proper decontamination. The decontamination requirements specified in Section 9.0 are designed to prevent this occurrence.

Chlorinated Solvents

Moderate exposures to TCE can cause symptoms similar to those of alcohol inebriation. Higher concentrations cause narcotic effects. Ventricular fibrillation has been cited as the cause of death following heavy exposures. TCE-induced hepatocellular carcinomas have been detected in mice during tests conducted by the National Cancer Institute. Organ systems affected by overexposure to TCE are the CNS (euphoria, analgesia, and anesthesia), degeneration of the liver and kidneys, the lungs (tachypnea), heart (arrhythmia) and skin (irritation, vesication, and paralysis of fingers when immersed in liquid TCE). Contact with the liquid defats the skin, causing topical dermatitis. Certain people appear to experience synergistic effects from TCE exposure concomitant with exposure to caffeine, alcohol, and other drugs. Other reported symptoms of TCE exposure include abnormal fatigue, headache, irritability, gastric disturbances, and intolerance to alcohol. Both the OSHA PEL and the ACGIH STEL are 100 ppm, and the ACGIH TLV is 50 ppm.

ACTIVITY-SPECIFIC HEALTH AND SAFETY PROCEDURES

Slips, Trips, Falls and Protruding Objects

Hazards from protruding objects, careless movements, or placement of materials on paths or foot traffic areas present a problem with regard to slips, trips, falls, and puncture wounds. Personnel will use a reasonable amount of effort to ensure the prevention of such injuries.

Hazardous Noise Safety

Large equipment often creates excessive noise. The effects of noise can include physical damage to the ear, pain, and temporary and/or permanent hearing loss. Workers can also be startled, annoyed, or distracted by noise during critical activities.

Available noise monitoring which indicate that working within 25 feet of operating heavy equipment (drill rigs, earthworking equipment, etc.) can result in exposure to hazardous levels of noise (levels greater than 90 A-weighted decibels [dBA]). Accordingly, all personnel are required to use hearing protection (earplugs or earmuffs) within 25 feet of any operating piece of heavy equipment.

The H&SP may also choose to monitor employee exposure to hazardous noise levels.

Explosive Gas Hazards

Intrusive activities increase the potential for the release of elevated concentrations of volatile organic compounds (VOCs). Explosive concentrations of these constituents could develop in small and confined spaces. Explosivity will be monitored with a combustible gas indicator.

Underground Utilities

Various forms of underground utility lines or pipes may be encountered during intrusive work activities. Underground Service Alert (Dig Alert) will be contacted at least 48 hours prior to the start of intrusive operations.

If intrusive operations cause equipment to come into contact with utility lines, the SSO and the H&SP will be notified immediately, and a Supervisor's Report of Incident (see Appendix C) will be completed. Work will be suspended until the appropriate actions for the particular situation can be taken.

Heavy Machinery

The use of heavy machinery (trenching and digging equipment, cranes, etc.) in areas where unprotected personnel are operating warrants special attention on the part of all personnel. Operators should ensure that equipment is working properly and is being run in a safe manner, and should be aware of the locations of unprotected personnel at all times while operating this machinery to avoid serious accidents.

Excavation Safety

All trenching and excavation operation will be accomplished in accordance with the requirements in this section. The following safe operating guidelines will apply to trenches or excavations exceeding 4 feet in depth, in accordance with the requirements of 29 CFR 1926.650.

Excavation Construction Guidelines

Excavated materials will be stored and retained at least 2 feet from the edge of the excavation (Note: this procedure should be observed even when excavation/trench entry would not occur).

Trees, boulders, and other surface encumbrances that create a hazard will be removed or made safe before excavation is begun.

Special precautions will be taken in sloping or shoring the sides of excavations adjacent to a previously backfilled excavation.

Except in hard rock, excavations below the level of the base of the footing of any foundation or retaining wall will not be permitted unless the wall is underpinned and all other precautions have been taken to ensure the stability of the adjacent walls.

All ladders used in excavation operations will be in accordance with the requirements of 29 CFR 1926 Subpart L.

Excavations will be inspected daily, or more often as conditions warrant, by a competent person to ensure that changes in temperature, precipitation, shallow groundwater, overburden, nearby building weight, vibrations, or nearby equipment operation has not caused weakening of sides, faces, and flows.

Diversion ditches, dikes or other suitable means will be used to prevent water from entering an excavation and for drainage of the excavation.

When mobile equipment is used or allowed adjacent to excavations, stop logs or barricades will be installed. The grade will always be away from the excavation.

Dust conditions during excavation will be kept to a minimum. Wetting agents shall be used at the direction of the SSO.

Field personnel shall not enter any excavation without specific direction for any reason except to rescue injured individuals who have fallen into the excavated area.

Trench Entry Requirements

None is anticipated.
Dust and Vapor Suppression

If airborne concentrations of contaminants are found to exceed established action levels (specified in Section 5.0), the SSO will implement appropriate mitigation measures, such as:

VOCs

Partially cover the open well head to reduce the escape of contaminants, or
Place a cover on the container of collected spoils if this material is identified as the source of measurable emissions.

DUST

Areas where minimal vegetation is present should be moistened with water to minimize dust.

If mitigation measures are found to be inadequate (i.e., contaminant concentrations cannot be reduced below HASP requirements), the SSO or Site Supervisor will halt on-site operations until effective control can be achieved.

UXO Safety

UXO items present hazards if encountered in subsurface areas while excavating, trenching, or drilling. The basic policies to be observed regarding UXO is DO NOT TOUCH, HANDLE OR OTHERWISE DISTURB ANY UXO ITEM.

In addition, use the following procedures to minimize the hazards to personnel from UXO.

UXO in Surface Areas

All personnel must be briefed concerning the potential for UXO in surface areas and any known identifying characteristics of UXO items. When moving about the site personnel should remain alert for any UXO items which might be present. Each work site should be thoroughly checked for the presence of UXO before any other activities commence. If any UXO item is observed or expected, the following procedures will be observed:

Personnel should note the location of the UXO item and alert all other personnel in the area to its presence.

Any work operations occurring within 20 feet of the item will cease. All CSU and subcontractor employees will evacuate this area.

Under no circumstances will any CSU or subcontractor employee attempt to move or otherwise handle any UXO or suspected UXO item.

COLLECTION OF “SOUVENIRS” IS PROHIBITED.

The installation representative will be alerted as to the location of the suspected item.

Excavating and Trenching Activities

Excavation activities may disturb subsurface UXO items. Throughout the excavation work a member of the site team will be posted as an observer, with the responsibility to monitor the trench conditions and observe if any suspected UXO items may be present. If any UXO item is encountered during excavation the following procedures will be observed.

UXO Item Encountered and Detonation Occurs

The work operation will cease immediately. Personnel will evacuate to a safe area or distance.

If injuries have occurred, the Emergency Contingency Plan will be activated.

Any equipment will be withdrawn from the site and the area will be delineated using yellow CAUTION tape.

Responsibility for the work location will be transferred to the installation.

Equipment will be thoroughly inspected for damage before being put back into service.

UXO Item Observed in the Trench

The work operation will cease immediately. Personnel will evacuate to a safe area or distance.

The equipment will be withdrawn from the site and the area will be delineated using yellow CAUTION tape.

Responsibility for the work location will be transferred to the installation.

UXO Observed in the Spoils

The work operation will cease immediately. All personnel will evacuate to a safe area or distance. The equipment will be left in place.

Delineate UXO with yellow caution tape or bright paint.

Any work operations occurring within 20 feet of the item will cease. All CSU and subcontractor employees will evacuate this area.

Under no circumstances will any CSU or subcontractor employee attempt to move or otherwise handle any UXO or suspected UXO item.
COLLECTION OF “SOUVENIRS” IS PROHIBITED

Responsibility for the work location will be transferred to the installation.

Drilling Activities

If any UXO item is encountered during drilling, the following procedures will be observed.

UXO Item Encountered Downhole and Detonation Occurs

The work operation will cease immediately.

If injuries have occurred the Emergency Contingency Plan will be activated

Once any necessary immediate response actions have been completed, the drilling auger will be blocked in place and disconnected from the drill rig. The drill rig will then be withdrawn from the site and the area will be delineated using yellow CAUTION tape.

Responsibility for the work location will be transferred to the installation.

The drill rig will be thoroughly inspected for damage before being put back into service (see Appendix E).

UXO Item Believed to be Encountered Downhole But No Detonation Occurs

The work operation will cease immediately.

If drilling, the drilling auger will be blocked in place and disconnected from the drill rig. The equipment (drill rig, backhoe, etc.) will then be withdrawn from the site and the area will be delineated using yellow CAUTION tape.

Responsibility for the work location will be transferred to the installation.

UXO Item Observed in the Spoils

The work operation will cease immediately and all personnel will evacuate the area. The equipment (drill rig, backhoe, etc.) will be left in place.

Any CSU work operations occurring within 20 feet of the item will cease. All CSU and subcontractor employees will evacuate the area.

Under no circumstances will any CSU or subcontractor employee attempt to move or otherwise handle any UXO or suspected UXO item.

COLLECTION OF “SOUVENIRS” IS PROHIBITED

The landfill’s operations manager or safety officer will be alerted as to the location of the suspected item, and responsibility for the work location will be transferred to the installation.

MONITORING PLAN

This section of the HASP outlines monitoring strategies and analytical methods, which will be employed as necessary to assess employee exposure to chemical and physical hazards. Monitoring will consist primarily of on-site determination of various parameters (airborne contaminant concentrations, heat stress effects, etc.), but may be supplemented by more sophisticated monitoring techniques if necessary.

AIRBORNE CONTAMINANT CONCENTRATIONS

To assess the concentrations of airborne organic vapors that may be released during certain intrusive operations (drilling, etc.) monitoring will be accomplished both in worker breathing zones and at the boundaries of the established controlled work areas. Monitoring will be conducted using the instrumentation specified in Table 7-1.

Table 7-3 Air Monitoring Instrumentation

Instrument	**Manufacturer/Model**	**Substances Detected**
Photoionization Detector (PID)	H-Nu PI-101 Photovac MicroTIP MSA Photon ThermoEnvironmental Organic Vapor Monitor (OVM)	Chlorinated (TCE) and aromatic hydrocarbons
Multigas Detector	Neotronics Exotox-55 ISC TMX-410 GasTech GX-91 MSA 360 or 361	Oxygen, %LEL (combustible and flammable vapors and gases), hydrogen sulfide, and methane

Workspace (Exclusion Zone) Monitoring

Workplace monitoring must be sufficient to properly characterize employee exposures and provide knowledge of work location conditions in enough detail to determine PPE requirements as work progresses. Required monitoring procedures, instrumentation, frequency and locations are specified in Table 7-2 along with response actions based upon monitoring results.

In general, monitoring will be used to evaluate worker breathing zone concentrations of site contaminants as a measure of exposure potential and for determination of the need for changes in specified respiratory protection. In addition, monitoring for explosive conditions shall be conducted as specified in Table 7-2.

Work Area Boundary Monitoring

Monitoring will be conducted to assess the release of contaminants to the surrounding "community" (the area and anyone in it not within the controlled work area(s) related to this project). Release of contaminants to the community can be monitored through determination of airborne levels of contaminants present at the boundary of the controlled area(s). This evaluation will be conducted using the same direct reading instrumentation employed for workspace evaluation (see Section 7.1.1 and Table 7-2).

Table 0-4 Monitoring Program Action Levels

Parameter and Methods	**Location And Interval**	**Response Level** (above background)	**Response**
VOCs (Total by PID)	Breathing zone, every 15 minutes during intrusive activities	< 20 units	Continue work in required PPE and continue monitoring.
		20 – 50 units (sustained for more than 5 minutes)	Contact the SSO, and upgrade PPE to Level C (organic vapor cartridge). Continue monitoring and use benzene detector tube. Downgrade if benzene levels are less than 0.5 ppm.
		> 50 units (sustained for more than 5 minutes)	Cease work, exit, and contact the SSO.
VOCs (Total by PID)	Edge of exclusion zones, every 15 minutes during intrusive activities	< 10 units	Continue work and continue monitoring.
		> 10 units (sustained for more than 5 minutes)	Implement mitigation measures and contact the SSO.
Explosivity (by multigas meter)	Inside boreholes during intrusive work, and upon opening any well	< 10% LEL	Continue work activities.
		10% LEL	Cease work, exit the area, and contact the SSO.

Personal Sampling

Measurement of employee exposure to chemical contaminants will be performed at the discretion of the H&SP. Monitoring techniques will also be determined by the H&SP and will conform with applicable OSHA and NIOSH sampling methods.

NOISE EXPOSURE

Data gathered in this effort indicates that workers may be exposed to hazardous levels of noise when working within 25 feet of operating heavy equipment (drill rigs, earthworking equipment, etc.).

MAINTENANCE AND CALIBRATION OF EQUIPMENT

All monitoring equipment will be maintained and calibrated in accordance with manufacturer's recommendations. All pertinent data will be logged in a health and safety logbook and maintained on-site for the duration of site activities. Calibration of all monitoring equipment will be performed daily.

Where personal sampling is performed, the CSU Environmental Health and will be responsible for informing employees and subcontractors of their monitoring results to comply with OSHA regulations and good occupational health practices. Within 5 working days after the receipt of monitoring results, the Health and Safety Department will notify each employee in writing of the results which represent that employee's exposure.

Where results indicate that employee exposure exceeds the PELs, notification shall be provided to the affected employee stating that the PEL was exceeded and providing a description of the corrective action(s) taken to control the exposure. Results of monitoring for other hazardous and harmful physical agents shall also be reported to employees in the same manner.

PERSONAL PROTECTIVE EQUIPMENT

General

The harmful effects that chemical substances may have on the human body often necessitate the use of protective clothing. Proper selection of PPE depends upon a number of factors. The protective equipment used must be suitable for the hazard(s) confronted.

Appropriate PPE ensembles are specified on a task-by-task basis in the task hazard analysis provided in Appendix D, and upgrade criteria are based upon on-site monitoring results as presented in Table 7-2. All personnel on-site will be equipped with the following work ensemble:

- Hard hat,
- Short-sleeved shirt (tank tops are not acceptable),
- Long pants (shorts or cut-offs are not acceptable),
- Safety-toe work boots [construction activities],
- Safety glasses, and
- Hearing protection (as required).

If desired, personnel can modify the above ensemble through selection of protective work gloves or similar items as needed to perform specific work tasks.

Where the use of chemical-protective gloves is specified, the following items will be acceptable:

Inner Gloves

Best Safety Model N-Dex nitrile rubber gloves, or
Other models approved on a case-by-case basis by the H&SP.

Outer gloves

North Model Solvex gloves (nitrile rubber), or

Other models approved on a case-by-case basis by the H&SP.

Chemical-Protective Clothing Ensembles

In response to the challenges presented by site contaminants, specific PPE ensembles have been developed. The designated levels of protection are, in increasing complexity: Level D, Modified and Level D. Work Level C, B, and A are not anticipated by this work plan.

Level D
Level D protection is the lowest level of personal protection allowed on HAZWOPER sites. Respiratory protection is not required, since concentrations of airborne contaminants are expected to be below applicable action levels.

During HAZWOPER activities, Level D protection will be the primary level of protection worn during all operations where contact with contaminated materials is unlikely (e.g., geophysical testing). The Level D ensemble provides minimal levels of skin protection. Upgrading to greater levels of protection will be executed as required in Table 7-2.

Level D Equipment List

Normal work ensemble (see Section 8.1), and

Modified Level D

If the potential exists for contact with chemical contaminants (e.g., splashes, "dirty operations," etc.), but the respiratory hazard is low, the use of a Modified Level D ensemble is appropriate. Modified Level D consists of protective clothing to preclude hazards from contact with contaminated materials, but does not provide increased respiratory protection. The use of protective clothing in a Modified Level D ensemble can also serve to aid in personal cleaning and decontamination efforts through the use of disposable outer protective garments.
The use of Modified Level D PPE will be required for on-site operations where contact with contaminated soils can be expected (e.g., sample collection, soil handling/containerization). The Modified Level D ensemble provides moderate skin protection against chemical contact, but no respiratory protection.

Modified Level D Equipment List

- Chemical-resistant disposable outer coveralls (e.g., Tyvek® or poly-coated Tyvek® coveralls),
- Chemical-resistant outer gloves (taped to outer coveralls),
- Chemical-resistant inner gloves,
- Butyl apron (optional, for use where splash potential is high),
- Hard hat,
- Safety glasses/faceshield,
- Chemical-resistant safety-toe boots (taped to outer coveralls), and
- Hearing protection (as required)

DECONTAMINATION

All personnel and equipment entering any controlled work area must be adequately decontaminated prior to exiting the area. Site-specific decontamination procedures should be adopted.

Personnel Decontamination

Decontamination procedures must be carried out on all personnel who have been in contact with contaminated materials. Under no circumstances (except emergency evacuations) will personnel be allowed to leave a controlled work area where contaminants are exposed without performing decontamination.

Decontamination of personnel should be performed at a Personal Decontamination Station on the site and should consist primarily of soap and water washing and water rinse of exterior protective gear to remove contaminants, followed by doffing of the gear. Coveralls should be removed by turning the clothing inside out. A procedure appropriate to the degree of contamination should be established. The extent of washing required, or modifications to the sequence, may be specified as appropriate.

Level D Personnel Decontamination

Personnel exiting an Exclusion Zone where site activities require the use of Level D PPE will perform decontamination in accordance with the following guidelines:

Place tools, instruments, samples and trash at an appropriate location. The equipment drop area should be clean and dry and, at a minimum, plastic bags should be available for trash. Waste PPE will not be placed in the same containers as general trash.

Inspect equipment, samples and, if applicable, tools for signs of residual amounts of contamination or excessive soil buildup. If present, soils and contamination must be completely cleaned off of equipment, samples, and tools prior to there removal from the Exclusion Zone areas.

Personnel will visually check themselves for signs of excessive soils and possible contamination. If observed, soils and contamination will be completely removed before further decontamination is performed.

Prior to exiting the Exclusion Zone areas, personnel will wash their hands with soap and water to minimize the potential for contaminant exposure.

Modified Level D Personnel Decontamination

Where activities are performed in Modified Level D PPE, personnel will perform decontamination using the following guidelines:

1. Place tools, instruments, samples and trash at an appropriate location. The equipment drop area should be clean and dry and, at a minimum, plastic bags should be available for trash. Waste PPE will not be placed in the same containers as general trash.

2. Inspect equipment, samples and, if applicable, tools for signs of residual amounts of contamination or excessive soil buildup. If present, soils and contamination must be completely cleaned off of equipment, samples, and tools prior to their removal from the exclusion zone areas.

3. Personnel will visually check themselves for signs of excessive soils and possible contamination. If observed, soils and contamination will be completely removed before further decontamination is performed.

4. Wash and rinse outer work gloves and boots (boot covers) with soap and water.

5. Wash or brush off outer protective coverall (Tyvek®).

6. *Untape wrists and ankles.*

7. Remove outer work gloves and place them in an appropriate container specified for waste PPE.

8. Remove outer Tyvek® coveralls and place them in an appropriate container specified for waste PPE.

9. Wash, rinse, and remove inner protective gloves and place them in an appropriate container specified for waste PPE.

10. Wash hands using soap and water (separate from other decontamination cleaners/solutions).

Equipment Decontamination

Equipment that might require decontamination includes heavy equipment, tools, monitoring equipment, sampling equipment, and sample containers; trucks and trailers; and the decontamination equipment itself when the decontamination station is closed down. Before entering the site, all equipment will be cleaned to remove grease, oil, encrusted dirt, or other potential contaminants. The following general guidance should be used in determining equipment decontamination procedures:

Hand Tools: Tools will be dropped into a plastic pail, tub or other container in the Exclusion Zone. They will be brushed off, rinsed, and transferred into a second pail to be carried to the decontamination station. Generally, tools will be washed with a detergent solution, and rinsed with clean water.

Avoid using wooden tools; they cannot be adequately decontaminated because of their absorptive properties. If used, wooden tools cannot be removed from the Exclusion Zone until the end of the project, and then only to be disposed of as hazardous waste.

Manual Sampling Equipment: Sampling equipment will be decontaminated before and between sampling to prevent cross contamination, and when the equipment leaves the Exclusion Zone. Sampling equipment may include trowels, shovels, bailers, submersible pumps, geotechnical samplers, sleeves, and backhoe buckets.
All sampling equipment will be decontaminated using an Alconox wash or equivalent, followed by two clean water rinses. The sampling tool will then be rinsed with deionized or distilled water and air dried.

Direct Push and Drilling Equipment: All direct push rods, augers and other components which are placed downhole will require decontamination. This decontamination can occur on-site or at an off-site location. If off-site decontamination is chosen, all procedures and waste disposal responsibility will be the sole responsibility of the contractor performing the work. The procedure for on-site decontamination will be as follows:

1. Decontamination will be performed using a steam cleaner or high-pressure washer system.

2. Decontamination will occur at a central location at which a temporary decontamination pad has been constructed to collect all wastewater. This can be accomplished using plywood and polyethylene sheeting.

3. Equipment will be thoroughly cleaned so that no visible contamination or dirt is present after decontamination is completed.

4. All decontamination water will be containerized in 55-gallon drums.

5. Upon disassembly of the decontamination pad the polyethylene sheeting will be placed in 55-gallon drums and disposed of as contaminated waste.

Monitoring Instruments: Monitoring equipment should be protected as much as possible from contamination. Drape, mask, or otherwise cover as much of the instruments as possible with plastic without hindering the operation of the unit. Many instruments can be placed in a clear plastic bag that allows reading of the scale and operation of the knobs.

Contaminated instruments will be taken from the drop area, their protective coverings removed, and disposed of in appropriate containers. Any remaining dirt or obvious contamination will be brushed or wiped with a damp disposable paper wipe. The units can then be placed in a clean plastic tub, taken inside, wiped with damp disposable wipes and dried.

9.3 Disposal of Decontamination Wastes

Solid and liquid decontamination wastes should be containerized. Solids may be double bagged or placed in a sealed drum or similar container. Liquids will be collected during decontamination and placed in sealed containers or pumped into holding tanks for future testing and disposal. Containers must be clearly labeled for content, the operation from which they were filled, and the dates.

Decontamination During Emergencies

Often during emergencies the need to quickly respond to an accident or injury must be weighed against the risk to the injured party from chemical exposure. It may be that the time lost or the additional handling of an injured person during the decontamination process may cause greater harm to the individual than the exposure that would be received by undressing that person without proper decontamination.

An additional consideration to include when bypassing decontamination of injured personnel is the acceptance of contaminated personnel at emergency medical facilities. Many facilities will not accept contaminated personnel. Site response personnel should accompany contaminated victims to the medical facility to advise on matters involving decontamination.

SITE CONTROL AND WORK ZONES

During subsurface investigation activities, CSU will ensure control of the areas immediately surrounding the location using the guidance specified in Section 4.3 of the Field Health and Safety Manual.

Controlled Work Areas

The area surrounding each sampling location presents hazards related to both the potential for the release of environmental contaminants and the from sample collection procedures (drilling, etc.). To minimize hazards to personnel not directly involved in sampling procedures a controlled work area (exclusion zone) will be established. The extent of each exclusion zone will be sufficient to ensure that personnel located at/beyond its boundaries will not be affected in any substantial way by hazards associated with sample collection activities. To meet this requirement, the following minimum distances will be used:

Hollow-Stem Auger Drilling. Determine the mast height of the drill rig. A distance equal to this height will be cleared, if practical, in all directions from the bore hole location and designated as the exclusion zone. The cleared area will be sufficient to accommodate movement of necessary equipment and the stockpiling of spoil piles.

Decontamination. Thirty feet will be cleared in all directions from the decontamination location, where practical, for large efforts (e.g., vehicle and drilling equipment) conducted at a decontamination pad. For personal and small parts decontamination conducted at the work location, keep decontamination activities within the applicable Exclusion or Contamination Reduction Zone established for that operation.
Samples will not be brought directly into the support zone. A separate table near the decontamination station or near the sample location shall be set up to handle samples as they are collected. A temporary disposable table (e.g., constructed of wood) is acceptable or a folding table with plastic sheeting may be used.

Exclusion Zone Control Records

On a daily basis, the SSO will record the identities of all personnel working within each exclusion zone. The identity of each visitor entering any exclusion zone, as well as the time of entry and exit, will also be recorded.

This information will be placed in the site log.

EMERGENCY CONTINGENCY PLAN

Three types of emergencies could occur during site activities. These include:

Illnesses and physical injuries (including injury-causing chemical exposure),
Catastrophic events (fire, explosion, earthquake, or chemical), and
Safety equipment problems.

Although a catastrophic event or severe medical emergency is unlikely to occur during work activity at the site, an emergency contingency plan has been prepared for this project should such critical situations arise.

Responsibilities
Site Supervisor/Site Safety Officer

The Site Supervisor/SSO will be the primary contact individual and coordinator of all emergency activities. He/she will be responsible for:

Evaluating the severity of the emergency,
Implementing appropriate response action,
Summoning appropriate emergency services (fire department, ambulance, etc.), and
Notifying all site personnel, the H&SP, and concerned authorities of the emergency situation.

Other On-Site Personnel

It will be the obligation of the field personnel to inform the SSO of all emergency situations and to abide by the response actions issued by the SSO. Special medical problems of field personnel such as allergies to insects, plants, prescription medication, etc. will be reported to the SSO.

Emergency Equipment

Provisions will be made to have the following emergency equipment available and in proper working condition.

First-Aid Kits

Each work site shall have a first-aid kit meeting the following requirements:

First-aid kits in weather-proof containers shall be present at all locations where CSU employees will be working.

Whenever a new first-aid kit is assembled, a new Inventory List/Physician's Authorization Certificate shall be placed in the first-aid kit as part of its inventory.

First-aid kits shall be available at the job site at all times.

Use of any item from the first-aid kit shall necessitate completion of a Supervisor's Employee Injury Report. The report shall be submitted to the Health and Safety Department within one working day.

For local field services work, first-aid kits shall be returned to the storeroom at the end of each workday.

First-aid kits shall be inspected and restocked weekly, and an inventory of first-aid supplies sufficient to restock kits on a weekly basis shall be maintained.

For jobs outside the local area, the site supervisors shall replenish the kit from the nearest pharmaceutical source, with equivalent supplies to those used (until proper restocking by the storeroom can be accomplished), unless such supplies can economically be made available to the job from the storeroom.

Personnel permitted to use first-aid kits shall possess a current first-aid card.

Eyewash Units

Eyewash units meeting the latest requirements of American National Standards Institute Standard 2358.1 will be utilized at the site. All units shall be capable of supplying hands-free irrigation for both eyes for at least 15 minutes at a flow rate of at least 0.4 gallon per minute.

Fire Extinguisher

A fire extinguisher capable of extinguishing Class A, B, and C fires will be available for use at the site at all times. Site personnel will be readily aware of the location of the fire extinguisher at all times in the event of an incident where a fire extinguisher may be utilized.

Safety Equipment Problems

An emergency may develop because of a malfunction or other problems associated with health and safety equipment being used by field personnel. These equipment problems must be corrected before proceeding with field activities. Health and safety problems that may occur include:

Leaks or tears in protective clothing,
Failure of respiratory protective devices (SCBA, air-purifying respirators); or
Encountering contaminants for which prescribed protective equipment may not be suitable.

In each case personnel affected by the equipment problem(s) will exit the work area until the problem can be corrected.

Response Actions - Non-catastrophic

Medical Emergencies

Medical emergencies can be described as situations that present a significant threat to the health of personnel. These can result from chemical exposures, heat stress, cold stress, or poisonous insect or snake bites. Medical emergencies must be dealt with immediately and proper care should be administered. This may be in the form of first-aid and/or emergency hospitalization.

Spill/Release of Hazardous Materials

If a small spill of fuel, cleaning solvent or other hazardous materials occurs, actions should be taken to immediately contain the spill. This can include the use of spill containment devices (spill "pillows," etc.) or other barriers. The SSO will direct the cleanup of spilled material as quickly as possible. Cleanup will be performed using an absorbent material the waste will be collected and containerized.

Response Actions - Medical Emergencies

Medical emergencies can be described as situations that present a significant threat to the health of personnel. These can result from chemical exposures, heat stress, cold stress, and poisonous insect bites. Medical emergencies must be dealt with immediately and proper care should be administered. This may be in the form of first aid and emergency hospitalization.
Response personnel will accompany victims to the medical facility, whenever possible, to advise on decontamination. Telephone numbers and locations for local fire department, hospitals, ambulance service, and other emergency services shall be maintained at the site by the SSO or

PM (Table 11-1). In the event of severe injury, personnel shall be transported to the designated hospital (Figure 11-1).

Information regarding non-emergency medical treatment for on-site injury, on-site illness, or on-site exposure to chemical contaminants will be provided to the hospital by the SSO.

Hospital Location Map Response Actions-Catastrophic Events

In the event of a catastrophic incident:

1. Work activities will cease and all project personnel will be evacuated from the work location. The evacuation will proceed in a direction opposite to the critically affected area with all personnel assembling in a pre-designated location outside of the job site proper.
2. A headcount will be taken of the assembled employees and any injured individuals shall be administered first-aid.
3. If not present at the work location, the SSO will be contacted immediately.

A universal signal for emergency evacuation (e.g., use of a horn) and designation of the evacuation assembly location shall be established by the SSO and briefed to all workers during initial site-specific training. Any changes mandated by changing site conditions shall be determined by the SSO and communicated to workers during the daily tailgate safety briefing.

Table 11-1 Emergency Contacts and Telephone Numbers

Emergency Personnel

Police	911
Fire Department	911
Ambulance	911
Medical Care (Emergency Room)	911 or (602) 848-5200

Information and Response Organizations

National Poison Control Center	(800) 458-5842
TSCA Hotline	(202) 554-1404
EPA Environmental Response Team (ERT)	(201) 321-6660
Resource Conservation and Recovery Act (RCRA) Hotline	(800) 424-9346

CSU Personnel

PI		
Dr. Tom Sale	CSU:	(970) 491-8413
	Home:	(970) 482-1793
Health and Safety Professional		
Dominic Leffler	CSU:	(970) 491-4830

Directions to Hospital

United Medical Center – West
300 E 23rd Street
Cheyenne, WY 82001-3790

- **Exit the base and proceed north on Interstate 25.**
- **Turn right (eastbound) on Pershing Boulevard and proceed approximately 1 mile to Hwy 85.**
- **Turn right (southbound) onto Hwy 85 and proceed approximately ½-mile to 23rd Street.**
- **Exit onto 23rd Street and turn left.**
- **The hospital is at the corner of 23rd Street and House Avenue.**