# FINAL

# COST AND PERFORMANCE REPORT

# ENHANCED *IN-SITU* ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS AT FF-87, FORMER NEWARK AIR FORCE BASE, OHIO

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**Prepared for:**

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## 1.0 INTRODUCTION

This report summarizes the cost and performance of a demonstration of enhanced *in situ* anaerobic bioremediation of chlorinated solvents in groundwater at the Former Facility 87 (FF-87), located at Former Newark Air Force Base (AFB), Ohio. Emulsified vegetable oil was injected into the subsurface in two phases to stimulate the anaerobic biodegradation of chlorinated ethenes and chlorinated ethanes in groundwater at the FF-87 site. The demonstration was conducted by Parsons Infrastructure & Technology Group, Inc. (Parsons) in support of the Air Force Center for Engineering and the Environment (AFCEE) *Enhanced In Situ Bioremediation Initiative*. The environmental program at Former Newark AFB is co-managed by AFCEE and the Air Force Real Property Agency (AFRPA), which facilitated site selection and implementation of this demonstration.

The performance objectives for this application were to reduce concentrations of chlorinated ethenes and chlorinated ethanes in groundwater to below Ground Water Protection Standards (GWPS) established for the site by the Ohio Environmental Protection Agency. Summary information for the FF-87 demonstration site are listed in Table 1.

**TABLE 1. SUMMARY INFORMATION**

| | |
|---|---|
| **Site Name, Location** | FF-87, Former Newark Air Force Base, Ohio |
| **Treatment Mechanism** | Anaerobic Reductive Dechlorination |
| **Technology** | Enhanced *In Situ* Anaerobic Bioremediation using Vegetable Oil Substrate |
| **Configuration** | Direct Subsurface Injection |
| **Technology Scale** | Full-Scale (Phase I and II) |
| **Media/Matrix Treated** | Groundwater |
| **Contaminants Targeted** | Chlorinated Ethenes and Chlorinated Ethanes |
| **Period of Operation** | September 2001 to October 2005 |

## 2.0 SITE DESCRIPTION

Former Newark AFB is located within the city limits of Heath in Licking County, Ohio, approximately 35 miles east of Columbus. The former Base encompasses approximately 70 acres. The production building is currently leased by Boeing Aircraft Corporation and is used to manufacture and calibrate instruments. Land use surrounding the former Base includes industrial development, farming, and residential areas.

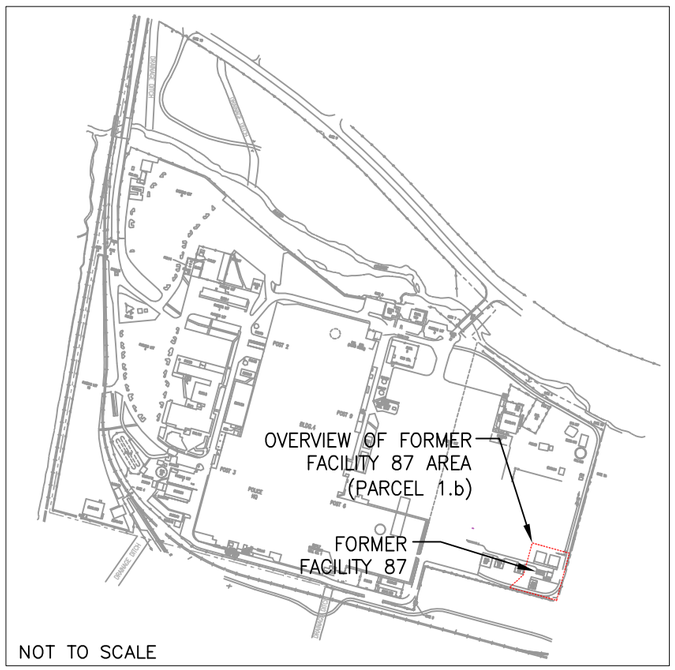
FF-87 is located in the southeast corner of Former Newark AFB (Figure 1). FF-87 was a three sided semi-enclosed structure with an asphalt floor that was used to temporarily store 55-gallon drums of used solvents and spent Freon 113. Drainage ditches and dirt berms extended along the three closed sides of the building and were installed to control any spills that may have occurred within the building. It is thought that the contaminants were spilled inside the building and migrated downward beneath FF-87 through the asphalt floor.

## LEGEND:

- DETECTION MONITORING WELL
- CORRECTIVE ACTION EFFECTIVENESS MONITORING WELL
- SUBSTRATE INJECTION WELL
- VAPOR MONITORING POINT

NOTES:

1. THE CURRENT CORRECTIVE ACTION EFFECTIVENESS MONITORING PROGRAM CONSISTS OF SAMPLE COLLECTION FROM DETECTION MONITORING WELLS, CORRECTIVE ACTION EFFECTIVENESS MONITORING WELLS, AND VAPOR MONITORING POINTS (SHAW, 2004a).
2. MW 87-1 AND MW 87-1A ALSO SERVE AS COMPLIANCE MONITORING WELLS.




0 25 50
SCALE: 1"=50'

**FIGURE 1**

**FF87 SITE LOCATION MAP**

Former Facility 87
Former Newark AFB, Ohio

**PARSONS**

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Chlorinated compounds detected at the site at concentrations above groundwater protection standards include tetrachloroethene (PCE), trichloroethene (TCE), *cis*-1,2-dichlorothene (*cis*-1,2-DCE), 1,1,1-trichloroethane (1,1,1-TCA), and 1,1-dichlorothane (1,1-DCA). The maximum concentration of PCE detected in groundwater prior to the demonstration was 1,300 micrograms per liter (µg/L), with lesser concentrations for the other chlorinated compounds (Table 2).

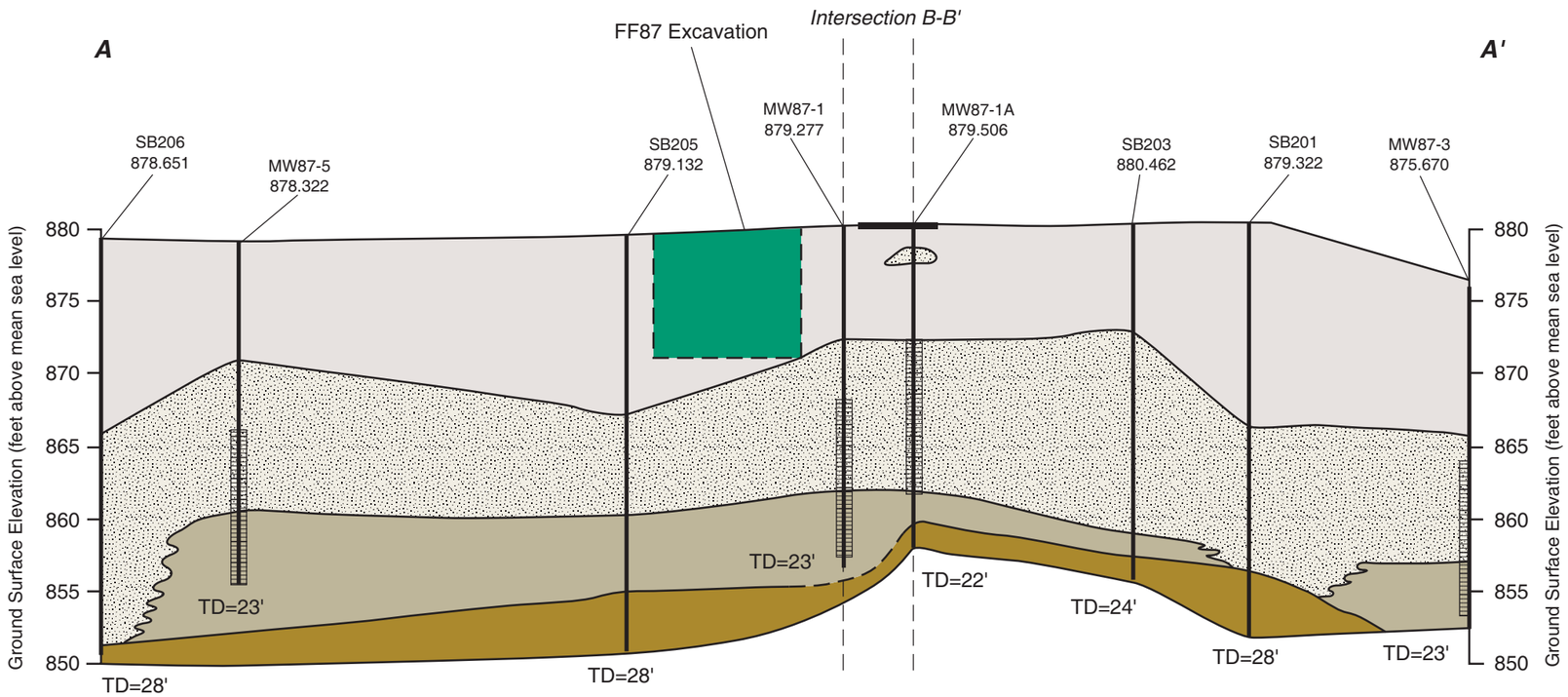
**TABLE 2. HYDROGEOLOGIC AND CONTAMINANT CHARACTERISTICS**

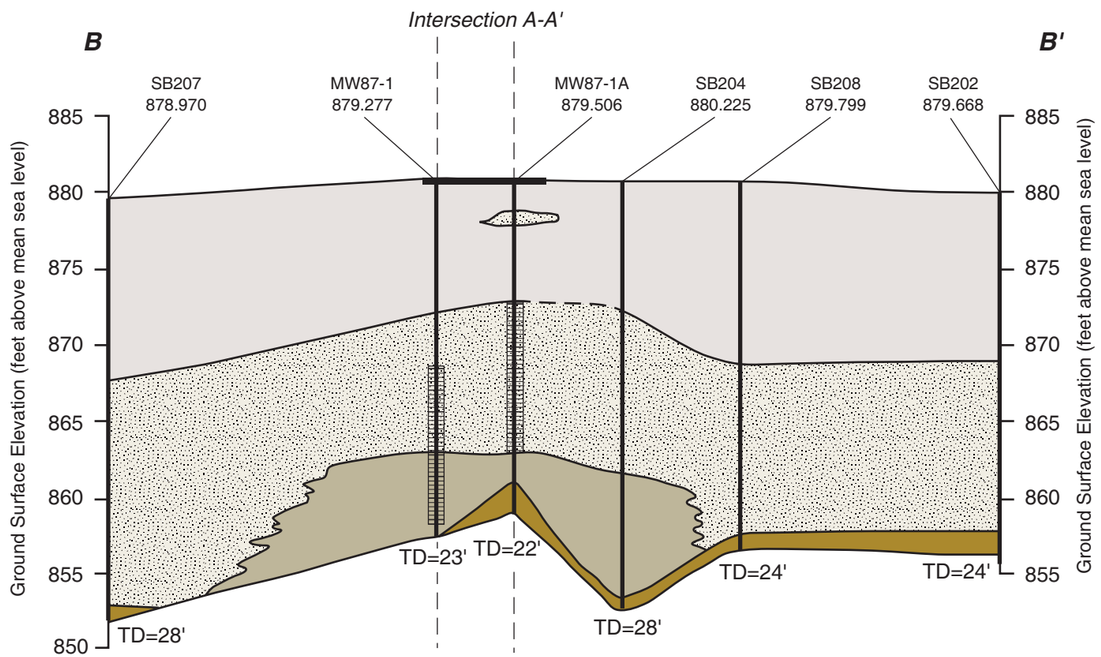
| Site Attribute | Description |
|---|---|
| **Aquifer Matrix** | Silty to Gravelly Sand, Silt and Clay |
| **Depth to Groundwater** | 9 to 14 feet below ground surface |
| **Thickness of Aquifer** | 10 to 14 feet |
| **Hydraulic Conductivity** | 33 feet per day |
| **Effective Porosity** | 25 percent (estimated) |
| **Hydraulic Gradient** | 0.018 to 0.019 foot per foot |
| **Groundwater Velocity** | 990 to 2,000 feet per year |
| **Maximum Groundwater Pre-Installation Contaminant Concentrations** [a/] | tetrachloroethene (PCE) = 1,300 micrograms per liter (µg/L)<br>trichloroethene (TCE) = 13 µg/L<br>*cis*-1,2- dichloroethene (*cis*-1,2-DCE) = 46 µg/L<br>1,1,1-trichloroethane (1,1,1-TCA) = 150 µg/L<br>1,1-dichloroethane (1,1-DCA) = 31 µg/L |
| **DNAPL Presence** | Not Encountered |
| **Fraction Organic Carbon** | Not Available |

[a/] Pre-injection concentrations at MW-87-1A.

The surficial geology of Former Newark AFB consists primarily of recent alluvium and Pleistocene glacial deposits. The subsurface beneath FF-87 is depicted on two cross sections shown on Figure 2. Beneath the demonstration site, the uppermost unit consists of silt and clay, and extends from the ground surface to a depth of approximately 8 feet below ground surface (bgs). Silty to gravelly sand, extending to depths of approximately 18 to 22 feet bgs, underlies the upper silt and clay unit. Unconfined groundwater occurs in these two units, which together are identified as the Upper Water Bearing Zone (UWBZ).

At the base of the UWBZ is a discontinuous "silt unit" that varies lithologically from fine silty-sand to silty-clay. Beneath and downgradient from the demonstration area, this silt unit varies in thickness from approximately 2 to 6 feet. Relatively impermeable clay till, known as the Upper Confining Layer (UCL), underlies the silt and extends to a depth of approximately 90 feet bgs.




**Legend**

| | |
|---|---|
| SB201 | Soil Boring ID |
| MW87-3 | Monitoring Well ID |
| 878.651 | Ground Surface Elevation (feet above mean sea level) |
| | Screened Interval |
| | Asphalt |
| | Clay, Silty Clay, Clayey Silt |
| | Sand and Gravel |
| | Silt |
| | Till |
| | Fill |

N

0 15 30
Horizontal Scale (feet)

0 5 10
Vertical Scale (feet)

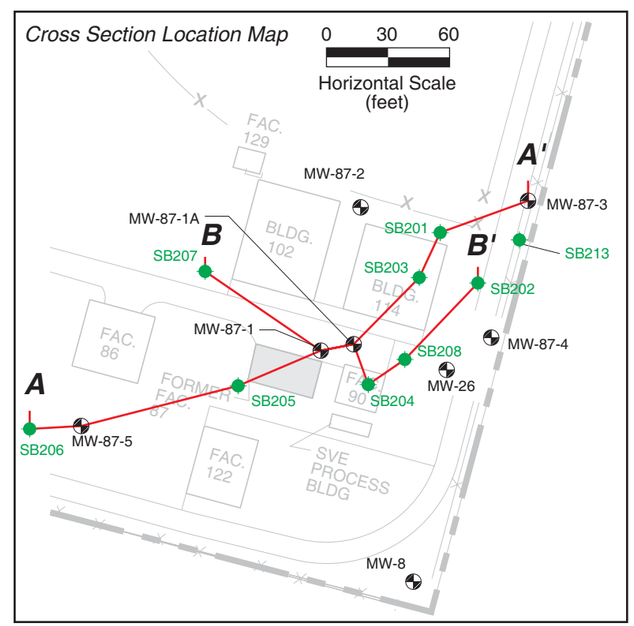



**FIGURE 2**

**GEOLOGIC CROSS SECTIONS**

Former Facility 87
Former Newark AFB, Ohio

**PARSONS**

**Source: Amended Post Closure Plan, Former Facility 87 (Shaw, 2004a).**

Illustrator\Geological Cross Sections.ai ma 7/26/06

Groundwater occurs under unconfined conditions within the UWBZ at a seasonally variable depth of approximately 9 to 14 feet bgs. The groundwater potentiometric surface slopes towards the northeast with an average gradient of approximately 0.02 foot per foot (ft/ft), based on water level measurements taken between 1995 and 2000 (IT, 2001). The hydraulic conductivity of the UWBZ in the field test area was calculated to be between 68.3 feet per day (ft/day) (using pumping test data) and 33.5 ft/day (using slug test data) for wells screened mostly in the gravelly sand layer (R.E. Wright Associates, Inc., 1995). Assuming an effective porosity of 25 percent (estimated), groundwater flow in the UWBZ at the site is approximately 2.7 to 5.5 ft/day, or approximately 990 to 2,000 feet per year (ft/yr).

## 3.0 TECHNOLOGY DESCRIPTION

Enhanced *in situ* anaerobic bioremediation is an effective method of degrading chlorinated aliphatic hydrocarbons (CAHs, commonly referred to as chlorinated solvents) dissolved in groundwater. One advantage of this technology is that it can lead to complete destruction of chlorinated solvents *in situ* with little impact on site infrastructure or a need for secondary treatment trains. In addition, enhanced anaerobic bioremediation can generally be implemented at a cost that is low relative to other engineered remedial options.

The addition of an organic substrate to an aquifer stimulates microbial growth, resulting in the formation of an anaerobic environment that may greatly enhance rates of anaerobic biodegradation of CAHs. To date, a variety of organic substrates have been applied to the subsurface to promote anaerobic degradation of CAHs. Examples of easily fermentable organic substrates include carbohydrates and sugars, vegetable oils, and low-molecular-weight fatty acids. Vegetable oil was selected as the primary organic substrate for the demonstration at FF-87 because it is a cost-effective, slow-release source of organic carbon.

Addition of an organic substrate depletes the aquifer of dissolved oxygen (DO) and lowers the oxidation-reduction potential (ORP), which results in stimulation of biogeochemical conditions that are conducive for anaerobic degradation processes to occur. After DO is consumed, anaerobic microorganisms use available native electron acceptors in the following order of preference: nitrate, manganese and ferric iron hydroxides or oxyhydroxides, sulfate, and finally carbon dioxide (methanogenesis). Evaluation of the distribution of these electron acceptors can provide evidence of where and how biodegradation of CAHs may be occurring.

Under anaerobic conditions, biodegradation of chlorinated solvents usually proceeds through the process of reductive dechlorination. During reductive dechlorination, the chlorinated hydrocarbon is used as an electron acceptor, and a chloride atom is removed and replaced with a hydrogen atom. Biologically mediated reductive dechlorination generally occurs sequentially. For example, with chlorinated ethenes dechlorination progresses from PCE to TCE to isomers of DCE to vinyl chloride (VC) to ethene. Ethene may be further reduced to ethane. This is the process targeted for stimulation by addition of the vegetable oil substrate at FF-87.

Other anaerobic biodegradation processes that may occur include biogeochemical reduction, where a CAH molecule is mineralized through direct contact with a reduced compound such as iron monosulfide (*e.g.*, Butler and Hayes, 1999); and anaerobic oxidation, a biologically-mediated reaction in which less chlorinated CAHs, such as *cis*-1,2-DCE and VC, are directly oxidized (*i.e.*, used as an electron donor) to carbon dioxide, hydrogen, and chloride (Bradley and

Chappelle, 1997; Bradley *et al.*, 1998a and 1998b). While these two processes may potentially occur, they were not targeted or evaluated as part of this demonstration.

Vegetable oil is an inexpensive, food-grade carbon source. The separate phase nature and low solubility of vegetable oil allows for its slow dissolution into groundwater, although it may be readily consumed by microbial activity (Parsons, 2004). One objective of this demonstration was to determine whether a single, low-cost injection of vegetable oil in the form of an oil-in-water emulsion could provide sufficient substrate to enhance reductive dechlorination for a period of 3 years or more.

## 4.0 TECHNOLOGY IMPLEMENTATION

The enhanced bioremediation demonstration at FF-87 was implemented by injecting vegetable oil (*i.e.*, organic substrate as an emulsion) into the subsurface to create an *in situ* treatment zone for degradation of CAHs in groundwater beneath an apparent source area at the site. The FF-87 source area in the vadose zone was previously excavated and removed for disposal.

### 4.1 Phase 1 Injection

Site-specific field activities in support the Phase I study included:

- Installation of six injection wells, nine groundwater monitoring points, and two soil vapor monitoring points (Figure 1) using hollow-stem auger and direct-push drilling methods;
- Initial condition (*i.e.*, pre-injection) sampling of groundwater in October 2001 at nine newly-installed monitoring points and two existing monitoring wells;
- Injection of approximately 5,120 pounds (660 gallons) of food-grade vegetable oil (refined soybean oil) emulsified in the field with approximately 2,550 gallons of native groundwater from an upgradient monitoring well in October 2001; and
- Post-injection sampling of groundwater at eight newly-installed monitoring points and two existing monitoring wells at 5 months (February 2002), 7 months (April 2002), 10 months (July 2002), 13 months (October 2002), and 16 months (January 2003) after substrate injection.

The Phase I injection consisted of injecting approximately 600 gallons of a vegetable oil/lecithin/water emulsion into each of the three shallow injection wells (SIW-04, SIW-05, and SIW-06), and injection of approximately 230 gallons of emulsion into each of the three deep injection wells (SIW-01, SIW-02, and SIW-03). The emulsion consisted of approximately 25 percent partially hydrogenated soybean oil and lecithin and 75 percent native groundwater.

The injection system consisted of two Ingersol-Rand ARO air-operated diaphragm pumps that were plumbed in a configuration that used four flow meters, pressure gauges, and valves to control the volume, pressure, and flow rate of the injected fluids. The configuration also used a ½-inch diameter Koflow™ static in-line mixer to emulsify the oil and water mixture. The system was configured to inject into two injection points simultaneously though 1-inch high pressure hoses, while being able to separately control the volume and pressure of injection into

each of the two injection points. Oil injection was performed over 3 days from September 23 to 25, 2001.

The maximum injection rate into the deep injection wells was 6.4 gallons per minute (gpm) at a maximum injection pressure of 18 pounds per square inch (psi) at the well head. The maximum injection rate into the shallow injection wells was 10 gpm at a maximum pressure of 10 psi. After injection of the emulsion, approximately 150 gallons of native groundwater was injected as a water push into each shallow injection point and approximately 50 gallons of water was injected into each deep injection point.

## 4.2 Phase II Injection

Approximately 24 months after the Phase I injection, additional substrate was injected to expand the footprint of the treatment zone to include the area around well MW-87-1A, an area not impacted by the Phase I injection (Section 5.1.3). The Phase II injection involved the following field activities:

- Installation of four direct injection points using direct-push drilling methods;
- Pre-Phase II injection sampling of groundwater in October 2003 at the nine Phase I monitoring points and two monitoring wells;
- Injection of approximately 1,720 pounds (220 gallons) of food-grade vegetable oil (refined soybean oil) emulsified in the field with approximately 2,300 gallons of native groundwater from an upgradient monitoring well in October 2003.; and
- Post-injection groundwater sampling at nine monitoring points and three monitoring points at 3 months (January 2004), 8 months (June 2004), 12 months (October 2004), 17 months (March 2005), 20 months (June 2005), 22 months (August 2005), and 24 months (October 2005) after the Phase II substrate injection.

For the Phase II injection, approximately 55 gallons of a vegetable oil/lecithin mixture were emulsified with approximately 550 gallons of native groundwater and injected into each of four shallow direct push substrate injection points (SIP-07, SIP-08, SIP-09 SIP-10). The emulsion consisted of approximately 10 percent soybean oil and lecithin and 90 percent native groundwater. Substrate injection was performed on October 8 and 9, 2003.

The injection rate at each point averaged approximately 6 gpm at injection pressures that ranged between 13 and 18 psi. After injection of the emulsion, approximately 25 gallons of native groundwater were injected into each point to improve the distribution of the vegetable oil emulsion in the subsurface.

The injection system consisted of three Ingersol-Rand ARO air-operated diaphragm pumps that were plumbed in a configuration that employed two flow meters, pressure gauges, and valves to control the emulsion mixture ratio, volume, pressure, and flow rate of the injected fluids. The configuration also used two ½-inch-diameter Koflow™ static in-line mixers to emulsify the oil and water mixture. The in-line mixers were positioned before and after an equilibration tank to ensure a uniform emulsion mixture. The system was configured to inject into one injection point at a time though 1-inch high pressure hoses. The emulsion was injected directly through direct-push probe rods with the screened interval set at 15 to 17 feet bgs.

# 5.0 TECHNOLOGY PERFORMANCE

## 5.1 Phase I Demonstration

### 5.1.1 Geochemistry

Concentrations of DO during the September 2001 Phase I baseline sampling event were less than 2.0 milligrams per liter (mg/L) in all of the wells sampled (Table 3). Concentrations of DO measured during the January 2003 sampling event were less than 0.3 mg/L, indicating that anaerobic conditions were prevalent throughout the treatment zone. The decrease in concentrations of DO over the first 16 months following the Phase I injection indicates that the groundwater geochemical environment became more reducing and more conducive to anaerobic biodegradation processes. ORP values measured during the January 2003 sampling event ranged from -124 millivolts (mV) at location MW-87-1A to -293 mV at location MW-87-1, and were lower than those measured during the baseline sampling event in September 2001. This lowering of ORP is consistent with the decrease in concentrations of DO, and is a further indication that groundwater geochemical conditions became more reducing following the Phase I substrate injection.

Nitrate reduction, manganese reduction, and iron reduction were not observed to be significant terminal electron-accepting processes (TEAPs) (Table 3). Decreasing concentrations of sulfate were observed at all monitoring locations following the Phase I substrate injection. Increasing concentrations of methane were also observed at all wells within the treatment zone. These trends in sulfate and methane concentrations suggest that sulfate reduction and methanogenesis were the predominant TEAPs occurring at this site following the Phase I injection. It should be noted that methane increased to greater than 1.0 mg/L at locations MW-87-1 (8.6 mg/L) and GMW-02 (6.3 mg/L), but not until the January 2003 sampling event. Thus, it appears that a lag time of greater than 10 months (September 2001 to at least July 2002) was required to induce methanogenic conditions at these locations.

### 5.1.2 Changes in Concentrations of CAHs Over Time

Groundwater analytical data for performance monitoring events are presented in Table 4. Concentrations of PCE at location MW-87-1, screened in the upper sand unit, declined sharply after the Phase I injection in September 2001, and decreased to less than 1.0 µg/L by July 2002. During the same period, concentrations of *cis*-1,2-DCE for MW-87-1 remained relatively low, at 5.0 µg/L or less. VC, 1,1,1-TCA, and 1,1-DCA have been detected sporadically at this location at low, estimated concentrations (J-flags, Table 4).

At location MW-87-1A, also screened in the upper sand unit, concentrations of PCE initially declined from 1,300 µg/L during the baseline sampling event to 740 µg/L during the February 2002 monitoring event. However, the concentration of PCE rebounded to 1,500 µg/L during the July 2002 sampling event. Concentrations of PCE for MW-87-1A subsequently declined to 1,000 µg/L in January 2003 as measured from a passive diffusion bag sampler (PDBS) collected at a depth of 13.4 feet (upper sand interval). During the same time, concentrations of *cis*-1,2-DCE increased from 40 µg/L in July 2002 to 72 µg/L in January 2003.

**TABLE 3**
**SUMMARY OF GROUNDWATER GEOCHEMICAL DATA**

| Sample Location | Sample Date | pH (su)[a/] | Dissolved Oxygen (mg/L)[b/] | Redox Potential (mV)[c/] | Total Organic Carbon (mg/L) | Manganese (mg/L) | Ferrous Iron (mg/L) | Sulfate (mg/L) | Alkalinity (mg/L) | Methane (µg/L)[d/] | Ethane (µg/L) | Ethene (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GMW-01 | 9/23/2001 | 7.29 | 0.4 | -163 | 5.3 | <0.04 | 3.2 | 124 | 260 | 10 | 0.058 | 0.035 |
| | 2/14/2002 | 6.25 | 1.6 | -54 | 1.3 | 0.11 | 1.9 | 74 | 280 | 1.2 J | ND | ND |
| | 4/16/2002 | 7.43 | 0.1 | -34 | ND | NA | 1.8 | NA | NA | 6.2 | 0.13 | 0.12 |
| | 7/18/2002 | 7.43 | NA | -183 | 1.7 | 0.11 | 0.0 | 100 | 280 | 11 | 0.047 | 0.23 |
| | 1/29/2004 | 7.24 | 4.2 | -192 | <1.0 | 0.068 | 1.6 | 110 | 300 | 17 | 0.053 | 0.059 |
| | 6/3/2004 | 7.07 | 3.5 | -213 | 2.0 | 0.13 | 1.1 | 95 | 290 | 26 | 0.041 | 0.036 |
| GMW-02 | 9/23/2001 | 7.25 | 0.4 | -143 | < 5.0 | <0.04 | 2.9 | 118 | 290 | 11 | 0.13 | 0.024 |
| | 2/14/2002 | 2.59 | 10.1 | -49 | 1,129 | 2.3 | NA | 0.73 J[g/] | 800 | 4,800 | ND | ND |
| | 4/16/2002 | 5.76 | < 0.1 | 27 | 980 | NA | 13.2 | NA | NA | 3.4 | 0.12 | 0.088 |
| | 7/18/2002 | NA | NA | NA | 1,800 | 3.4 | NA | ND | 780 | 3.9 | 0.11 | 0.13 |
| | 1/28/2004 | NA | NA | NA | <110 | 1.0 | >25 | 1.2 | 750 | 9,800 | 0.011 | 0.067 |
| | 6/4/2004 | 6.01 | 9.0 | -125 | 200 | 1.3 | >3.3 | 1.4 | 660 | 12,000 | <0.005 | <0.005 |
| GMW-06 | 9/20/2001 | 6.88 | 0.9 | -91 | < 5.0 | 0.20 | 1.12 | 107 | 360 | 1.2 | 0.27 | 0.11 |
| | 2/13/2002 | 6.74 | 2.4 | -57 | 11 | 0.36 | NA | 78 | 380 | 5.5 | ND | ND |
| | 4/15/2002 | 6.98 | < 0.1 | -117 | 30.3 | NA | 5.2 | NA | NA | 5.3 | 0.11 | ND |
| | 7/17/2002 | NA | NA | NA | 5.8 | 0.23 | NA | 85 | 320 | 4.8 | 0.081 | 0.013 |
| | 1/15/2003 | 7.10 | 0.2 | -243 | NA | NA | NA | NA | NA | 8,300 | <0.50 | <0.50 |
| | 1/28/2004 | 6.84 | 4.5 | -199 | 7.9 | 0.26 | 0.8 | 47 | 390 | 11,000 | 0.062 | 0.040 |
| | 6/3/2004 | 6.78 | 2.6 | -148 | 2.2 | 0.22 | 0.2 | 65 | 340 | 5,400 | 0.055 | <0.005 |
| | 3/2/2005 | 6.83 | <0.3 | -37 | 2.1 | NA | 1.7 | 70 | 350 | 6,600 | <0.005 | <0.005 |
| | 6/2/2005 | 7.15 | <0.3 | -102 | 1.6 | NA | 0.6 | 73 | 341 | 4,170 | <0.815 | <0.698 |
| | 8/15/2005 | 7.00 | 0.2 | -64 | 1.6 | NA | 1.2 | 73 | 352 | 5,120 | <0.815 | <0.698 |
| | 10/19/2005 | 6.62 | 0.6 | -122 | <1.0 | NA | 0.6 | 84 | 380 | 5,460 | <0.815 | <0.698 |
| GMW-07 | 9/20/2001 | 6.87 | 1.1 | -87 | < 5.0 | 0.90 | 1.1 | 103 | 360 | 1.5 | 0.31 | 0.20 |
| | 2/12/2002 | 6.69 | 2.9 | -80 | 39 | 0.59 | NA | 57 | 440 | 5.6 | ND | ND |
| | 4/12/2002 | 7.12 | 0.2 | -102 | 20.1 | 0.43 | 9.4 | 73 | 390 | 5.5 | 0.06 | ND |
| | 7/17/2002 | NA | NA | NA | 8.7 | 0.25 | NA | 84 | 320 | 2.6 | 0.072 | 0.022 |
| | 1/28/2004 | 6.68 | 2.4 | -101 | 1.4 | 0.33 | 2.6 | 60 | 400 | 11,000 | 0.10 | 0.075 |
| | 6/2/2004 | 6.78 | 9.7 | -62 | 2.3 | 0.27 | 0.97 | 75 | 370 | 6,400 | 0.047 | 0.008 |
| | 3/1/2005 | 6.77 | <0.3 | -19 | 1.9 | NA | 1.1 | 77 | 340 | 4,700 | <0.005 | <0.005 |
| | 6/2/2005 | 7.16 | <0.3 | -64 | 2.3 | NA | 1.2 | 77 | 356 | 4,820 | <0.815 | <0.698 |
| | 8/15/2005 | 7.40 | 1.3 | -54 | 1.5 | NA | 0.80 | 76 | 344 | 1,220 | <0.815 | <0.698 |
| | 10/19/2005 | 6.74 | 0.7 | -131 | 1.4 | NA | 1.2 | 87 | 390 | 4,010 | <0.815 | <0.698 |
| GMW-08 | 9/20/2001 | 6.82 | 0.9 | -115 | < 5.0 | 0.60 | 1.6 | 91 | 380 | 0.98 | 0.19 | 0.056 |
| | 2/12/2002 | 6.79 | 2.7 | -60 | 1.6 | 0.41 | NA | 73 | 370 | 8.1 | ND | ND |
| | 4/12/2002 | 7.16 | 0.2 | -93 | ND | 0.43 | 6.8 | 79 | 340 | 9.2 | 0.073 | ND |
| | 7/16/2002 | 7.28 | 9.8 | -114 | 2.1 | 0.34 | NA | 79 | 310 | 8.3 | 0.082 | 0.007 |
| | 1/27/2004 | 6.88 | 3.0 | -119 | 1.5 | 0.33 | 2.4 | 66 | 350 | 9,800 | 0.073 | 0.11 |
| | 6/2/2004 | 6.80 | 3.8 | -91 | 2.3 | 0.31 | 2.6 | 77 | 340 | 7,000 | 0.048 | 0.006 |
| | 3/1/2005 | 6.77 | <0.3 | -58 | 2.8 | NA | 2.4 | 74 | 330 | 9,600 | <0.005 | <0.005 |
| | 6/2/2005 | 7.26 | <0.3 | -95 | 1.5 | NA | 2.0 | 73 | 338 | 4,040 | <0.815 | <0.698 |
| | 8/15/2005 | 7.40 | 1.4 | -109 | 1.6 | NA | 1.6 | 74 | 348 | 5,410 | <0.815 | <0.698 |
| | 10/19/2005 | 6.76 | 0.3 | -72 | 1.4 | NA | 2.2 | 83 | 400 | 8,450 | <0.815 | <0.698 |

**TABLE 3 (Continued)**
**SUMMARY OF GROUNDWATER GEOCHEMICAL DATA**

| Sample Location | Sample Date | pH (su)[a/] | Dissolved Oxygen (mg/L)[b/] | Redox Potential (mV)[c/] | Total Organic Carbon (mg/L) | Manganese (mg/L) | Ferrous Iron (mg/L) | Sulfate (mg/L) | Alkalinity (mg/L) | Methane (µg/L)[d/] | Ethane (µg/L) | Ethene (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GMW-09 | 9/20/2001 | 6.75 | 0.9 | -104 | < 5.0 | 0.80 | 2.28 | 93 | 360 | 1.2 | 0.28 | 0.084 |
| | 2/12/2002 | 6.64 | 3.5 | -74.8 | 22 | 0.67 | NA | ND | 560 | 13 | ND | ND |
| | 4/12/2002 | 6.95 | 0.5 | -100 | 6.5 | 0.70 | 13.2 | 2.0 | 490 | 14 | 0.036 | ND |
| | 7/16/2002 | 7.11 | < 0.1 | -139 | 2.7 | 0.45 | NA | 15 | 410 | 9.9 | 0.068 | 0.032 |
| | 1/27/2004 | 6.60 | 2.3 | -119 | 17 | 0.54 | 12 | 25 | 550 | 21,000 | 0.044 | 0.10 |
| | 6/2/2004 | 6.53 | 7.6 | -102 | 3.0 | 0.45 | >3.3 | 43 | 500 | 11,000 | 0.027 | 0.008 |
| MW-87-1 | 4/12/2001 | 6.90 | < 0.1 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| | 9/19/2001 | 6.86 | 0.8 | -74 | 60 | 0.4 | 2.3 | 115 | 290 | 4.4 | 0.15 | 0.050 |
| | 12/12/2001 | 6.64 | < 0.1 | -225 | NA | NA | NA | NA | NA | NA | NA | NA |
| | 2/14/2002 | 4.81 | 2.1 | -33 | 27 | 0.09 | NA | 53 | 340 | 5.4 | ND | ND |
| | 4/11/2002 | 6.93 | < 0.1 | -307 | 28 | 0.10 | 0.41 | 20 | 360 | 4.6 | 0.28 | 0.026 |
| | 7/18/2002 | 7.06 | NA | -336 | 11 | 0.08 | 0.07 | 46 | 340 | 5.6 | 0.05 | 0.081 |
| | 10/23/2002 | 6.58 | < 0.1 | -320 | NA | NA | NA | NA | NA | NA | NA | NA |
| | 1/16/2003 | 6.90 | 0.2 | -293 | NA | NA | NA | NA | NA | 8,600 | <0.50 | <0.50 |
| | 10/23/2003 | 6.88 | 4.3 | -338 | 3.7 J | 0.80 | 0.09 | 35 | 269 | 11,000 | 0.028 | 0.0099 |
| | 1/29/2004 | 6.87 | 3.5 | -302 | 2.8 | 0.07 | < 0.07 | 33 | 390 | 16,000 | 0.019 | 0.005 |
| | 6/3/2004 | 6.96 | 2.5 | -302 | 3.4 | 0.06 | >3.3 | 59 | 330 | 13,000 | 0.023 | 0.005 |
| | 3/3/2005 | 6.98 | <0.3 | -139 | 2.0 | NA | 1.3 | 76 | 320 | 9,800 | <0.005 | 0.069 |
| | 6/1/2005 | 7.45 | <0.3 | -269 | 1.6 | NA | 2.6 | 75 | 331 | 2,830 | <0.815 | <0.698 |
| | 8/15/2005 | 7.48 | <0.3 | -313 | 1.5 | NA | 0.90 | 81 | 312 | 5,730 | <0.815 | <0.698 |
| | 10/19/2005 | 6.89 | 0.4 | -265 | 1.4 | NA | 0.90 | 73 | 340 | 15,500 | <0.815 | <0.698 |
| MW-87-1A | 4/12/2001 | 6.80 | < 0.1 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| | 9/19/2001 | 6.43 | 1.1 | -101 | < 5.0 | 0.6 | 0.09 | 87 | 335 | 1.6 | 0.14 | 0.087 |
| | 12/12/2001 | 6.35 | < 0.1 | -165 | NA | NA | NA | NA | NA | NA | NA | NA |
| | 2/14/2002 | 4.26 | 4.0 | 162 | 3.0 | 0.072 | NA | 110 | 340 | 120 J | ND | ND |
| | 4/11/2002 | 7.07 | < 0.1 | -164 | 8.2 | 0.098 | 4.72 | 90 | 320 | 100 | 0.064 | 0.014 |
| | 7/18/2002 | 6.98 | < 0.1 | 154 | 2.2 | 0.055 | < 0.07 | 90 | 280 | 130 | 0.16 | 0.053 |
| | 10/24/2002 | 6.55 | NA | -112 | NA | NA | NA | NA | NA | NA | NA | NA |
| | 1/15/2003 | 6.90 | 0.2 | -124 | NA | NA | NA | NA | NA | 340 | <0.50 | <0.50 |
| | 10/23/2003 | 6.88 | 4.1 | -37 | 2.7 | 0.3 | 0.3 | 71 | 300 | 1,400 | 0.059 | 0.016 |
| | 1/29/2004 | 6.13 | 8.9 | -105 | 62 | 1.0 | 13.2 | 52 | 300 | 12,000 | 0.18 | 1.8 |
| | 6/3/2004 | 6.11 | 5.7 | -102 | 180 | 1.7 | >3.3 | 41 | 320 | 12,000 | 0.14 | 0.83 |

[a/] su = standard pH units.
[b/] mg/L = milligrams per liter.
[c/] mV = millivolts.
[d/] µg/L = micograms per liter.
[e/] ND = not detected.
[g/] ND = not detected.
[h/] J = estimated concentration.

**TABLE 4**
**SUMMARY OF CAHs DETECTED IN GROUNDWATER**

| Well ID | Sampling Date [e/] | PCE [a/] (µg/L) [b/] | TCE [a/] (µg/L) | cis-1,2-DCE [a/] (µg/L) | trans-1,2-DCE (µg/L) | VC [a/] (µg/L) | 1,1,1-TCA [a/] (µg/L) | 1,1-DCA [a/] (µg/L) |
|---|---|---|---|---|---|---|---|---|
| Ground Water Protection Standard (GWPS) | | 5.0 | 5.0 | 20 | 39 | 2.0 | 68 | 43 |
| GMW-01 | 9/23/2001 | <5 U [c/] | <5 U | <5 U | <5 U | <5 U | <5 U | <5 U |
| | 2/14/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 7/18/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 1/29/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/3/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/28/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 3/4/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 8/15/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/18/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| GMW-02 | 2/14/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 7/18/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 1/28/2004 | < 1 U | < 1 U | 0.49 F [d/] | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/4/2004 | < 1 U | < 1 U | 0.37 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/28/2004 | < 1 U | < 1 U | 0.47 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 3/2/2005 | < 1 U | < 1 U | 0.30 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/2/2005 | < 1 U | < 1 U | 0.23 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 8/15/2005 | < 1 U | < 1 U | 0.18 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/18/2005 | < 1 U | < 1 U | 0.21 F | < 1 U | < 1 U | < 1 U | < 1 U |
| GMW-03 | 2/13/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 7/17/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 1/28/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/3/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/27/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 3/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/2/2005 | < 1 U | < 1 U | 0.09 J | < 1 U | < 1 U | < 1 U | < 1 U |
| | 8/15/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/18/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| GMW-04 | 2/13/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 7/17/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 1/28/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/4/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/27/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 3/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 8/15/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/18/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| GMW-05 | 2/13/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 0.18 J |
| | 7/17/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 1/28/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/2/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 8/24/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/27/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 3/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 0.06 J |
| | 8/15/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/18/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U |
| GMW-06 | 9/23/2001 | <5 U | <5 U | <5 U | <5 U | <5 U | 23 | 32 |
| | 2/13/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 36 | **46** |
| | 7/17/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 65 | **56** |
| | 1/28/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 48 | 32 |
| | 6/3/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 60 | 30 |
| | 10/27/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | **76** | **51** |
| | 3/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 28 | 18 |
| | 6/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 25 | 17 |
| | 8/15/2005 | < 1 U | < 1 U | 0.08 F | < 1 U | < 1 U | 26 | 19 |
| | 10/19/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 29 F | 25 |

**TABLE 4 (Continued)**
**SUMMARY OF CAHs DETECTED IN GROUNDWATER**

| Well ID | Sampling Date [e/] | PCE [a/] (µg/L) [b/] | TCE [a/] (µg/L) | cis-1,2-DCE [a/] (µg/L) | trans-1,2-DCE (µg/L) | VC [a/] (µg/L) | 1,1,1-TCA [a/] (µg/L) | 1,1-DCA [a/] (µg/L) |
|---|---|---|---|---|---|---|---|---|
| Ground Water Protection Standard (GWPS) | | 5.0 | 5.0 | 20 | 39 | 2.0 | 68 | 43 |
| GMW-07 | 9/23/2001 | <5 U | <5 U | <5 U | <5 U | <5 U | 5.7 | 39 |
| | 2/12/2002 | < 1 U | < 1 U | 7.8 | < 1 U | < 1 U | 9.6 | **49** |
| | 4/12/2002 | < 1 U | < 1 U | 6.8 | < 1 U | < 1 U | 15 | **57** |
| | 7/17/2002 | < 1 U | < 1 U | 1.5 | < 1 U | < 1 U | 21 | **53** |
| | 1/28/2004 | < 1 U | < 1 U | 6 | < 1 U | 0.26 F | 7.4 | **43** |
| | 6/2/2004 | < 1 U | < 1 U | 3.5 | < 1 U | < 1 U | 8.1 | 32 |
| | 10/27/2004 | < 1 U | < 1 U | 2.2 | < 1 U | 0.39 F | 19 F | **85** |
| | 3/1/2005 | < 1 U | < 1 U | 2.8 | < 1 U | < 1 U | 12 | 35 |
| | 3/1/2005 | < 1 U | < 1 U | 2.8 | < 1 U | < 1 U | 12 | 35 |
| | 6/2/2005 | < 1 U | < 1 U | 1.2 | < 1 U | < 1 U | 6 | 24 |
| | 8/15/2005 | < 1 U | < 1 U | 0.13 F | < 1 U | < 1 U | 11 | 31 |
| | 10/19/2005 | < 1 U | < 1 U | 1.2 | < 1 U | < 1 U | 14 | **51 F** |
| GMW-08 | 9/23/2001 | <5 U | <5 U | <5 U | <5 U | <5 U | <5 U | **68** |
| | 2/12/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | **47** |
| | 4/12/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 29 |
| | 7/16/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 12 |
| | 1/27/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 5.6 |
| | 6/2/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 3.5 |
| | 10/26/2004 | < 1 U | < 1 U | 0.22 J | < 1 U | < 1 U | < 1 U | 24 |
| | 3/1/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 4.7 |
| | 6/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 3.7 |
| | 8/15/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 11 |
| | 10/19/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 20 |
| GMW-09 | 9/23/2001 | <5 U | <5 U | 1.1 J | <5 U | <5 U | <5 U | 11 |
| | 2/12/2002 | < 1 U | < 1 U | 0.65 J | < 1 U | < 1 U | < 1 U | 7.9 |
| | 4/12/2002 | < 1 U | < 1 U | 0.59 J | < 1 U | < 1 U | < 1 U | 5.8 |
| | 7/16/2002 | < 1 U | < 1 U | 1.7 | < 1 U | < 1 U | < 1 U | 6.6 |
| | 1/27/2004 | < 1 U | < 1 U | **89** | < 1 U | 1.0 | < 1 U | 6.6 |
| | 6/2/2004 | < 1 U | < 1 U | **79** | < 1 U | 1.0 | < 1 U | 5.9 |
| | 10/26/2004 | < 1 U | < 1 U | **76** | < 1 U | < 1 U | < 1 U | 16 |
| | 3/1/2005 | < 1 U | < 1 U | **37** | < 1 U | < 1 U | < 1 U | 11 |
| | 6/2/2005 | < 1 U | < 1 U | **32** | < 1 U | 0.58 F | < 1 U | 8.5 |
| | 8/16/2005 | < 1 U | < 1 U | **27** | < 1 U | 0.22 F | < 1 U | 12 |
| | 10/19/2005 | < 1 U | < 1 U | **30** | < 1 U | < 1 U | < 1 U | 21 |
| MW-87-1 | 4/12/2001 | **150** | 1.3 | 3.3 | 0.58 F | < 1.1 U | 3.2 | 0.69 |
| | 9/23/2001 | **180** | 1.1 F | 1.5 F | <5 U | <5 U | 3.9 F | <5 U |
| | 12/12/2001 | 0.7 F | < 1 U | 0.28 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 2/14/2002 | **25** | 0.2 F | 4.9 | < 1 U | 0.19 F | 0.76 F | 0.33 F |
| | 4/11/2002 | 1.3 | < 1 U | 2.8 | < 1 U | 0.32 F | < 1 U | < 1 U |
| | 7/18/2002 | 0.24 F | < 1 U | 2.1 | < 1 U | 0.3 F | < 1 U | < 1 U |
| | 10/23/2002 | < 1 U | < 1 U | 2.1 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 5/15/2003 | < 1 U | < 1 U | 1.3 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/23/2003 | 0.95 F | < 1 U | 3.9 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 1/29/2004 | 0.24 F | < 1 U | 3.1 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/3/2004 | < 1 U | < 1 U | 0.94 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 8/25/2004 | < 1 U | < 1 U | 2 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 10/28/2004 | 0.16 F | < 1 U | 1.8 | < 1 U | < 1 U | < 1 U | < 1 U |
| | 3/3/2005 | < 1 U | < 1 U | 0.50 F | < 1 U | < 1 U | < 1 U | < 1 U |
| | 6/1/2005 | **33 F** | 0.27 F | 4.2 | < 1 U | < 1 U | 1.5 | 0.42 F |
| | 8/16/2005 | **29** | 0.28 F | 6.7 | < 1 U | < 1 U | 1.7 | 0.44 F |
| | 10/19/2005 | **16** | < 1 U | 12 | < 1 U | < 1 U | 0.96 F | 0.37 F |

**TABLE 4 (Continued)**
**SUMMARY OF CAHs DETECTED IN GROUNDWATER**

| Well ID | Sampling Date [e/] | PCE [a/] (µg/L) [b/] | TCE [a/] (µg/L) | cis-1,2-DCE [a/] (µg/L) | trans-1,2-DCE (µg/L) | VC [a/] (µg/L) | 1,1,1-TCA [a/] (µg/L) | 1,1-DCA [a/] (µg/L) |
|---|---|---|---|---|---|---|---|---|
| Ground Water Protection Standard (GWPS) | | 5.0 | 5.0 | 20 | 39 | 2.0 | 68 | 43 |
| MW-87-1A | 4/12/2001 | **1200** | **9.3** | **34** | 5.1 | < 1.1 U | **170** | 26 |
| | 9/23/2001 | **1300** | **13** | **46** | 7.0 | <5 U | **150** | 31 |
| | 12/12/2001 | **1200** | **13** | **39** | 6.4 | < 1 U | **200** | 40 |
| | 2/14/2002 | **740** | **7.7** | **32** | 4.2 | < 1 U | **160** | 25 |
| | 4/11/2002 | **1200** | **17** | **110** | 4.6 | < 1 U | **170** | 21 |
| | 7/18/2002 | **1500** | **13** | **40** | 5.1 | < 1 U | **230** | 25 |
| | 10/24/2002 | **1100** | **39** | **260** | 6.4 | 0.51 F | **92** | 29 |
| | 5/15/2003 | **1200** | **13** | **76** | 4.2 | < 1 U | **200** | 25 |
| | 10/23/2003 | **1000** | **19 F** | **150** | 3.5 F | 0.33 F | **160** | 26 |
| | 1/29/2004 | **190** | **38 F** | **1000** | 3.1 | **38 F** | **70 F** | 25 F |
| | 6/3/2004 | **250** | **47 F** | **2000** | 4.5 | **75** | **100** | 37 F |
| | 10/28/2004 | **130** | **51** | **1900** | 11 | **28** | 39 | **51** |
| | 3/3/2005 | **62** | **12 F** | **1400** | < 50 U | < 50 U | 54 | **59** |
| | 6/2/2005 | **270** | **28** | **880** | 6.8 F | **4.8 F** | 18 | 18 |
| | 8/16/2005 | **87** | **17 F** | **1500** | 4.6 F | **9.9 F** | 11 F | 20 F |
| | 10/19/2005 | **59** | **14** | **2000 F** | 6.8 | **19** | 13 | 32 |
| MW-87-3 | 4/11/2001 | < 1.4 U | < 1 U | 2.3 | < 0.6 U | < 1.1 U | < 0.8 U | 8.5 |
| | 12/12/2001 | < 1 U | < 1 U | 0.18 J | < 1 U | < 1 U | < 1 U | 10 |
| | 4/11/2002 | < 1 U | < 1 U | 0.2 J | < 1 U | < 1 U | < 1 U | 8.5 |
| | 10/23/2002 | < 1 U | < 1 U | 0.26 J | < 1 U | < 1 U | < 1 U | 10 |
| | 5/15/2003 | < 1 U | < 1 U | 0.37 J | < 1 U | < 1 U | < 1 U | 8.5 |
| | 10/22/2003 | < 1 U | < 1 U | 1.1 | < 1 U | < 1 U | < 1 U | 8.2 |
| | 6/2/2004 | < 1 U | < 1 U | 1.2 | < 1 U | < 1 U | < 1 U | 11 |
| | 10/26/2004 | < 1 U | < 1 U | 0.37 J | < 1 U | < 1 U | < 1 U | 14 |
| | 6/2/2005 | < 1 U | < 1 U | 22 J | 0.22 J | 0.31 J | < 1 U | 12 |
| | 10/19/2005 | < 1 U | < 1 U | 0.71 J | < 1 U | < 1 U | < 1 U | 19 |
| MW-87-4 | 4/11/2001 | < 1.4 U | < 1 U | < 1.2 U | < 0.6 U | < 1.1 U | < 0.8 U | 2 |
| | 12/12/2001 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 2 |
| | 4/11/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 4.1 |
| | 10/23/2002 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 2.4 |
| | 5/15/2003 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 1.1 |
| | 10/22/2003 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 1.3 |
| | 6/2/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 0.72 J |
| | 10/26/2004 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 0.98 J |
| | 6/2/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 0.47 J |
| | 10/18/2005 | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | < 1 U | 0.67 J |

Note: values that exceed respective GWPS have been bolded.

[a/] PCE = tetrachloroethene; TCE = trichloroethene; DCE = dichloroethene; VC = vinyl chloride; TCA = trichloroethane; DCA = dichloroethane.

[b/] µg/L = micrograms per liter.

[c/] < 1 U indicates that the subject compound was not detected at a concentration above the method detection limit.

[d/] F-flag indicates that the concentration is estimated.

Elevated concentrations of 1,1,1-TCA and 1,1-DCA persisted in the upper sand unit following the Phase I injection at MW-87-1A, and at downgradient monitoring locations GMW-06 through GMW-09 (Table 4). The maximum concentration of 1,1,1-TCA following the Phase I injection was 230 µg/L at location MW-87-1A in July 2002; and the maximum concentration of 1,1-DCA was 85 µg/L at GMW-07 in October 2004.

### 5.1.3 Phase I Summary

During the Phase I injection, emulsified vegetable oil was injected into the upper sand unit through wells SIW-04, SIW-05, and SIW-06, screened from approximately 17 to 20 feet bgs. Observations from groundwater monitoring of wells screened in the upper sand unit indicated that vegetable oil was present at location GMW-06 in February 2002, and at location GMW-07 in January 2003, as indicated by the presence of emulsion or free-phase vegetable oil in the well casing. However, concentrations of total organic carbon (TOC) indicated that elevated levels of organic carbon in groundwater (greater than 30 mg/L) occurred at location GMW-06 only in April 2002, and at location GMW-07 only in February and April 2002 (Table 3). Therefore, the presence of substrate downgradient of the upper sand unit injection wells following the Phase I injection appeared to be limited in lateral extent and inconsistent over time.

A notable exception to the presence of elevated levels of organic carbon after the Phase I injection is location MW-87-1A, also screened in the upper sand unit. While oil emulsion was observed at MW-87-1A during the monitoring event in November 2001, concentrations of TOC have never exceeded 10 mg/L at this location. It is apparent that elevated levels of organic carbon did not migrate from the injection area to this location to the degree anticipated. MW-87-1A is located approximately 8 to 10 feet cross-gradient from shallow injection wells SIW-04 and SIW-06, and approximately 18 feet downgradient from shallow injection well SIW-05. The theoretical radius of influence of the injected emulsion for the shallow injection wells was approximately 4.6 feet (Parsons, 2002). Thus, MW-87-1A was located outside of the immediate injection area and the effective Phase I treatment zone.

As of October 2003, the enhanced bioremediation application at Site FF-87 had achieved performance objectives for all but one monitoring location in the upper sand unit. PCE remained above cleanup criteria at well MW-87-1A. Performance objectives have been met in the lower silt unit.

While elevated levels of TOC and metabolic acids (data not shown) were observed at many monitoring locations following the Phase I injection, there was an apparent lack of both substrate and evidence of enhanced microbial activity at upper sand unit well MW-87-1A, located immediately downgradient of the injection area. The lack of adequate substrate distribution appears to be the cause for persistence of PCE in the upper sand unit at this location. Although analytical and geochemical data suggested that that some reductive dechlorination was beginning to occur at MW-87-1A, a compelling argument could not be made that performance criteria would be met at this location. Therefore, a Phase II injection was conducted during which additional vegetable oil substrate was injected into the upper sand unit in the vicinity of well MW-87-1A.

## 5.2 Phase II Results

### 5.2.1 Geochemistry

Following the Phase II injection, concentrations of TOC measured in monitoring well MW-87-1A increased from a pre-injection concentration of less than 5.0 mg/L to a maximum concentration of 180 mg/L. During the same time, DO concentrations decreased from a pre-injection concentration of 4.1 mg/L to less than 0.1 mg/L and ORP decreased from -37 mV to -206 mV. These trends indicate that the area around MW-87-1A was impacted by the Phase II injection, and that groundwater geochemical conditions became more strongly reducing. After the Phase II injection, concentrations of ferrous iron and methane increased while concentrations of sulfate decreased, indicating that iron reduction, methanogenesis, and sulfate reduction were TEAPs stimulated by the injected substrate at this location. Geochemical data collected from the entire FF-87 monitoring well network following the Phase II injection indicates that the Phase II injection primarily impacted the area in the vicinity of MW-87-1A, as designed.

### 5.2.2 Changes in CAH Concentrations Over Time

Within approximately 3 months following the Phase II injection, the concentration of PCE at MW-87-1A decreased from a pre-injection concentration of 1,000 µg/L to 190 µg/L (Figure 3). During the same time, the concentration of TCE remained relatively stable at approximately 20 to 30 µg/L; the concentration of *cis*-1,2-DCE increased from 150 µg/L to 1,000 µg/L; and the concentration of VC increased from 0.33F µg/L to 38F µg/L (F-flag indicates estimated concentrations). These data indicate that reductive dechlorination of PCE and TCE proceeded to at least VC at MW-87-1A within the first 3 months following the Phase II injection. Between January 2004 and March 2005, concentrations of PCE and TCE continued to decrease while the concentrations of *cis*-1,2-DCE and VC peaked and then started to decline.

However, during the March and June 2005 sampling events the concentrations of PCE and TCE increased significantly. The March and June 2005 data sets correspond with high groundwater table elevations across the site, suggesting that the observed increase in parent compound concentrations may be due to the dissolution of contaminant mass from the soil matrix in the capillary fringe or vadose zone. During subsequent sampling events, concentrations of PCE and TCE decreased while concentrations of *cis*-1,2-DCE and VC concentrations increased, indicating that the mass of PCE/TCE that was added to the groundwater system during periods of high groundwater elevations is being dechlorinated. Figure 4 is a plot of groundwater elevation and TCE concentrations over time at MW-87-1A. Inspection of this plot indicates that in four instances a peak in the concentration of PCE was immediately preceded by a peak in the groundwater table elevation.

Concentrations of 1,1,1-TCA at well location MW-87-1A decreased after the Phase II injection, from 160 µg/L in October 2003 (just prior to the Phase II injection) to 13 µg/L in October 2005 (Table 4). The concentration of 1,1,1-DCA initially increased from 26 µg/L in October 2003 to 59 µg/L in March 2005, before decreasing to a range of 18 to 32 µg/L from June to October 2005. Only low levels of chloroethane (CA) have been observed at less than 6.0 µg/L (data not shown), indicating that transformation of 1,1,1-TCA to 1,1,1-DCA has been stimulated by substrate addition, but that transformation of 1,1-DCA to CA appears to be limited. As of March 2005, concentrations of 1,1,1-TCA did not exceed its respective GWPS at any monitoring location, while concentrations of 1,1-DCA only exceeded its respective GWPS at location GMW-07.

**FIGURE 3: CONCENTRATIONS OF CHLORINATED ETHENES AT DOWNGRADIENT LOCATION MW-87-1A**

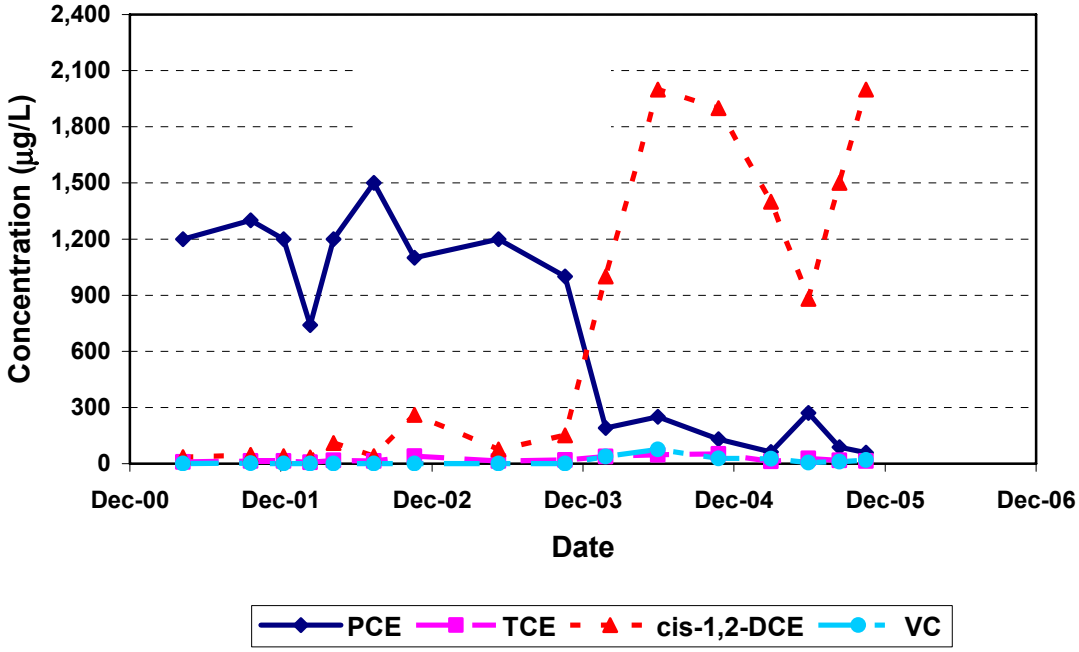
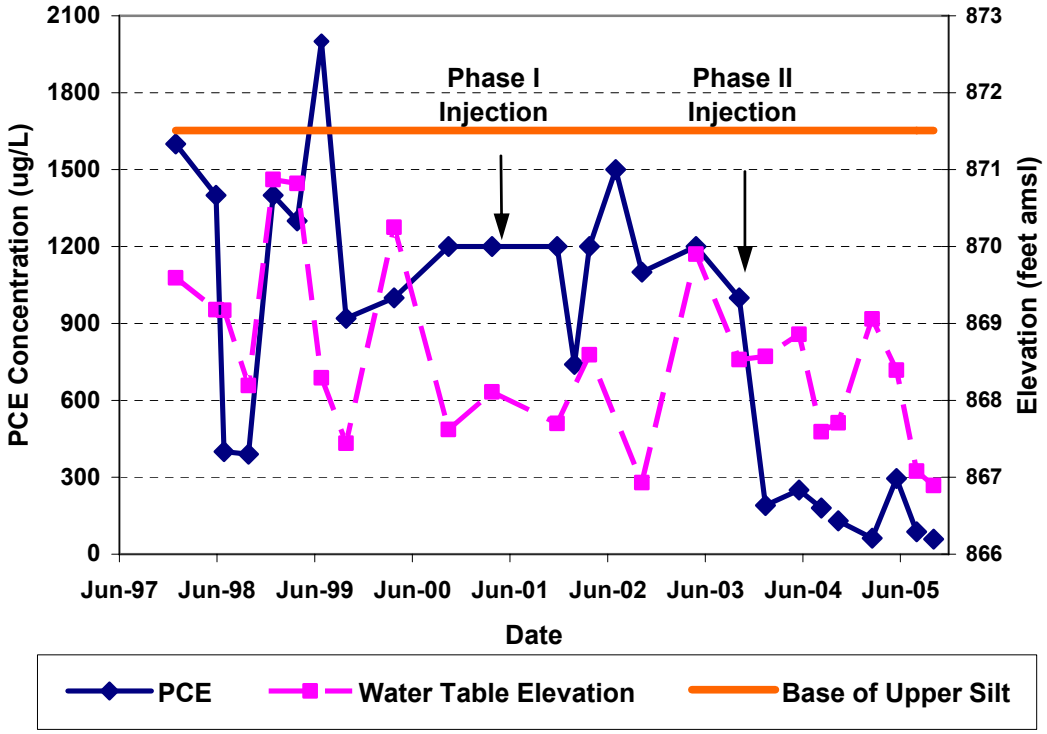



**FIGURE 4: CONCENTRATION OF PCE AND GROUNDWATER ELEVATION OVER TIME AT MONITORING WELL MW87-1A**



## 6.0 TECHNOLOGY COSTS

The capital/startup and operating costs for the FF-87 application are presented in Table 5. The total capital costs associated with the Phase I test were approximately $79,600. This includes approximately $9,800 that was spent on a work plan and mobilization costs, approximately $14,100 for well installation by a local drilling subcontractor, and approximately $2,400 for the vegetable oil substrate. The capital cost also includes approximately $15,900 that was spent to prepare a project construction report immediately after the installation activities were completed.

**TABLE 5. TECHNOLOGY DEMONSTRATION COSTS**

| **Element Cost** | | |
|---|---|---|
| **Capital Cost** | | |
| | Phase I | Phase II |
| Work Plan and Mobilization | $9,800 | $8,600 |
| Travel and Subsistence | $8,600 | $6,100 |
| Site Labor | $10,000 | $5,300 |
| Equipment and Appurtenances<br>-Injection/monitoring well installation<br>-Expendable Materials Purchase<br>-Substrate (vegetable oil, delivered)<br>-Injection Equipment Rental<br>-Monitoring equipment and supplies<br>-IDW Disposal | <br>$14,100<br>$1,400<br>$2,400<br>$2,800<br>$8,400<br>$0 | <br>$4,600<br>$1,100<br>$1,900<br>$1,200<br>$6,900<br>$1,600 |
| Baseline Laboratory Analyses | $5,600 | $5,100 |
| Surveying | $600 | $0 |
| Project Completion Report | $15,900 | $9,900 |
| **Total Capital Costs** | **$79,600** | **$52,300** |
| **Operating Costs (Performance Monitoring)[a/]** | | |
| Mobilization/Demobilization/Per Diem | $2,200 | |
| Direct Labor (Performance Monitoring) | $9,000 | |
| Sampling Equipment and Supplies | $2,500 | |
| Laboratory Analysis | $5,600 | |
| Project Management/ Procurement | $1,500 | |
| **Operating Costs per Event**<br>($228,800 for 11 events over 49 months**)** | **$20,800** | |

[a/] Performance monitoring was conducted by the Base contractor. Monitoring Costs are estimated.

The capital cost for the Phase II injection was approximately $52,300, which is significantly less than the capital cost associated with the Phase I injection. The primary differences between the two was that the Phase I project included the installation of nine groundwater monitoring wells and six injection wells, while the Phase II project included the installation of only four temporary direct-push injection points. The cost savings were realized through a large reduction in subcontractor costs and site labor.

The total operating cost to date for the FF-87 pilot testing program is $228,800. This only includes costs associated with performance monitoring. Annual reporting costs are not included because the pilot test results are documented in annual site inspection and monitoring reports as part of a larger restoration program. The FF-87 operating cost consists of 11 sampling events over approximately 4 years of monitoring ($20,800 per event). The sampling frequency for the FF-87 application was specified by the regulatory agencies involved, and is more frequent than a typical semi-annual frequency that is applied to many enhanced bioremediation applications.

## 7.0 SUMMARY OBSERVATIONS

The injection of vegetable oil has stimulated anaerobic conditions conducive for the reductive dechlorination of chlorinated ethenes (PCE, TCE, DCE, and VC) in groundwater at FF-87. The Phase I application successfully enhanced CAH degradation at MW-87-1, resulting in significant decreases in CAH concentrations at this location without the accumulation or migration of regulated dechlorination products (*e.g.*, VC). The reaction area established during the Phase I injection did not impact the aquifer in the vicinity of well MW-87-1A. As a result, CAH concentrations in well MW-87-1A remained relatively unchanged through the Phase I monitoring period. The Phase II injection was conducted to expand the treatment area to include the area around well MW-87-1A.

Within approximately 3 months of the Phase II injection, concentrations of PCE at MW-87-1A decreased by approximately 80 percent, while concentrations of *cis*-1,2-DCE, VC, and ethene increased substantially. During this time, the molar fraction of the parent compounds (PCE and TCE) decreased while the molar fractions of the dechlorination products (*cis*-1,2-DCE, VC, and ethene) increased. These trends in contaminant concentration and molar fractions indicate that a completed dechlorination pathway from PCE to ethene was stimulated at MW-87-1A as a result of the Phase II injection.

Since January 2004, concentrations of PCE have continued to decline while TCE, *cis*-1,2-DCE and VC concentrations have peaked and then declined. There have been several temporal increases in PCE concentration, followed by temporal increases in TCE, *cis*-1,2-DCE, and VC. These CAH concentration spikes are preceded by increases in groundwater elevation, indicating that PCE mass is being added to the system, likely from a residual contaminant source located in soils within the capillary fringe or vadose zone. This continuing source of PCE may skew the results of the demonstration in that more PCE mass has been degraded than was initially present within the saturated treatment zone. This also results in occasional increases in concentrations of dechlorination products. This previously unrecognized source of sorbed contaminant mass may continue to release PCE to the aqueous phase during times of high water table elevations.

## 8.0 CONTACT INFORMATION

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## 9.0 REFERENCES

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