COST AND PERFORMANCE REPORT

Electrical Resistive Heating at the
Charleston Naval Complex Site
Charleston, South Carolina

June 2005

SITE INFORMATION

IDENTIFYING INFORMATION [3]

Site Name: Charleston Naval Complex (CNC), Area of Concern (AOC) 607
Location: Charleston, South Carolina
Regulatory Context: Resource Conservation and Recovery Act (RCRA)
Technology: Electrical Resistive Heating (ERH)
Scale: Full-Scale

TECHNOLOGY APPLICATION [3]

Period of Operation: ERH system operation occurred over 9 months from October 2001 to July 2002.

Type/Quantity of Material Treated during Application:

The target treatment area (TTA) occupied approximately 4,300 cubic yards, based on a 7-foot that extended over 16,525 square feet (ft^2). The saturated zone extended from 4 to 11 feet below ground surface (bgs). The total mass of PCE and CVOCs recovered during ERH system operation was calculated at 234 and 247 pounds, respectively. The TTA was defined by groundwater bearing total CVOCs at concentrations exceeding 2,000 micrograms per liter (µg/L).

BACKGROUND [3]

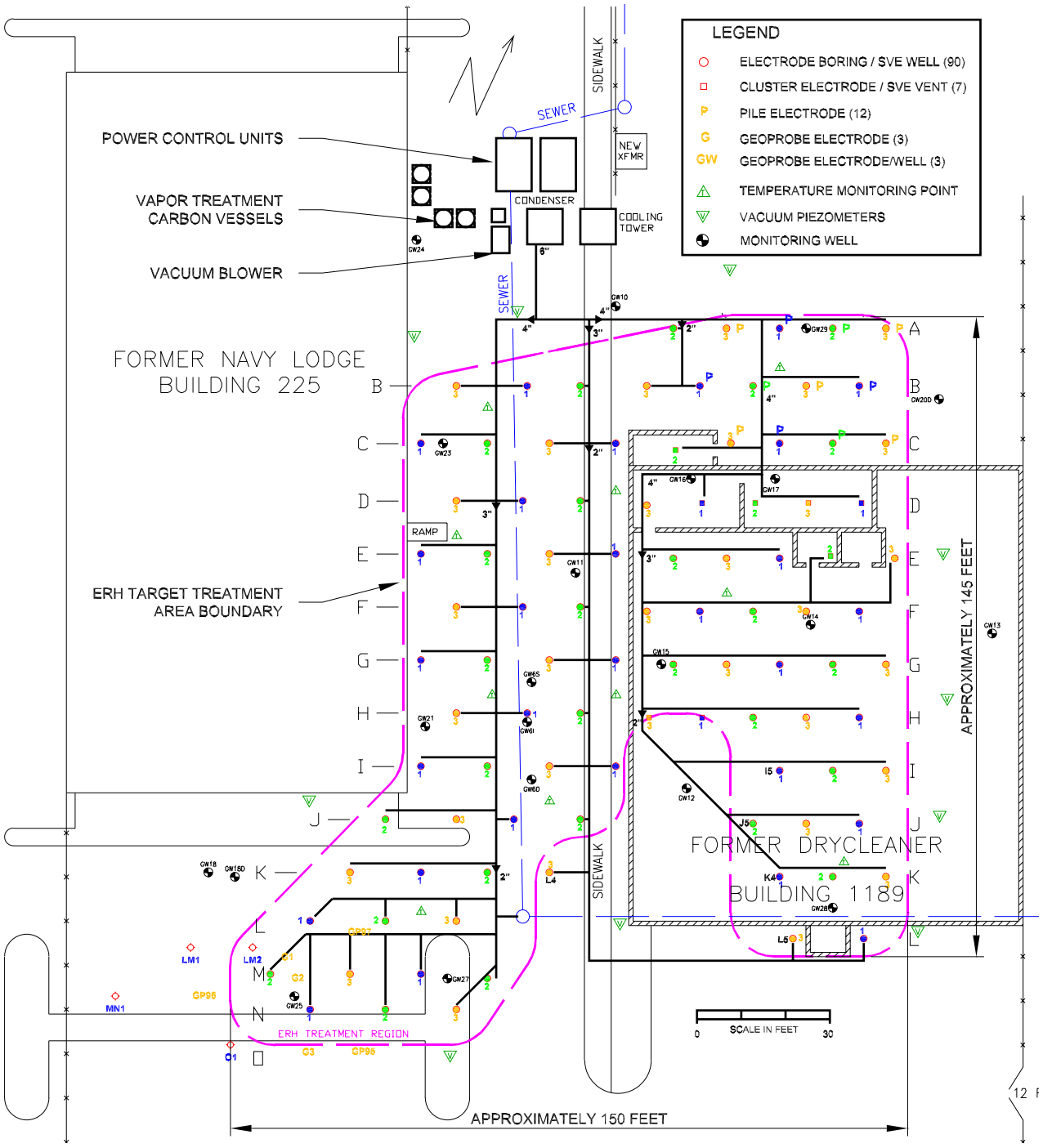
The CNC was formed as a result of the disestablishment of the Charleston Naval Shipyard and Naval Base on April 1, 1996.

AOC 607 contained a former dry cleaning facility, Building 1189 (see Figure 1), that supported the former local seamen's housing units from 1942 to 1986. Toward the end of its operational period, the dry cleaning facility was used as a general purpose laundry and had two industrial washers and dryers.

Tetrachloroethene (PCE), a typical dry cleaning solvent, was one of the primary materials used, stored, disposed of, and accidentally released at the site. A RCRA facility investigation conducted in 1996 and 1997 revealed dissolved-phase CVOCs in the saturated zone, including PCE; trichloroethene (TCE); cis-1,2-dichloroethene (cis-1,2-DCE); 1,1-dichloroethene (1,1-DCE); and vinyl chloride (VC). In addition, PCE in the form of a dense nonaqueous-phase liquid (DNAPL) appeared to have migrated into the shallow saturated zone.

This report discusses an interim measure (IM) conducted to address the DNAPL contamination in the shallow saturated zone as part of a RCRA corrective measure.

Figure 1. Layout of AOC 607 [1]



Note: Figure modified from original

CONTACTS

U.S. Environmental Protection Agency (EPA) Region 4
Mr. Dann Spariosu
61 Forsyth Street, S.W.
Atlanta, Georgia 30303-8960
Telephone: (404) 562-8552
E-mail: spariosu.dann@epa.gov

Owner's Contractor
CH2M Hill
Mr. Dean Williamson, P.E.
Telephone: (352) 335-7991
E-mail: dean.williamson@ch2m.com

South Carolina Department of Health and Environmental Control
Bureau of Land and Waste Management
Mr. David Scaturo
2600 Bull Street
Columbia, South Carolina 29201
Telephone: (803) 896-4185
E-mail: scaturdm@dhec.sc.gov

Technology Vendor
Thermal Remediation Services, Inc.
Mr. Greg Beyke, P.E.
Telephone: (615) 791-5772
E-mail: gbeyke@thermalrs.com

MATRIX DESCRIPTION

MATRIX AND CONTAMINATION IDENTIFICATION [3]

Type of Media Treated with Technology System: Groundwater

Primary Contaminant Groups: CVOCs (PCE; TCE; cis-1,2-DCE; 1,1-DCE; and VC)

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [3]

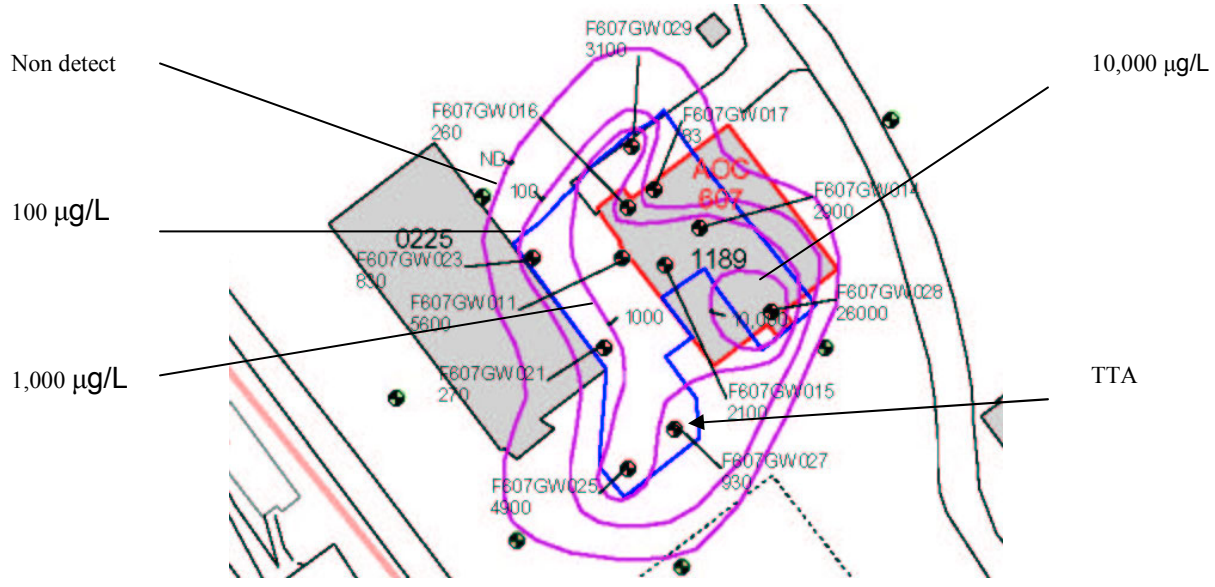
The subsurface geology consists of varying amounts of fill material to depths of up to approximately 5 feet bgs. The fill is underlain by undifferentiated Quaternary age sands, silts, and clays of the Wando Formation to approximately 20 to 25 feet bgs. These deposits consist of discontinuous clay layers and lensatic sands in many locations and have many minor, alternating interbeds of 1 foot or less in thickness. The Quaternary deposits are underlain by undifferentiated Tertiary age marine silt. The marine silt at the site varies in thickness from 10 to 20 feet.

The local hydrogeology consists of an unconfined aquifer system. The unconfined aquifer varies in total thickness from approximately 21 to 35 feet. The depth to groundwater is typically 4 to 5 feet bgs.

The hydraulic conductivity of the aquifer was measured as 0.44 foot per day (ft/day) on average. Groundwater flow velocities were found to average approximately 0.01 ft/day, or generally less than 5 ft per year. Table 1 lists matrix characteristics.

PCE appears to have migrated downward as a DNAPL through fill and shallow subsurface soil until it encountered a clay unit at approximately 10 to 11 feet bgs. The PCE DNAPL appears to have accumulated on top of and within the clay layer, which provides a continuing source for the dissolved-phase chlorinated solvents detected in the shallow groundwater. Figure 2 presents the extent of PCE contamination; PCE was not detected beyond the outermost contour.

Figure 2. Extent of Contamination [3]



Notes: Figure not to scale; PCE concentrations in µg/L

Table 1. Matrix Characteristics [3]

Parameter	Value
Soil Classification	Quaternary age sands, silts, and clays
Clay Content and/or Particle Size Distribution	Not available
Depth to Groundwater	4 to 5 feet bgs
Hydraulic Conductivity	0.44 ft/day
Air Permeability	Not available
Porosity	Not available
Presence of Nonaqueous-Phase Liquid	DNAPL present
Moisture Content	Saturated
Total Organic Carbon	Not available
Electrical Resistivity of Soil	Not available

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY [3]

ERH: Six-Phase Heating™

TREATMENT SYSTEM DESCRIPTION AND OPERATION [3, 4, 6]

The use of ERH technology during the IM for AOC 607 focused on the saturated zone above the existing clay unit that underlies the site at an approximate depth of 10 to 11 feet bgs. The remediation system included an ERH system for subsurface heating, a soil vapor extraction (SVE) system for vapor recovery, and an aboveground treatment system to process vapor and liquid wastes generated by SVE. Figure 1 presents the TTA and the layout of the remediation system.

The ERH and SVE systems were constructed between August and October 2001. The ERH system was designed to heat the contaminated saturated zone to the boiling point of PCE under hydrostatic pressure (89 °C at 7 feet bgs and 92 °C at 11 feet bgs). ERH was focused on the interface between the clay and sand units where the bulk of the contamination was believed to exist. The ERH system consisted of two 500-kilowatt (kW) power control units (PCU) operating

101 electrodes. Each PCU operated approximately half the total number of electrodes. The electrodes were installed to a depth of approximately 10 to 10.5 feet bgs with a lateral spacing of approximately 14 feet.

The SVE system was constructed in the vadose zone to collect steam and volatilized contaminants generated by ERH in the underlying saturated zone. Extracted vapor was processed in aboveground vapor treatment systems that included a condenser (to remove water vapor), a cooling tower (to cool condensate), and granular activated carbon (GAC) adsorption units (to treat dry vapor prior to its atmospheric release). Liquid-phase treatment was not used because concentrations of contaminants in the effluent from the cooling tower were below permissible levels.

ERH system operation occurred over 9 months from October 2001 to July 2002. PCU 1 began operating in the more contaminated "southern" portion of the TTA on October 3, 2001. PCU 2 began operating in the "northern" portion of the TTA, which included the asphalt parking area outside Buildings 1189 and 225 (see Figure 1), on December 13, 2001.

Treatment was originally anticipated to take 4 months. However, the drying of saturated soil in the high-temperature zones around each electrode reduced the soil's electrical conductivity and made it less conducive to ERH. Various improvements were made to the ERH system from October 2001 to April 2002. The improvements included modification of electrode spacing as discussed below.

A total of 244 ¾-inch-diameter ground rods were installed to a depth of approximately 10 feet bgs in order to decrease the lateral electrode spacing from about 14 to 7 feet. A total of 66 additional ground rods were installed to a depth of 12 feet bgs in order to ensure heating of the most contaminated zone approximately 11 feet bgs. Six 2-inch-diameter Geoprobe electrodes were installed in the southwestern portion of the site. Of these, three were installed with a 2-foot well screen (to allow groundwater monitoring) and were placed at an approximate depth of 9.5 to 11.5 feet bgs. The other three electrodes were installed without the screen. Four electrodes were installed in the southwestern portion of the site, extending the treatment area 19 feet beyond its former western boundary. The expansion was necessary because of the high concentrations of CVOCs detected in that area.

From April 15 to May 15, 2002, the entire ERH system operated using 101 electrodes, 12 8-inch-diameter steel piles, six Geoprobe electrodes, and 310 ¾-inch-diameter ground rods. To optimize performance, both PCUs were cycled with 50 minutes of operation followed by 10 minutes of shutdown to allow "re-wetting" of the electrodes and prevent drying of soils close to the electrodes.

To further optimize performance during the last 2 months of system operation and to cease power application in areas of low-level contamination (that is, less than 500 µg/L of total CVOCs), PCU 1 was removed from service on May 16, 2002. The TTA was heated for the rest of the project using PCU 2. Elimination of PCU 1 resulted in the disconnection of 34 electrodes and 70 ground rods in the "northern" part of the TTA.

The average weekly power input during the 9-month period of ERH system operation was approximately 278 kW. A maximum power input of 520 kW occurred during the week immediately following the startup of PCU 2. The ERH system was shut down on July 8, 2002.

Following completion of the ERH IM in July 2002, TTA monitoring continued until March 2004.

Pilot Study of In Situ Bioremediation Using Enhanced Reductive Dechlorination [2]

From June to December 2004, a pilot study of enhanced reductive dechlorination (ERD) was performed using lactate injections in two wells. ERD was conducted at the pilot scale to gather information about the effectiveness of lactate as a substrate for native microorganisms as well as to determine the ability of these microorganisms to degrade the contaminants of concern (COC). The ERD pilot test further reduced COC concentrations in the TTA. A summary of the ERD pilot test is presented in Appendix A.

TIMELINE [3]

- August to October 2001: construction of ERH system
- September 2001: ERH system testing and first IM groundwater sampling event
- October 3, 2001: commencement of PCU 1 operation in more contaminated "southern" portion of TTA
- October 2001: commencement of ERH system improvement and expansion
- December 13, 2001: commencement of PCU 2 operation in "northern" portion of TTA
- April 2002: completion of ERH system improvement and expansion
- April 15 to May 15: operation of entire (PCU 1 and PCU 2) ERH system
- May 16, 2002: shutdown of PCU 1 in "southern" portion of TTA
- July 8, 2002: shutdown of entire ERH system because of continuing decrease in PCE recovered
- January 2003: final IM groundwater sampling event
- September 11, 2003: IM completion report submitted
- March 2004: completion of post-ERH monitoring
- June to December 2004: ERD pilot study (see Appendix A)

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [3, 5]

The objectives of the IM were to remove CVOC DNAPL present in the aquifer to the maximum extent practicable, thereby reducing the DNAPL's potential to act as a continuing source for dissolved-phase contamination, and to achieve a 95 percent reduction in the average dissolved-

phase PCE concentration in shallow groundwater. The exact quantity of DNAPL present in the subsurface was not known, and there was no quantifiable target for DNAPL removal.

TREATMENT PERFORMANCE [3, 4, 5]

Fourteen monitoring wells in the TTA were sampled in September 2001 prior to ERH system startup. These wells were then sampled monthly from February 2002 until system shutdown in July 2002. These wells were sampled again in January 2003, or 6 months after system shutdown. In addition, six monitoring wells in the "southern" portion of the TTA were sampled in January 2002. Perimeter groundwater monitoring was conducted to monitor CVOC concentrations in the peripheral areas outside the TTA. Figure 3 shows the CVOC and PCE plumes before and after ERH treatment. This figure indicates that ERH resulted in a decrease in the areas of the plumes and a decrease in the number of high-concentration zones. Figure 4 shows the size of the PCE plume during and after treatment.

The ERH system was shut down before achievement of the targeted 95 percent reduction in the average dissolved-phase PCE concentration. The system was shut down because PCE recovery rates had become relatively insignificant and dissolved-phase PCE concentrations did not show an appreciable reduction.

In March 2004 (22 months after ERH system shutdown), the monitoring wells were sampled again. The sample analytical data showed that the concentrations of PCE had decreased while the concentrations of TCE and DCE had increased above their respective baseline concentrations. VC was not detected (the method detection limit was 250 µg/L) before ERH treatment but was detected in March 2004 at a concentration of 6.3 µg/L. The total mass of PCE and CVOCs recovered during ERH system operation was calculated at 234 and 247 pounds, respectively. The decline in PCE concentrations following ERH system shutdown and the increase in concentrations of degradation products were attributed to reductive dechlorination by native microbes.

Figure 3. Pre- and Post-ERH CVOC Plumes [1]

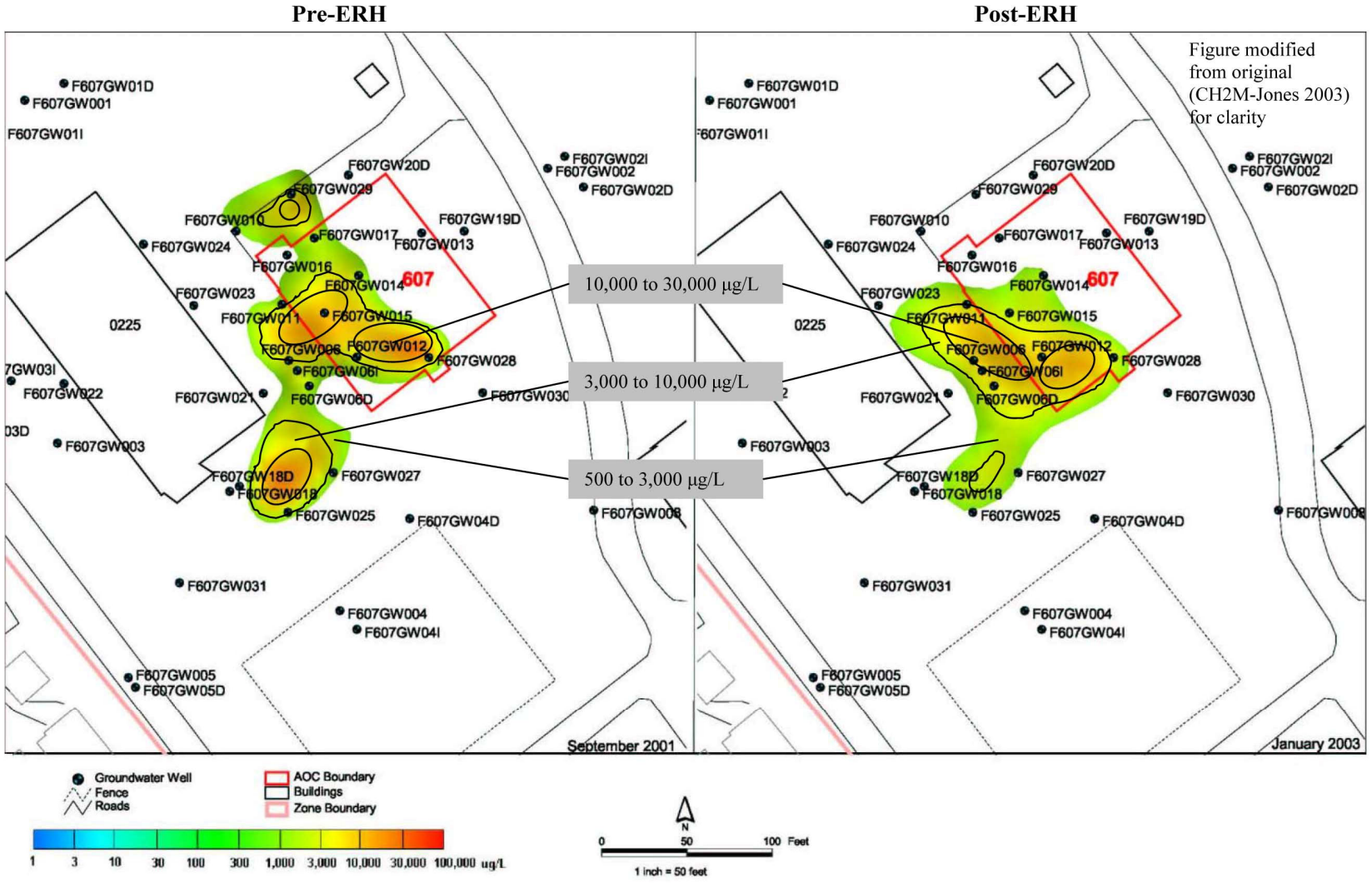
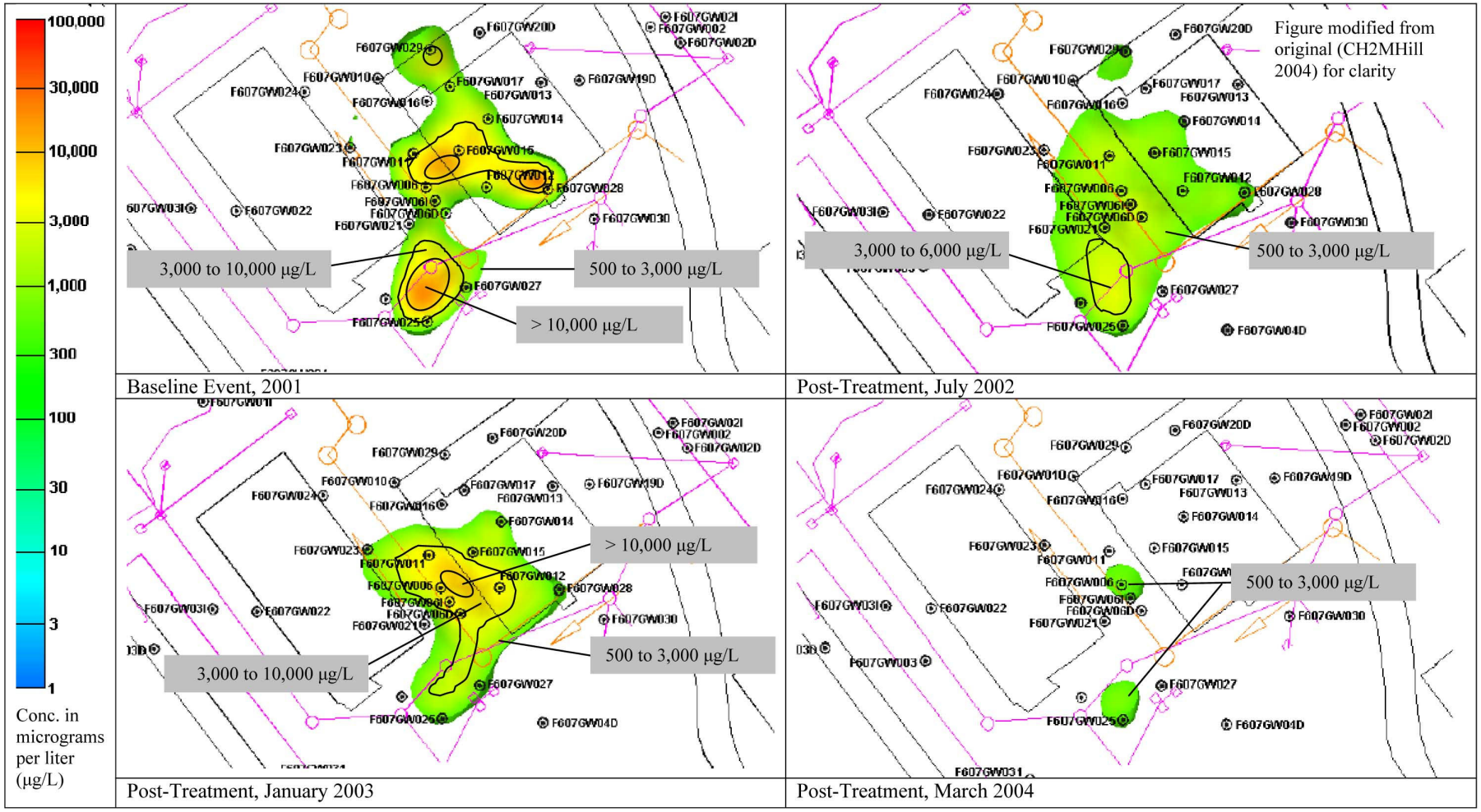


Figure 4. Progress of PCE Plume – 2001 through March 2004 [3]



COST OF THE TECHNOLOGY SYSTEM

COST DATA [5, 6]

The IM cost approximately $1,274,000. Cost details are presented below:

Item	Cost
Pilot-scale test	$ 32,000
Full-scale implementation	
Mobilization/demobilization and reporting	$ 71,000
Capital costs	$ 373,000
Operation	$ 473,000
Retrofitting (electrode installation and well replacement)	$ 60,000
Monitoring (laboratory analytical services)	$ 50,000
Project oversight	$ 215,000
TOTAL	**$ 1,274,000**

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED [5]

ERH treatment was terminated before achievement of the targeted 95 percent reduction in the average dissolved-phase PCE concentration. The system was shut down because PCE was no longer being recovered in significant quantities. However, the site owner's contractor suggested that, considering the relatively insignificant change in dissolved-phase PCE concentrations toward the end of the IM, ERH treatment could have been terminated even sooner. As later observed, once the ERH system was shut down, ERD (discussed in Appendix A) was able to reduce dissolved-phase PCE concentrations over a period of several years.

ERH treatment took longer than anticipated. The site owner's contractor suggested that this was primarily due to groundwater heating proceeding more slowly than was projected in the design stage, especially in deeper portions of the saturated zone. ERH system enhancement, including installation of additional electrodes, was found to be necessary to achieve adequate heating.

The dissolved-phase PCE concentration did not correlate strongly with the mass of PCE removed. This fact was especially evident toward the end of the IM, when PCE removal produced no appreciable change in dissolved-phase concentrations.

REFERENCES

1. Beyke, Greg, Thermal Remediation Services, Inc. 2005. E-Mail to Chitranjan Christian, Tetra Tech EM Inc., Containing Source File on Electrical Resistive Heating (ERH) Remediation Plot Plan for Area of Concern (AOC) 607 at the Charleston Naval Complex. April 2.
2. CH2M-Jones. 2005. "Pilot Study Completion Report and Full-Scale Implementation Plan, Enhanced Reductive Dechlorination, AOC 607, Zone F, Revision 0, Charleston Naval Complex, North Charleston, South Carolina." January.
3. CH2M-Jones. 2003. "Interim Measure Completion Report, IM Completion Report/CMS Work Plan/Investigation Work Plan - AOC 607, Zone F, Revision 1, Charleston Naval Complex, North Charleston, South Carolina." November.
4. CH2M Hill. 2004. "Baseline PCE > 500 µg/L at AOC 607." Presentation on Progress of Contaminant Plume at the Charleston Naval Complex After ERH System Shutdown. June.
5. Williamson, Dean, CH2M Hill. 2005. E-Mails to Chitranjan Christian, Tetra Tech EM Inc., Regarding Information Gaps in Charleston Naval Complex AOC 607 Cost and Performance Report. March 25 and April 14.
6. Wolf, Jerry, Thermal Remediation Services, Inc. 2005. E-Mail to Chitranjan Christian, Tetra Tech EM Inc., Regarding Information Gaps in Charleston Naval Complex AOC 607 Cost and Performance Report. March 18.

ACKNOWLEDGEMENTS

This report was prepared for the U.S. Environmental Protection Agency's (EPA) Office of Solid Waste and Emergency Response, Office of Superfund Remediation and Technology Innovation (OSRTI). Assistance was provided by Tetra Tech EM Inc. under EPA Contract No. 68-W-02-034.

SUMMARY OF THE ENHANCED REDUCTIVE DECHLORINATION PILOT STUDY FOR AREA OF CONCERN 607, ZONE F, AT THE CHARLESTON NAVAL COMPLEX

Site: Charleston Naval Complex, Charleston, SC

Area of Concern (AOC): AOC 607

Contaminants of Concern (COC): Tetrachloroethene (PCE), Trichloroethene (TCE), 1,2-Dichloroethene (DCE), and vinyl chloride (VC)

Technology Used: Enhanced reductive dechlorination (ERD)

Period of Operation: Pilot study performed from June through December 2004

Background: The shallow aquifer in AOC 607 contained a dense nonaqueous-phase liquid (DNAPL) that acted as a source for groundwater contamination. The area containing DNAPL was treated using electrical resistive heating (ERH) under an interim measure in 2001 and 2002. Use of ERH reduced the amount of DNAPL present in the shallow aquifer. ERH treatment also reduced dissolved-phase COC concentrations in the shallow aquifer, although not below site cleanup goals (the maximum contaminant level [MCL] for the COCs). The plan for AOC 607 was to implement ERD for further reduction of residual COC concentrations in groundwater. As a precursor to full-scale remediation, ERD was implemented in AOC 607 at a pilot scale. The pilot-scale test targeted a small part of the shallow groundwater within AOC 607 (see Figure A-1). Based on a 10-foot radius of influence for each injection well and a 7-foot-thick aquifer, the test was conducted on approximately 163 cubic yards of saturated media.

Goal of Pilot Study:

(1) Determine the effectiveness of lactate as a substrate for native microorganisms

(2) Determine the ability of native microorganisms to degrade COCs

(3) Determine the appropriate injection frequency, amendment dosage, and injection well spacing for full-scale remediation

Pilot Study Approach:

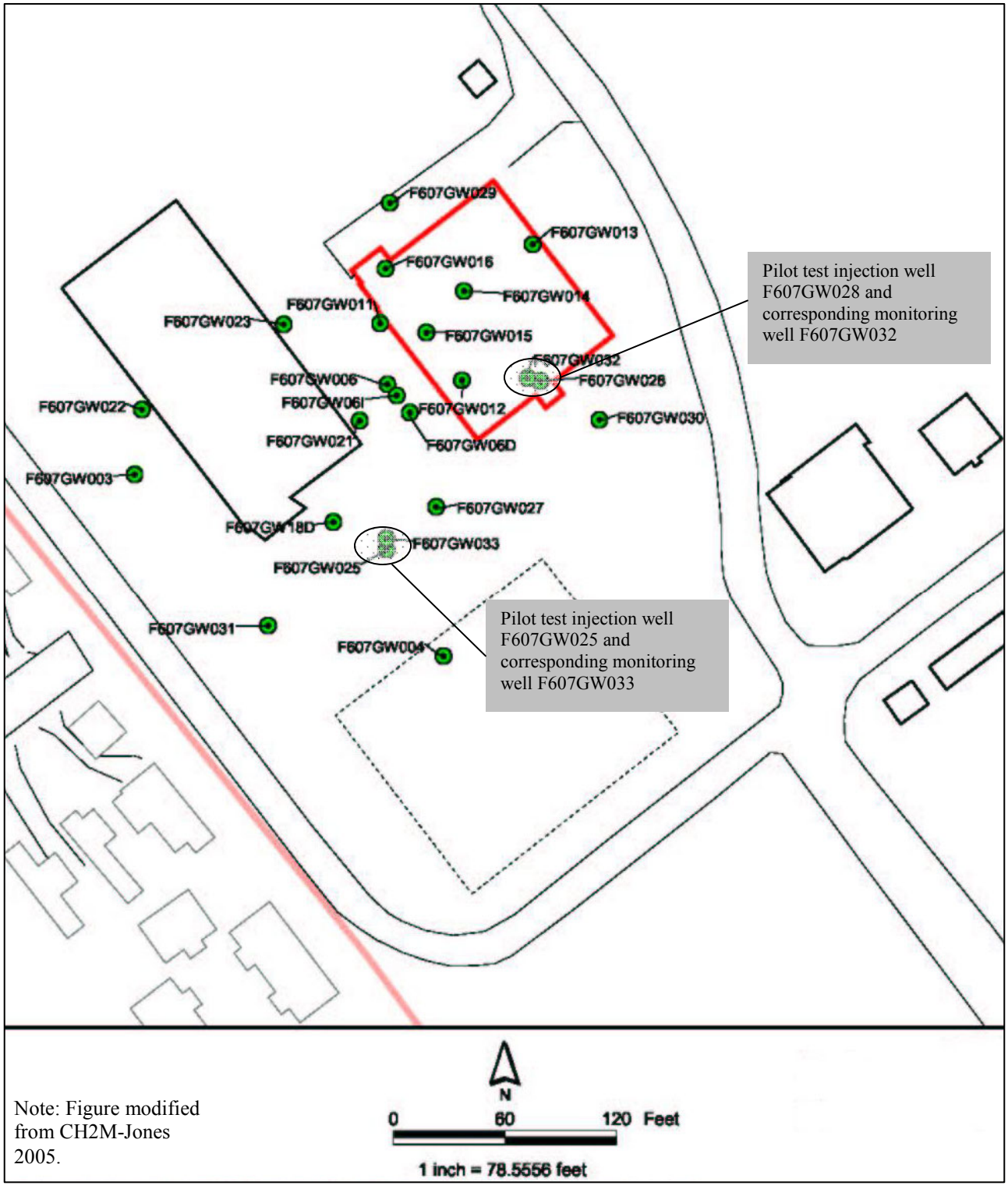
(1) Install monitoring wells

(2) Perform baseline groundwater characterization

(3) Implement amendment injection pilot test

(4) Monitor progress during the pilot study

Figure A-1. AOC 607 ERD Pilot Test Area [1]



Note: Figure modified from CH2M-Jones 2005.

Monitoring Well Installation: Two new monitoring wells, F607GW032 and F607GW033, were installed approximately 10 feet downgradient of existing monitoring wells F607GW028 and F607GW025 respectively (see Figure A-1).

Baseline Characterization: Ten wells were sampled on June 2 and 9, 2004. Field parameters including pH, dissolved oxygen (DO), conductivity, oxidation-reduction potential (ORP), and temperature, were measured in all of these wells. Samples from the four key pilot study wells (F607GW025, F607GW028, F607GW032, F607GW033) were also analyzed for volatile organic compounds (VOCs), alkalinity, bromide, dissolved gases (methane, ethane, and ethene), sulfate, sulfide, total organic carbon (TOC), volatile fatty acids (VFA), and several dissolved metals (including potassium, iron, and manganese).

Pilot Test:

(1) Nutrient solution was injected into two wells (F607GW025 and F607GW028) on June 9 and 10, 2004. The nutrient solution contained 10 percent lactate (500 milligrams per liter [mg/L]), bromide tracer, and a pH buffer (sodium bicarbonate), and 230 gallons of nutrient solution was injected into each well.

(2) Performance monitoring was conducted for the next 3 months.

(3) On October 13, 2004, 230 gallons of 3 percent lactate solution followed by 20 gallons of clean water was injected into each of the two injection wells.

Post-Injection Monitoring:

(1) Only on two downgradient wells (F607GW032 and F607GW033) were monitored.

(2) After the first injection event, monthly monitoring was performed for field parameters (DO, ORP, pH, temperature, and conductance), VFAs, TOC, methane, ethane, ethene, and VOCs.

(3) After the first injection event, bimonthly monitoring was performed for alkalinity, bromide, sulfate, iron, manganese, potassium, and *Dehalococcoides ethenogenes* (DHE) microorganisms.

Results:

(1) Monitoring well F607GW032:

a. October 2004 sampling showed an overall reduction in VOC concentration. The total VOC concentration decreased by 40 percent from 18,000 to 10,687 micrograms per liter (µg/L). The PCE concentration decreased by 99 percent from 8,090 to 100 µg/L. The VC concentration increased, as anticipated, above the baseline concentration but subsequently decreased. The 1,2-DCE concentration fluctuated during the monitoring period.

b. VFAs were sporadically detected at low concentrations, indicating use of the lactate substrate by microorganisms.

c. Methane, ethane, and ethene were detected at 10 to 100 times their baseline concentrations. Elevated methane concentrations indicated the presence of a reducing environment. Elevated ethene concentrations indicated dechlorination of chlorinated VOCs.

d. The ORP decreased below baseline measurements. The ORP readings indicated the presence of a strongly reducing environment.

e. Sulfate was detected below its baseline concentration, indicating that it was being readily reduced. Iron was detected below its baseline concentration, indicating a lesser degree of iron reduction.

f. The concentration of DHE in groundwater increased from undetectable quantities in baseline samples to 726,000 genomes per milliliter (gnms/mL) in samples collected in August 2004. This finding indicated successful stimulation of microorganisms by the injectant.

(2) Monitoring well F607GW033:

a. October 2004 sampling showed an overall reduction in VOC concentrations. The total VOC concentration decreased by 83 percent from 860 to 140 µg/L. PCE was not detected after August 2004. The VC concentration increased, as anticipated, above the baseline concentration, but subsequently decreased. The 1,2-DCE concentration fluctuated during the monitoring period.

b. VFAs were sporadically detected at low concentrations, indicating use of the lactate substrate by microorganisms. However, results indicated that the fermentative environment had not matured to the degree observed in well F607GW032.

c. Ethane was not detected. Ethene was detected in the first monthly sampling event but was not detected in subsequent events. Methane was detected at 10 times its baseline concentration. The elevated methane concentrations indicated the presence of a reducing environment.

d. The ORP decreased below baseline measurements. The ORP readings indicated the presence of a strongly reducing environment.

e. Sulfate was detected below its baseline concentration, indicating that it was being readily reduced. Dissolved iron was detected above its baseline concentration, indicating that it was being readily reduced.

f. The concentration of DHE in groundwater increased from trace quantities to 41,600 gnms/mL. This finding indicated successful stimulation of microorganisms by the injectant.

Overall Findings by the Site Contractor:

(1) Lactate proved to be an effective substrate. Substrate injection significantly stimulated native bacteria.

(2) The native bacteria were capable of fully degrading PCE to ethene.

(3) The effects of each lactate injection lasted 1 to 3 months.

(4) Injection impacted media up to 10 feet away.

(5) The existing monitoring wells could be used for future injection of substrate.

(6) The pilot-scale test was successful and ERD was recommended for full-scale implementation.

Reference

1. CH2M-Jones. 2005. "Pilot Study Completion Report and Full-Scale Implementation Plan, Enhanced Reductive Dechlorination, AOC 607, Zone F, Revision 0, Charleston Naval Complex, North Charleston, South Carolina". January.