COST AND PERFORMANCE REPORT

Electrical Resistive Heating at the
Former Manufacturing Facility
Skokie, Illinois

June 2003

SITE INFORMATION

IDENTIFYING INFORMATION

Site Name: Former manufacturing facility (confidential commercial client)
Location: Skokie, Illinois (near Chicago, Illinois)
Regulatory Context: State voluntary cleanup
Technology: Electrical Resistive Heating
Scale: Full-scale

TECHNOLOGY APPLICATION

Period of Operation: June 4, 1998 to November 20, 1998 (initial area treated); December 1998 to April 30, 1999 (additional area treated)

Type/Quantity of Material Treated during Application [7,8]: Initial source zone area - approximately 23,100 cubic yards of soil and groundwater, based on a treatment area of 26,000 square feet and a depth of 24 feet below ground surface (bgs). Additional source zone area - 11,500 cubic yards of soil and groundwater

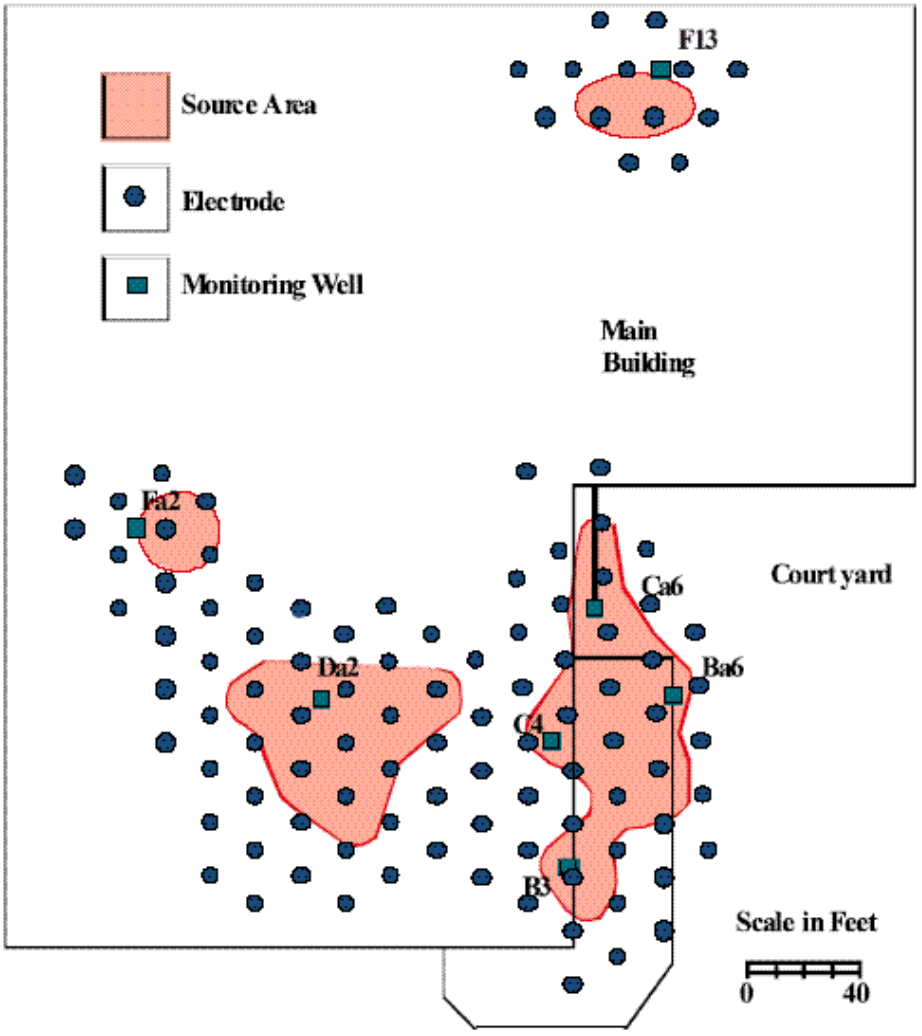
BACKGROUND [2,4,5,7,8,9,13]

The site is a former electronics manufacturing facility located in Skokie, Illinois. Manufacturing at this location began in 1958 and included machining, electroplating, heat treating, silk screening, silicon chip production, and research and development. Trichloroethene (TCE) and 1,1,1-trichloroethane (TCA) were feedstock chemicals associated with various manufacturing processes. By 1988, all processes had been discontinued, and the facility was sold and redeveloped.

Releases occurred from spill containment systems and underground storage tanks that leaked. Figure 1 shows the areas where soil and groundwater at the site were found to be contaminated with pools of dense nonaqueous phase liquids (DNAPL). The site was remediated under Illinois' voluntary Site Remediation Program. From 1991 to 1998, steam injection combined with groundwater and vapor extraction was used to clean up the site. After seven years of operation, the area of contamination had been reduced from about 115,000 square feet to about 23,000 square feet. As of early 1998, the remaining area to be remediated represented four source locations where manmade subsurface features limited the effectiveness of the previously used steam-based remediation system. These locations consisted of a closed-end catch basin acting as a heat sink, a subsurface void, two areas with very dense soil near a building (believed to be limiting vapor extraction), and an additional area adjacent to a wall with a deep foundation (where foundation backfill was believed to be providing a preferential pathway for injected steam).

To complete the remediation, the site owner selected Electrical Resistive Heating (ERH) technology that combines electrically heating the subsurface with electrodes inserted in the ground, and soil vapor extraction. This report focuses on the use of ERH and not the steam injection previously completed at the site.

Figure 1. Layout of the Skokie Site [7,13]



MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION

Type of Media Treated With Technology System: Source zone (saturated and unsaturated)

Primary Contaminant Groups: Chlorinated Solvents (TCE and TCA, as well as degradation products cis- and trans-1,2-dichloroethene, 1,1-dichloroethene, 1,1-dichloroethane, vinyl chloride and chloroethane)

Former Manufacturing Facility, Skokie, Illinois

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [3,4,7,13]

The facility overlies heterogeneous silty sands with clay lenses to 18 feet bgs and a hydraulic conductivity ranging from 10^{-4} to 10^{-5} cm/sec. Below 18 feet bgs, a dense clay till or ground moraine forms an aquitard with a hydraulic conductivity of 10^{-8} cm/sec. Groundwater is encountered at 7 feet bgs. The majority of the remaining DNAPL at the site was pooled on top of the clay till at 18 feet bgs.

At the initiation of ERH, aqueous phase concentrations and concentration trends indicated the presence of DNAPL. Sampling indicated that DNAPL resided in proof-rolled clays at depths of 5 to 8 feet bgs, and in the soil pores from the water table (7 feet bgs) to depths of 18 to 20 feet bgs. Concentrations in groundwater at the initiation of SPH for cis-1,2-dichloroethene (DCE) were as high as 160 mg/L, for TCE as high as 130 mg/L, and for TCA as high as 150 mg/L.

Table 1 lists the matrix characteristics affecting treatment cost or performance for this application.

Table 1. Matrix Characteristics [3,4,7,13]

Parameter	Value
Soil Classification	Heterogeneous sandy and silty clays
Clay Content and/or Particle Size Distribution	Two discrete clay intervals: 1) silty clay from 5 to 18 feet bgs, and 2) denser clay below 18 feet bgs
Depth to Groundwater	7 feet bgs
Hydraulic conductivity	Ranges from 10^{-4} to 10^{-5} centimeters/second (cm/sec) in silty sand and less than 10^{-8} cm/sec in the denser clay
Air permeability	Not available
Porosity	Not available
Presence of NAPLs	DNAPL present
Moisture content	Typical for water saturated clay (quantitative information not available)
Total organic carbon	0.12%
Electrical resistivity of soil	3 ohms

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY

Electrical Resistive Heating (Six-Phase Heating™) and air stripping for extracted groundwater condensate

TREATMENT SYSTEM DESCRIPTION AND OPERATION [1,3,4,5,6,7,8,9,13]

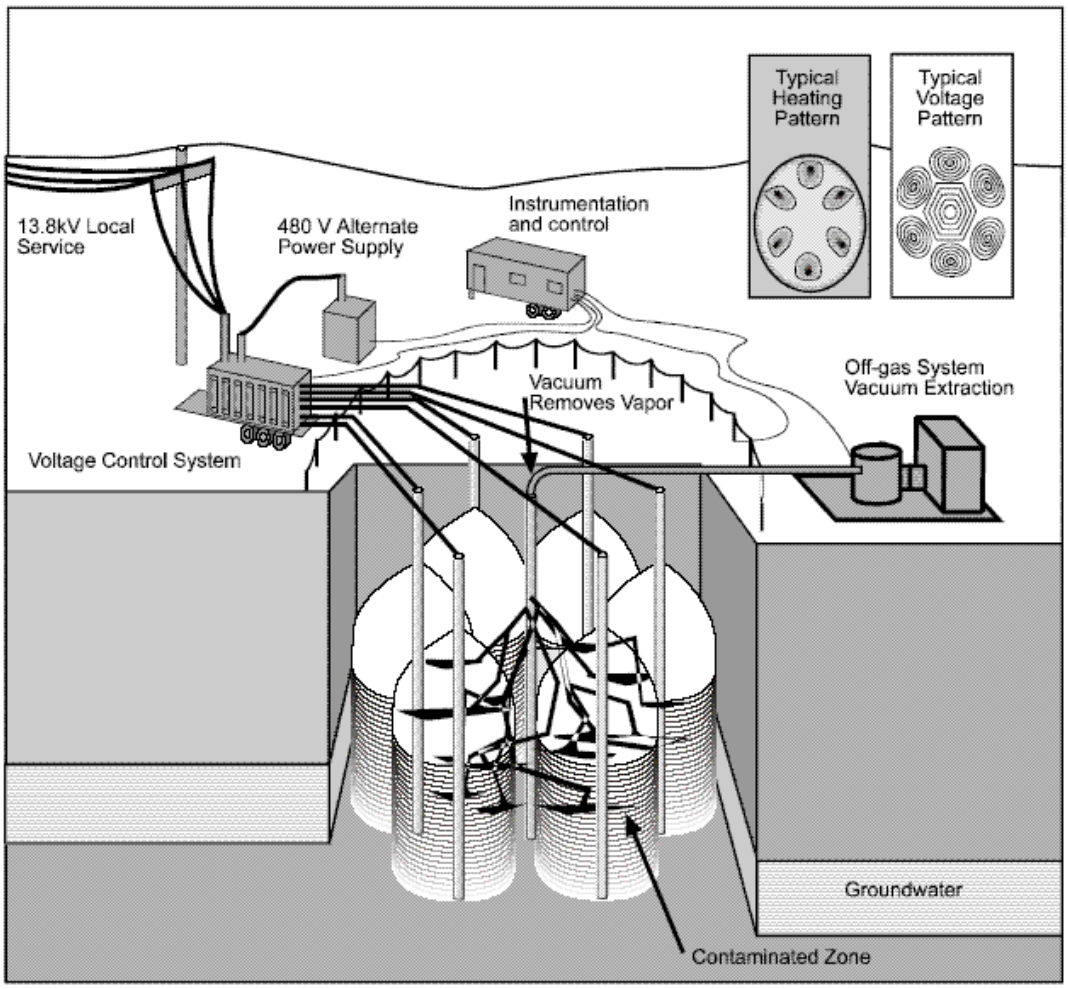
For the Skokie site, a network of 107 electrodes was designed and installed in the initial treatment area, with 85 of the electrodes constructed beneath the floor of a warehouse building. After November 20, 1998, the system was shut down for about a month while 78 more electrodes were installed (185 electrodes total). All electrodes were designed to be electrically conductive throughout a depth interval of 11 to 21 feet bgs and to increase the subsurface temperature in the depth interval of 5 to 24 feet bgs to the boiling point of water. A network of 37 soil vapor extraction wells, screened to 5 feet bgs, were used to capture vapors. The off gas system consisted of a vacuum extraction blower and a steam condenser. Figure 1 shows the location of the electrodes and monitoring wells at the site, while Figure 2 shows typical ERH equipment layout.

The ERH process operated at the Skokie site from June 4, 1998 to November 20, 1998 to remediate the initial estimated 23,000 cubic yards of contaminated soil. Results of sampling conducted in December 1998 indicated there was a potential for vinyl chloride to be produced outside the initial treatment area at levels in excess of the Tier III cleanup levels. As a result, the treatment area was expanded, restarted in December 1998, and operated until April 30, 1999.

During system operation, the ERH process was controlled remotely via software, allowing real-time adjustment of electrode voltage to control power delivered to the soil. According to the vendor, thermocouples placed in the soil were used to monitor the heating pattern as a basis for adjusting the distribution of power and to assist in determining the best electrical configuration for power delivery as the cleanup progressed. The electrical configuration was adjusted in the field by reconnecting electrical jumpers between electrodes to re-focus electrical energy as needed to maintain rapid treatment. During all phases of the operation, the total power, energy delivered, and electrical current, voltage, and power factors were measured and recorded along with soil temperatures using a computer based data acquisition and control system.

During treatment, the source zone was heated to 100° C, and the system achieved an operating vacuum of 7.5 inches of mercury. Electric power input was 1,775 Mw-hrs from June 4 to November 20, 1998. Information on power input was not provided for December 1998 to May 1999.

Figure 2. Typical ERH Equipment Layout [7]



Treatment progress was monitored by measuring vapor concentrations in the soil off-gas exiting the condenser and by periodically monitoring in situ concentrations through groundwater samples collected from wells. The off-gas measurements were used to estimate the rate of contaminant removal and total removed mass throughout the site operation. According to the vendor, approximately 99% of the removed mass was found to remain in the vapor phase past the off-gas condenser while the remaining 1% was collected in the condensed phase. This partitioning reflects the relatively high volatility and modest solubility of the contaminants. The condensate was treated with air stripping prior to discharge.

Groundwater monitoring data were available for March 1998, before the ERH was initiated, and from April 1998 through May 1999. During ERH treatment, up to 40 well points (from the previous steam injection system) were sampled on a periodic basis. According to the vendor, all of these well points were abandoned in July 1999 in accordance with Cook County Department of Public Health-approved procedures.

TIMELINE [3,4,5,8,9,13]

•	1991-3/98	Steam injection and soil and groundwater extraction used at site
•	6/4/98	ERH system began operation
•	8/4/98 (approx.)	Temperatures throughout entire soil volume reach boiling point of water
•	10/98	ERH system temporarily shut off
•	12/98	Additional ERH system began operation
•	4/30/99	System shut off and demobilization began
•	7/29/99	Illinois EPA issues a no further remediation letter
•	5/99-12/99	Post-remedial monitoring conducted

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [4,10,13,14]

Table 2 shows the Tier III cleanup criteria for groundwater proposed by the vendor and approved by Illinois EPA as the cleanup goals for the site. According to Illinois EPA's Site Remediation Program guidelines, Tier III allows conduct of variable-scale risk assessment activities and more complex contaminant fate and transport modeling than is allowed in more stringent cleanup tiers. The more stringent Tier I standards are shown for comparison.

Table 2. Cleanup Criteria for Skokie Site (Tier III) [13,14]

Contaminant	Tier III Cleanup Level for Groundwater (µg/L)	Tier I Cleanup Level for Groundwater (µg/L)
cis 1,2-Dichloroethene (DCE)	35,500	200
1,1,1-Trichloroethane (TCA)	8,850	1,000
Trichloroethene (TCE)	17,500	25

TREATMENT PERFORMANCE [4,6,8,9,13]

Performance data are available for the remediation of the initial 23,000 cubic yards of remaining contamination at the site conducted from June to November 1998 (Table 3) and for the remediation of the additional 11,000 cubic yards of contamination at the site conducted from December 1998 to April 1999 (Table 4). Groundwater monitoring continued after system shutdown in April and data are available through May 1999. Figures 3, 4, and 5 show the changes in groundwater contaminant concentrations by well for DCE, TCA, and TCE, respectively, from March 1998 through May 1999.

As shown in Table 3, by November 20, 1998, the Tier III cleanup goals had been achieved for the three constituents of concern in all seven wells. In addition, as of November 1998, contaminant concentrations in a number of wells had been reduced to the more stringent Tier I cleanup levels. For example, the Tier I cleanup level for TCA had been met in all seven wells, for DCE in one well, and for TCE in two wells.

In October 1998, following 18 weeks of ERH operation, elevated levels of TCE (81,000 µg/L) were detected in well Ca6. According to the vendor, the source of the high concentrations of TCE was not known. To address the elevated concentrations: 1) well Ca6 was converted to an electrode to improve heating;

and 2) Fenton's reagent was added in and around the catch basin to oxidize oils which may have potentially leaked from the catch basin. By November 1998, TCE concentrations in the Ca6 well area had decreased to levels ranging from 250 µg/L to 1,600 µg/L.

Table 4 presents a summary of groundwater monitoring data for the remediation of the additional area of contamination, conducted from December 1998 to April 1999. As shown in Table 4, concentrations of DCE and TCE were higher than the Tier III cleanup levels in well Ca6 in January 1999. By February 1999, TCE concentrations in this well had decreased to between the cleanup levels. As of April 1999 contaminant concentrations in all wells were below the cleanup goals and the system was shut down. Groundwater monitoring data for May 1999 showed that contaminant concentrations remained below cleanup levels.

Groundwater samples were collected monthly and analyzed via head space extraction using an HP 5890 gas chromatograph equipped with an electron capture detector (GC/ECD). A subset of the sample population was analyzed using a gas chromatograph with a mass spectrometer (GC/MS) following EPA Method 8240. Contaminant concentrations in the collected condensate were monitored periodically. Off-gas concentrations exiting the condenser were monitored using a flame ionization detector (FID).

The Illinois Environmental Protection Agency issued a letter on July 29, 2002 granting the site's request for a no further action determination and provided several conditions and terms for the determination, including installation of a passive ventilation system (vent wells) to provide a preferential pathway for vapors to migrate.

Two additional rounds of groundwater monitoring sampling were performed following completion of ERH in April 1999. Table 5 shows the concentrations of TCE, TCA, and DCE in groundwater monitoring wells from May 1999 (1 month after completion of the remediation) and December 1999 (8 months after completion of the remediation). During this time, the concentrations of TCE, TCA, and DCE remained below the Tier III groundwater cleanup levels, and contaminant concentrations remained stable or continued to decrease.

Table 3. Monthly Groundwater Quality During ERH Remediation of Area of Remaining Contamination [4] (June 1998 to November 1998)

Well No.	Constituent	Tier III Clean-up Level (µg/L)	Prior to SPH Remediation	During Remediation					
			3/24/98 (µg/L)	6/26/98 (µg/L)	7/15/98 (µg/L)	8/20/98 (µg/L)	9/17/98 (µg/L)	10/6/98 (µg/L)	11/20/98 (µg/L)
B3	cis 1,2-DCE	35,500	48,000	22,000	390	18,000	4,200	780	390
	1,1,1-TCA	8,850	82,000	4,000	500	17,000	500	500	500
	TCE	17,500	34,000	640	240	58,000	2,900	790	250
Ba6	cis 1,2-DCE	35,500	9,800	18,000	NR	NR	3,500	200	1,200
	1,1,1-TCA	8,850	88,000	52,000	NR	NR	2,600	50	50
	TCE	17,500	7,000	23,000	NR	NR	10,000	510	470
C4	cis 1,2-DCE	35,500	43,000	160,000	22,000	47,000	16,000	1,300	550
	1,1,1-TCA	8,850	11,000	13,000	8,800	1,000	1,000	100	100
	TCE	17,500	75,000	24,000	89,000	120,000	17,000	1,600	ND
Ca6	cis 1,2-DCE	35,500	1,800	52,000	1,800	52,000	8,400	22,000	250
	1,1,1-TCA	8,850	10,000	NR	1,200	4,200	2,000	2,000	20
	TCE	17,500	83,000	NR	5,200	230,000	12,000	81,000	1,600
Da2	cis 1,2-DCE	35,500	18,000	8,100	4,000	11,000	9,100	7,300	3,000
	1,1,1-TCA	8,850	28,000	94,000	51,000	5,600	5,000	500	100
	TCE	17,500	47,000	130,000	230,000	44,000	370,000	8,800	320
F13	cis 1,2-DCE	35,500	510	500	1,000	218	120	480	38
	1,1,1-TCA	8,850	16,000	150,000	14,000	2,000	100	250	250
	TCE	17,500	800	2,800	1,000	830	400	260	12
Fa2	cis 1,2-DCE	35,500	3,900	2,400	50	850	590	470	210
	1,1,1-TCA	8,850	24,000	810	420	200	100	50	50
	TCE	17,500	22,000	4,800	880	3,100	280	1,200	12
Average	cis 1,2-DCE	35,500	17,900	37,600	4,900	21,500	6,000	4,600	800
	1,1,1-TCA	8,850	37,000	52,300	12,700	5,000	1,600	500	200
	TCE	17,500	38,400	30,900	54,400	76,000	58,900	13,500	400

Figure 3. Monthly Cis-DCE Concentrations (• g/L) In Groundwater in Initial Area of Contamination (March 1998 to May 1999, log-scale) [4]

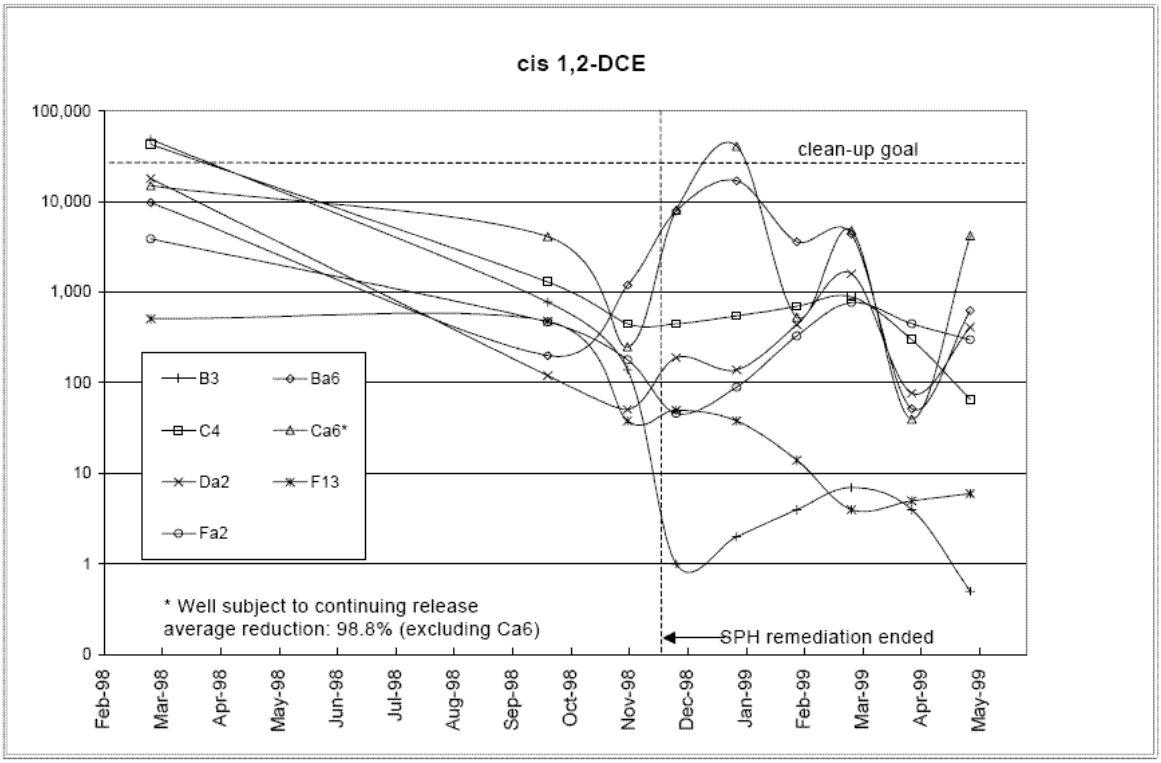


Figure 4. Monthly 1,1,1-TCA Concentrations (• g/L) in Groundwater in Initial Area of Contamination (March 1998 to May 1999, log-scale) [4]

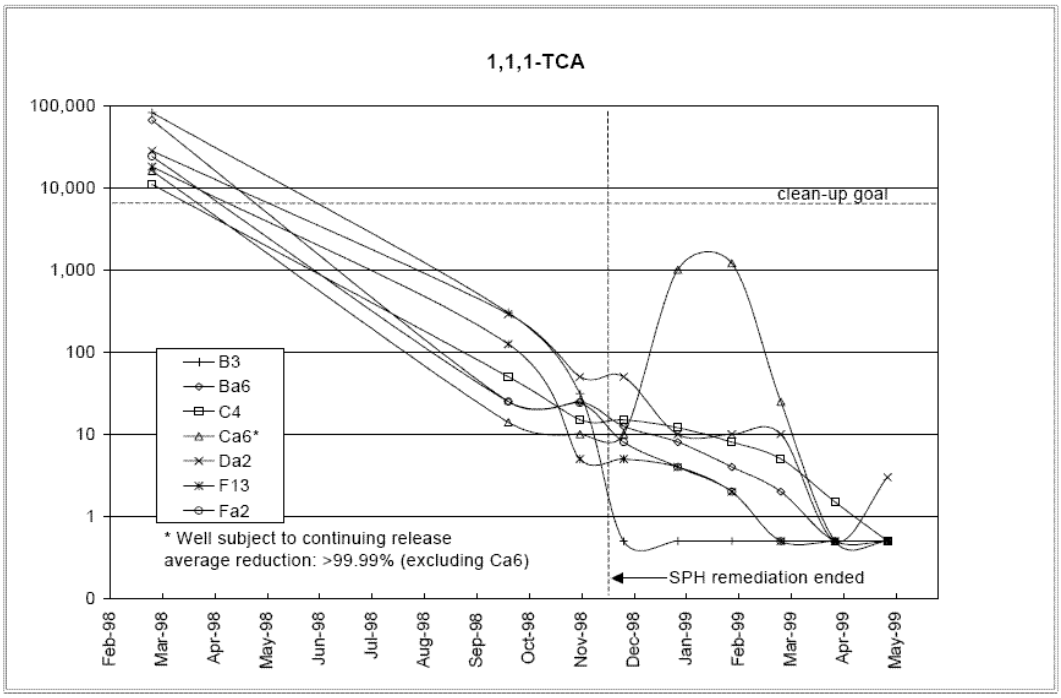


Figure 5. Monthly TCE Concentrations (• g/L) in Groundwater in Initial Area of Contamination (March 1998 to May 1999, log-scale) [4]

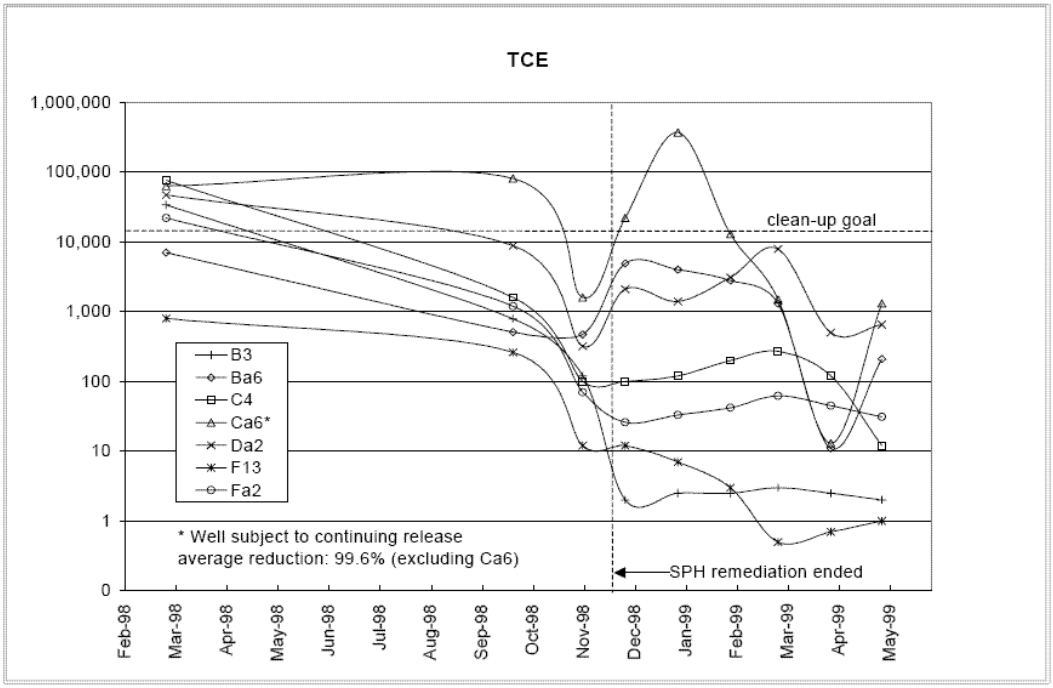


Table 4. Monthly Groundwater Quality During ERH Remediation of Additional Area of Contamination [11] (December 1998 to May 1999)

Well No.	Constituent	Tier III Clean-up Level (• g/L)	December-98 (• g/L)	January-99 (• g/L)	February-99 (• g/L)	March-99 (• g/L)	April-99 (• g/L)	May-99 (• g/L)
B3	cis-1,2-DCE	35,500	1	NR	NR	7	NR	<1
	1,1,1-TCA	8,850	<1	NR	NR	<1	NR	<1
	TCE	17,500	2	NR	NR	3	NR	2
Ba6	cis-1,2-DCE	35,500	7,900	17,000	3,600	4,400	52	630
	1,1,1-TCA	8,850	<25	<25	<25	<25	<1	<1
	TCE	17,500	4,900	4,000	2,800	1,300	11	210
C4	cis-1,2-DCE	35,500	450	NR	NR	890	NR	66
	1,1,1-TCA	8,850	15	NR	NR	<10	NR	<1
	TCE	17,500	100	NR	NR	270	NR	12
Ca6	cis-1,2-DCE	35,500	8,100	41,000	530	4,800	40	4,200
	1,1,1-TCA	8,850	<20	<2,000	1,200	<50	<1	<25
	TCE	17,500	22,000	370,000	13,000	1,500	13	1,300
Da2	cis-1,2-DCE	35,500	190	140	NR	1,600	77	410
	1,1,1-TCA	8,850	<100	<20	NR	<20	<1	3
	TCE	17,500	2,100	1,400	NR	7,900	500	650
F13	cis-1,2-DCE	35,500	50	NR	NR	4	NR	6
	1,1,1-TCA	8,850	<10	NR	NR	<1	NR	<1
	TCE	17,500	12	NR	NR	<1	NR	1
Fa2	cis-1,2-DCE	35,500	46	NR	NR	770	NR	300
	1,1,1-TCA	8,850	8	NR	NR	<1	NR	<1
	TCE	17,500	26	NR	NR	62	NR	31
Average *	cis-1,2-DCE	NR	2,391	8,306	2,065	1,782	56	240
	1,1,1-TCA	NR	14	341	606	8	1	1
	TCE	NR	4,163	125,000	7,900	1,577	196	150

*Not detects (<) were assumed to be present at one-half the detection limit in computing average concentrations.
NR - not reported

Table 5. Groundwater Quality After ERH Remediation [15]

Well No.	Constituent	5/99 (µg/L)	12/99 (µg/L)
A6	cis 1,2-DCE	1,100	5
	1,1,1-TCA	ND	7
	TCE	1,000	ND
Ba3	cis 1,2-DCE	390	150
	1,1,1-TCA	ND	ND
	TCE	ND	ND
D3	cis 1,2-DCE	3	19
	1,1,1-TCA	ND	ND
	TCE	32	ND
D7	cis 1,2-DCE	1,300	160
	1,1,1-TCA	ND	ND
	TCE	250	ND
D9	cis 1,2-DCE	300	140
	1,1,1-TCA	ND	ND
	TCE	1	1
E5	cis 1,2-DCE	740	430
	1,1,1-TCA	ND	ND
	TCE	4	ND
F9	cis 1,2-DCE	760	900
	1,1,1-TCA	ND	ND
	TCE	6	ND
F13	cis 1,2-DCE	12	26
	1,1,1-TCA	ND	ND
	TCE	1	3
G3	cis 1,2-DCE	460	12
	1,1,1-TCA	ND	ND
	TCE	12	ND
Ga8	cis 1,2-DCE	150	27
	1,1,1-TCA	ND	ND
	TCE	ND	ND
Ga13	cis 1,2-DCE	90	10
	1,1,1-TCA	ND	ND
	TCE	19	3
Ja4	cis 1,2-DCE	180	94
	1,1,1-TCA	ND	ND
	TCE	ND	2
Ja9	cis 1,2-DCE	100	53
	1,1,1-TCA	ND	ND
	TCE	ND	ND

ND = Not detected, detection limit not provided.

COST OF THE TECHNOLOGY SYSTEM

COST DATA [5,7,12]

While data about the total cost of remediation efforts to date was confidential, the vendor provided costs on a per unit basis for the full-scale ERH remediation through November 1998 (initial treatment of 23,100 cubic yards). The cost of $32 per cubic yard included the installation and operation of the ERH power system and electrodes, vapor extraction and condensate treatment, project permitting, preparation of work plans, electrical use, waste disposal, interim sampling, and progress reporting. As of November 20, 1998, a total of 1,775 MW-hr of electrical energy had been consumed by the ERH system at a cost of as much as $14,000/month plus $40 per MW-hr for a total cost for electricity of $148,000. This corresponded to $6.40 per cubic yard of treatment volume, or 20% of the total cost of $32 per cubic yard.

In addition, the vendor provided a unit cost for treatment from December 1998 through May 1999 (treatment of 11,500 cubic yards). This unit cost also was $32 per cubic yard.

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED

The ERH system used at this site achieved the established Tier III cleanup goals for the remediation of the initial estimated 23,000 cubic yards of remaining contamination at the site in about six months and for the remediation of the additional 11,500 cubic yards of contamination at the site in about five months. In addition, the concentrations of constituents in a number of wells had been reduced to the more stringent Tier 1 standards.

REFERENCES

1. Eastep, Lawrence W., Illinois Environmental Protection Agency. Review of Remedial Action Completion Report. July 29, 1999.

2. Beyke, Gregory, CES, et al. DNAPL Remediation Closure With Six-Phase Heating. The Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Monterrey, CA. Pages 183-189. May 22-25, 2000.

3. Fleming, David. Corporate Development Leader, Current Environmental Solutions (CES). Personal communication with Bryan Smith, Tetra Tech EM Inc., December 1998.

4. CES. "Applications Analysis Report: DNAPL Remediation in the Saturated Zone Using Six-Phase Heating™." Former Manufacturing Facility in Chicago [Skokie], Illinois. November 1998.

5. CES. "Skokie Site Update and Cost and Effectiveness Information." November 1998.

6. CES. "Soil Vapor Extraction to the Sixth Degree." Reprint from *Soil and Groundwater Cleanup* magazine. July 1997.

7. Heath, Bill. Comments on Draft Cost and Performance Report. Six-Phase Heating™ (SPH) at a Former Manufacturing Facility near Chicago, Illinois. March 1999.

8. Heath, Bill. Update on site activity. Personal communication with Bryan Smith, Tetra Tech EM Inc., April 28, 1999.

9. Beyke, Greg. Update on site activity. Personal communication with Bryan Smith, Tetra Tech EM Inc., April 29, 1999.

10. Illinois Environmental Protection Agency. *Site Remediation Program*. http://www.epa.state.il.us/land/site-remediation/overview.html

11. Beyke, Greg. E-mail to Bryan Smith, Tetra Tech EM Inc. Skokie Groundwater Data. May 6, 1999.

12. Beyke, Greg. Update on site activity. Personal communication with Bryan Smith, Tetra Tech EM Inc., April 29, 1999 and with Richard Weisman, Tetra Tech EM Inc. on June 29, 1999.

13. Smith, Gregory. Comments on Draft Report for Six-Phase Heating Application, Skokie, IL. July 23, 1999.

14. Komperda, Stan. Comments on Draft Report for Six-Phase Heating Application, Skokie, IL via personal communication with Richard Weisman, Tetra Tech EM Inc., July 26, 1999.

15. Smith, Gregory, et al. Closure of Trichloroethene and 1,1,1-Trichloroethane DNAPL Remediation Using Thermal Technologies. The Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Monterrey, CA. Pages 167-174. May 22-25, 2000.

16. Komperda, Stan, Illinois EPA. Personal communication with Mary Sherrill, Tetra Tech EM Inc. August 21, 2002.

17. Adams, Tim, ENSR. Personal communication with Mary Sherrill, Tetra Tech EM Inc. September 4, 2002.