

COST AND PERFORMANCE REPORT

Six-Phase Heating™ (SPH) at a
Former Manufacturing Facility
Skokie, Illinois

October 1999



U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office

SITE INFORMATION

IDENTIFYING INFORMATION

Site Name: Former manufacturing facility (confidential commercial client)

Location: Skokie, Illinois (near Chicago, Illinois)

Regulatory Context: State voluntary cleanup

TECHNOLOGY APPLICATION

Period of Operation: June 4, 1998 to November 20, 1998 to remediate initial 23,000 cubic yards of contamination. December 1998 to April 30, 1999 to remediate additional 11,500 cubic yards of contamination.

Quantity of Material Treated during Application [7,8]: From June to November 1998, approximately 23,100 cubic yards of soil and groundwater were treated. The total volume treated was calculated based on a treatment area of 26,000 square feet and a depth of 24 feet below ground surface (bgs). From December 1998 to April 1999 an additional 11,500 cubic yards of soil and groundwater were treated.

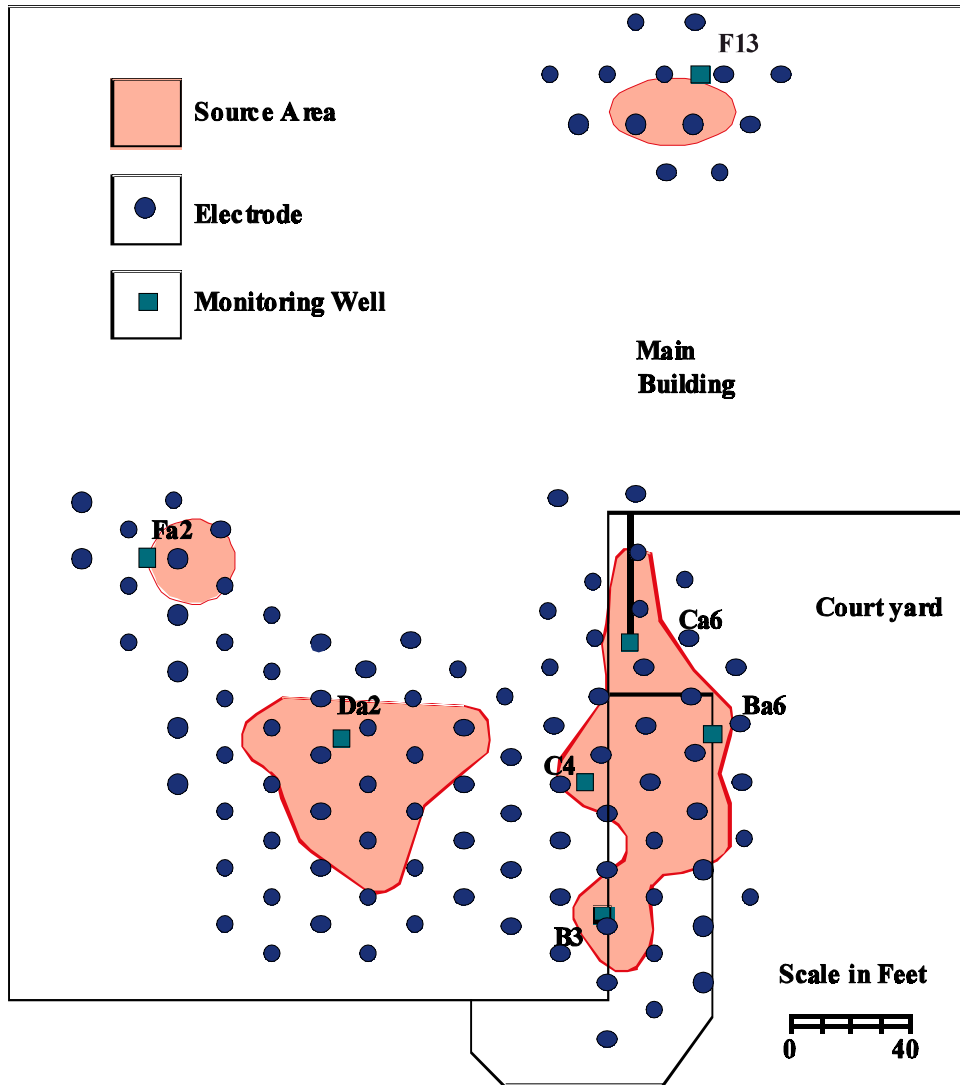
BACKGROUND [4,5,7,8,9,13]

Waste Management Practice That Contributed to Contamination: Releases occurred from spill contaminant systems and underground storage tanks that leaked. The releases of trichloroethene (TCE) and 1,1,1-trichloroethane (TCA) were feedstock chemicals associated with various manufacturing processes.

Site History: The site is a former electronics manufacturing facility located in Skokie, Illinois. Figure 1 shows that the soil and groundwater at the site are contaminated with solvents (TCE and TCA) and that large pools of dense nonaqueous phase liquids (DNAPL) were found at the site. Manufacturing at this location began in 1958 and included machining, electroplating, heat treating, silk screening, silicon chip production, and research and development. By 1988, all processes had been discontinued, and the facility was sold and redeveloped. The site is being 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. To complete the remediation, the site owner selected Six-Phase Heating™ (SPH), a technology that combines electrically heating the subsurface with electrodes inserted in the ground, and soil vapor extraction. An additional area of contamination (about 11,500 cubic yards) was identified at the site in December 1998. The SPH system was expanded and operated from December 1998 to April 1999.



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



SITE LOGISTICS/CONTACTS

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MATRIX DESCRIPTION

MATRIX IDENTIFICATION

Type of Media Treated With Technology System: Soil and groundwater

CONTAMINANT CHARACTERIZATION [3,4,7,13]

Primary Contaminant Groups and Concentrations Measured During Site Investigation: The primary contaminants at the site were TCE and TCA. Degradation products included cis-and trans-1,2-dichloroethene, 1,1-dichloroethene, 1,1-dichloroethane, vinyl chloride and chloroethane.

At the initiation of SPH, 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. Groundwater samples were obtained from seven monitoring wells (see Figure 1).

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Contaminant Properties [1,2]:

Contaminant	Boiling Point (°C)	Solubility	Density (at 4 °C)
DCE	31.6	0.04%	1.213
TCE	86.7	0.10%	1.465
TCA	74.1	0.40%	1.338

MATRIX CHARACTERISTICS AFFECTING TECHNOLOGY COST OR PERFORMANCE [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

SITE GEOLOGY/STRATIGRAPHY [3,4,7]

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.



TECHNOLOGY SYSTEM DESCRIPTION

PRIMARY TECHNOLOGY

Six-Phase Heating™ (electrical resistive heating combined with soil vapor extraction)

SUPPLEMENTAL TECHNOLOGY TYPES

Air stripping (for extracted groundwater condensate)

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

System Description

SPH is a polyphase electrical technique for resistively heating soil and groundwater, creating an in situ source of steam to volatilize contaminants from the subsurface and remove the contaminants using soil vapor extraction. Steel pipes that serve as electrodes are installed in the subsurface and used to increase the temperature in the formation to the boiling point of water. As the temperature increases, dissolved contaminants partition to the vapor phase. Steam, created from boiling groundwater, acts as a carrier gas for stripping the volatile contaminants from the soil and saturated zone. According to the vendor, continuous heating also appears to cause pressure-driven microfracturing in low permeability soils, providing an accelerated release mechanism for removing contaminants from tight (low permeability) soil layers within the aquifer and soil column. In addition, the presence of DNAPL causes boiling to occur at a relatively lower temperature than that of either a pure contaminant or water; therefore, boiling results in the preferential release of DNAPL from the formation.

The SPH technology uses conventional 60-hertz utility transformers connected in a delta-star configuration to convert three-phase electricity from standard power lines into six electrical phases delivered to the subsurface. Electrodes are inserted using standard drilling techniques to couple the electrical power to the subsurface and are connected in a spatially phase-sequenced pattern. The voltage of each electrical phase can be adjusted as required to accomplish uniform heating throughout the formation. Figure 2 shows a layout of a typical SPH system.

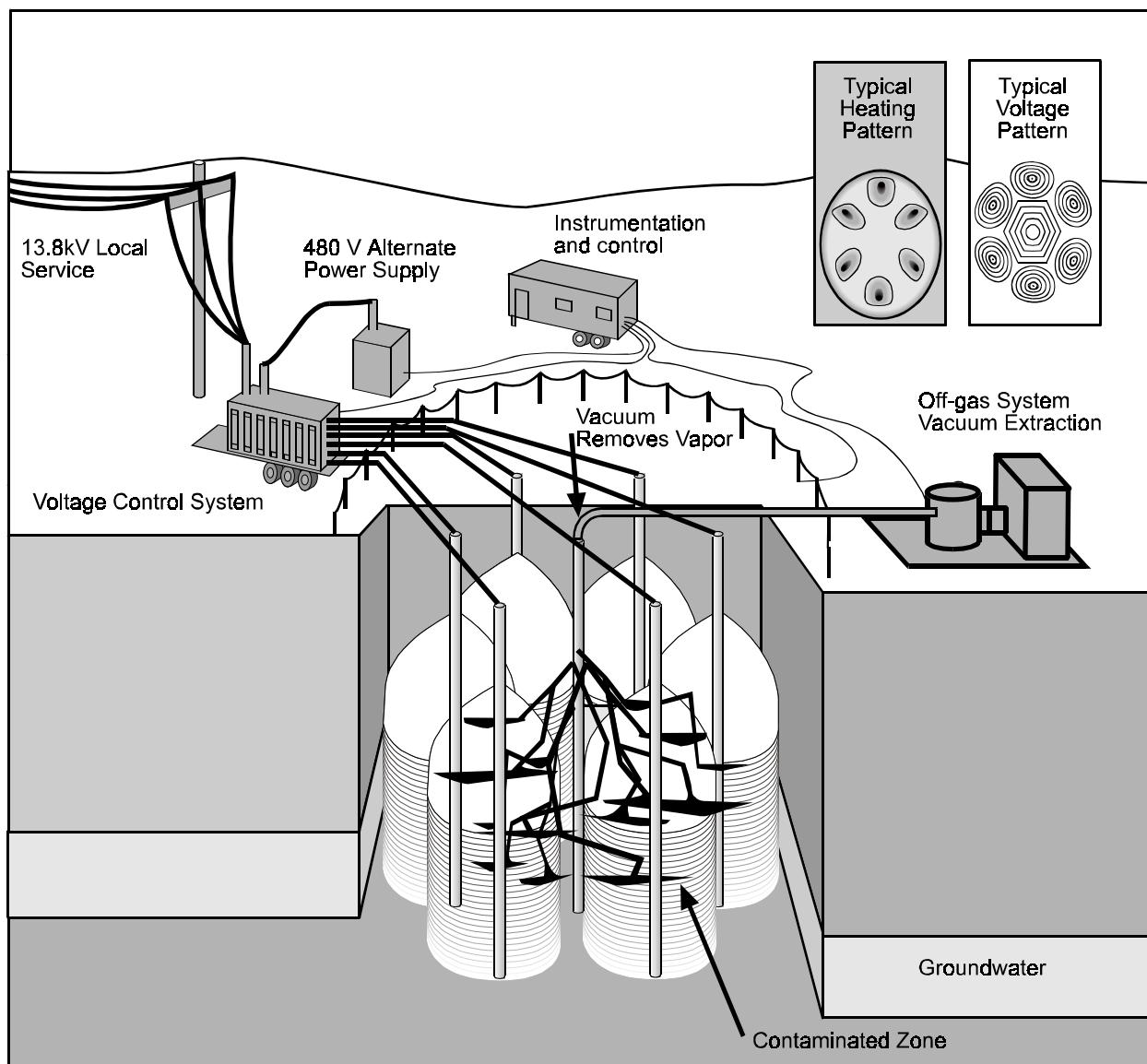
In addition to the electrodes and power supply, the other major components of an SPH treatment system are:

- A computer control and data acquisition system with fully remote communication.
- Vapor extraction vents and monitoring wells (temperature and pressure).
- An off-gas collection system (including piping, a blower, a steam condenser, and a condensate holding tank).
- An off-gas treatment system.

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.



Figure 2. Typical SPH™ Equipment Layout [7]



System Operation

The SPH 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. Based on the results of sampling conducted in December 1998 that 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, the treatment area was expanded. The SPH system was then expanded and restarted in December 1998 and operated until April 30, 1999.

During system operation, the SPH 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.

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 are available for March 1998, before the SPH was initiated, and from April 1998 through May 1999. During SPH treatment, up to 40 well points (from the previous steam injection system) were sampled on a periodic basis. According to ENSR, all of these well points were abandoned in July 1999 in accordance with Cook County Department of Public Health-approved procedures, after Illinois EPA issued a no further remediation letter. Post-remedial (natural attenuation) monitoring will be conducted using 10 well points.

OPERATING PARAMETERS AFFECTING TECHNOLOGY COST OR PERFORMANCE [3,6,7]

Parameter	Value
Temperature	100°C
Operating pressure/vacuum	7.5 inches of mercury (Hg)
pH	Not available
Electrical power input	13.8 kV local service at 1250 kW; 1,775 megawatt hours (MW-hrs.) consumed from June 4 to November 20, 1998; information not provided for Dec. 1998/Jan. 1999 through May 1999
Depth bgs (feet)	Electrodes conductive from 11 to 21 feet bgs, temperatures increased to boiling point of water from 5 to 24 feet bgs

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

- 1991-3/98 Steam injection and soil and groundwater extraction used at site
- 6/4/98 SPH system begins operation
- 8/4/98 (approx.) Temperatures throughout entire soil volume reach boiling point of water
- 11/20/98 Remediation to Tier III cleanup standards complete; system temporarily shut off
- 12/98-1/99 Additional system started; contamination found, based on groundwater contamination analysis
- 4/30/99 System shut off and demobilization began
- 7/99 Illinois EPA issues a no further remediation letter and well points abandoned
- 7/99-present Post-remedial (natural attenuation) monitoring conducted



TECHNOLOGY SYSTEM PERFORMANCE

CLEANUP GOALS/STANDARDS [4,10,13,14]

The following Tier III cleanup criteria for groundwater were developed by ENSR and reviewed 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.

Contaminant	Tier III Cleanup Level for Groundwater ($\mu\text{g/L}$)	Tier I Cleanup Level for Groundwater ($\mu\text{g/L}$)
cis 1,2-dichloroethene (DCE)	35,500	200
1,1,1-trichloroethane (TCA)	8,850	1,000
trichloroethene (TCE)	17,500	25

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

Performance data are presented for the remediation of the initial 23,000 cubic yards of remaining contamination at the site conducted from June to November 1998 and for the remediation of the additional 11,000 cubic yards of contamination at the site conducted from December 1998 to April 1999. Groundwater monitoring continued after system shutdown in April and data are available through May 1999.

Table 1 presents a summary of groundwater monitoring data from June to November 1998 for the three constituents of concern (DCE, TCA, and TCE). Figures 3, 4, and 5 are graphs showing changes in contaminant concentrations by well for DCE, TCA, and TCE, respectively, through May 1999.



**Table 1. Monthly Groundwater Quality During SPH Remediation of Area of Remaining Contamination [4]
(June 1998 to November 1998)**

Well No.	Constituent	RBCA Tier III Clean-up Level ($\mu\text{g/L}$)	Prior to SPH Remediation	During Remediation					
			3/24/98 ($\mu\text{g/L}$)	6/26/98 ($\mu\text{g/L}$)	7/15/98 ($\mu\text{g/L}$)	8/20/98 ($\mu\text{g/L}$)	9/17/98 ($\mu\text{g/L}$)	10/6/98 ($\mu\text{g/L}$)	11/20/98 ($\mu\text{g/L}$)
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 ($\mu\text{g/L}$) In Groundwater in Initial Area of Contamination (March 1998 to May 1999) [4]

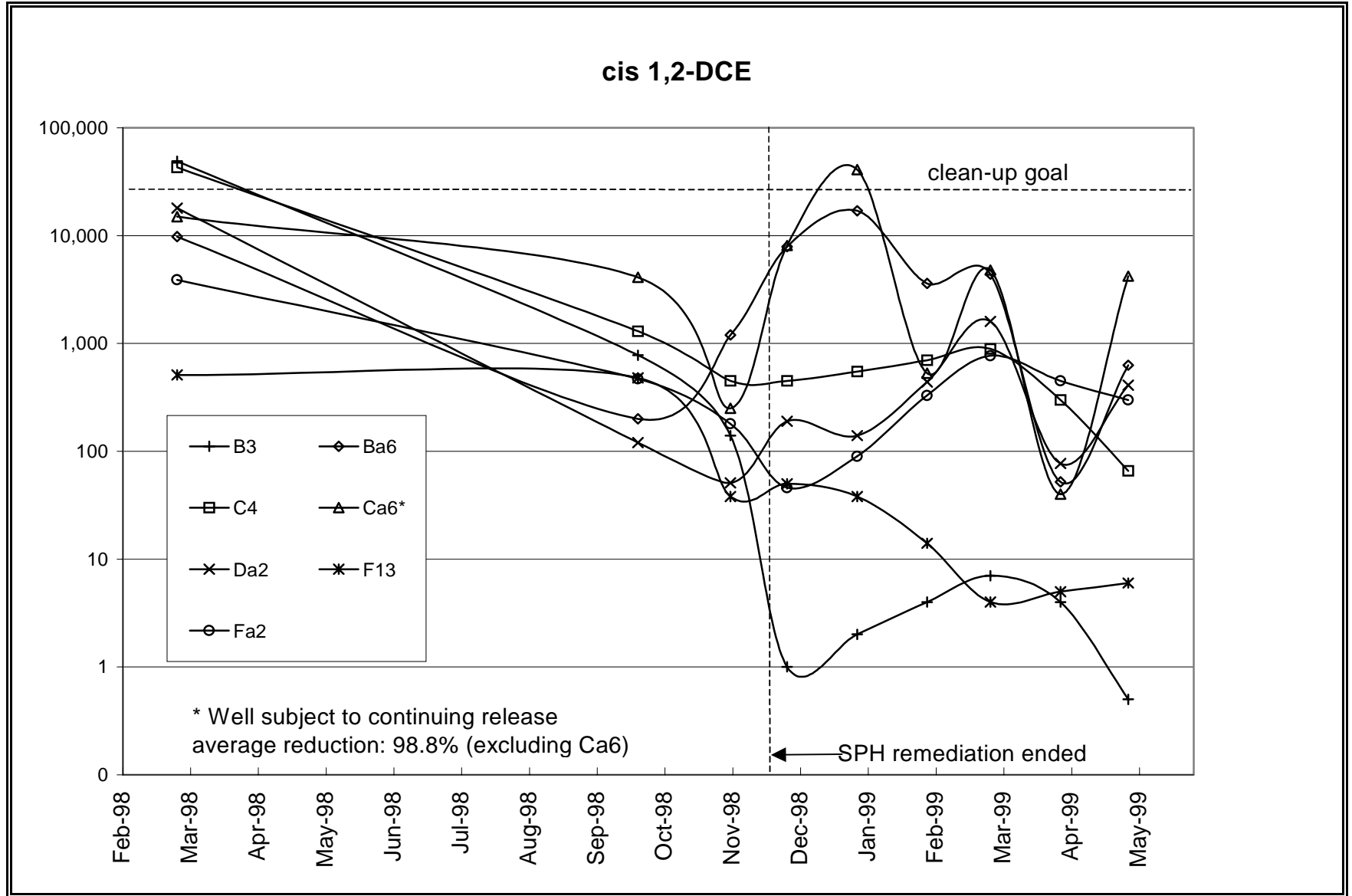


Figure 4. Monthly 1,1,1-TCA Concentrations (µg/L) in Groundwater in Initial Area of Contamination (March 1998 to May 1999) [4]

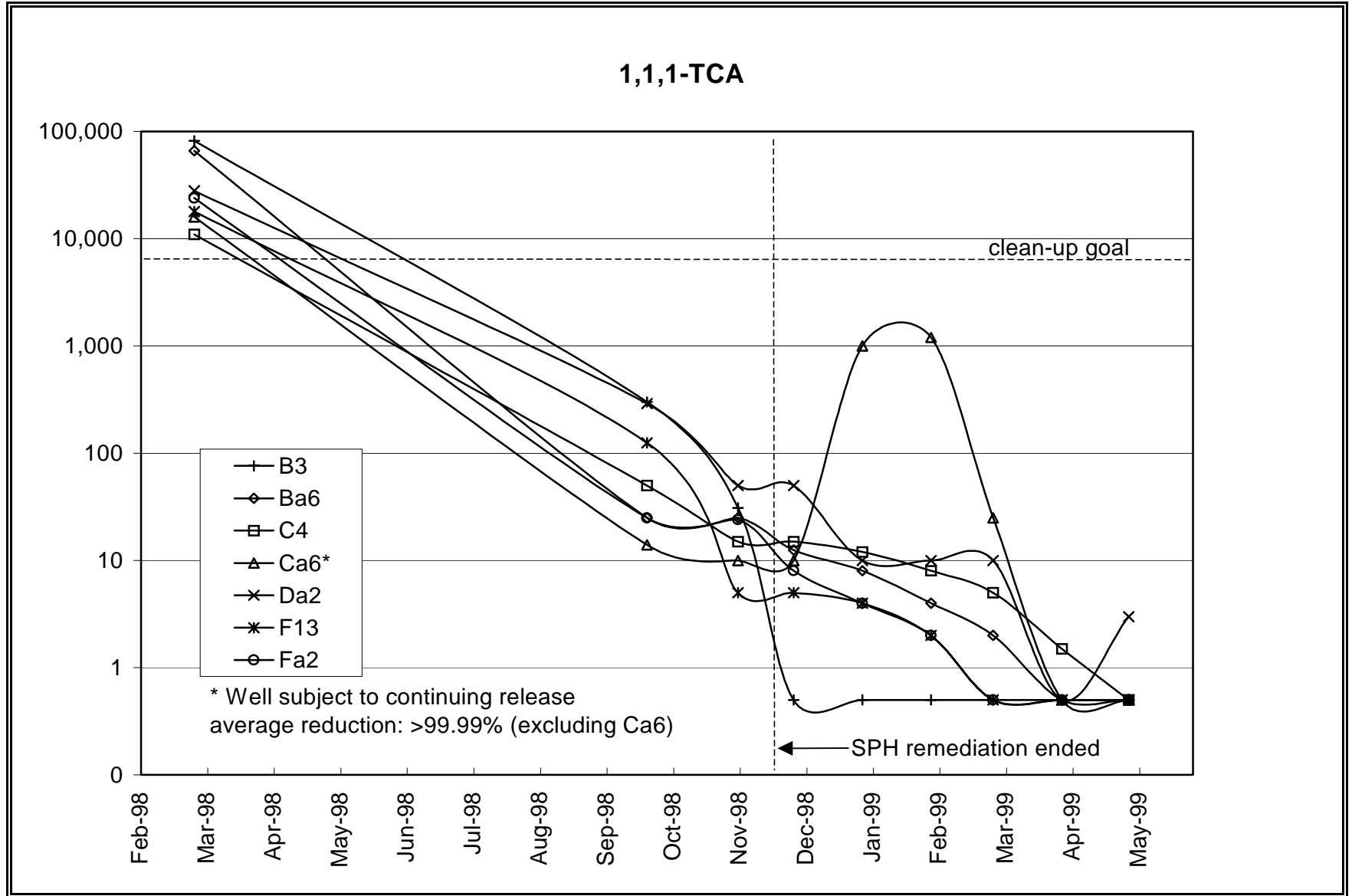
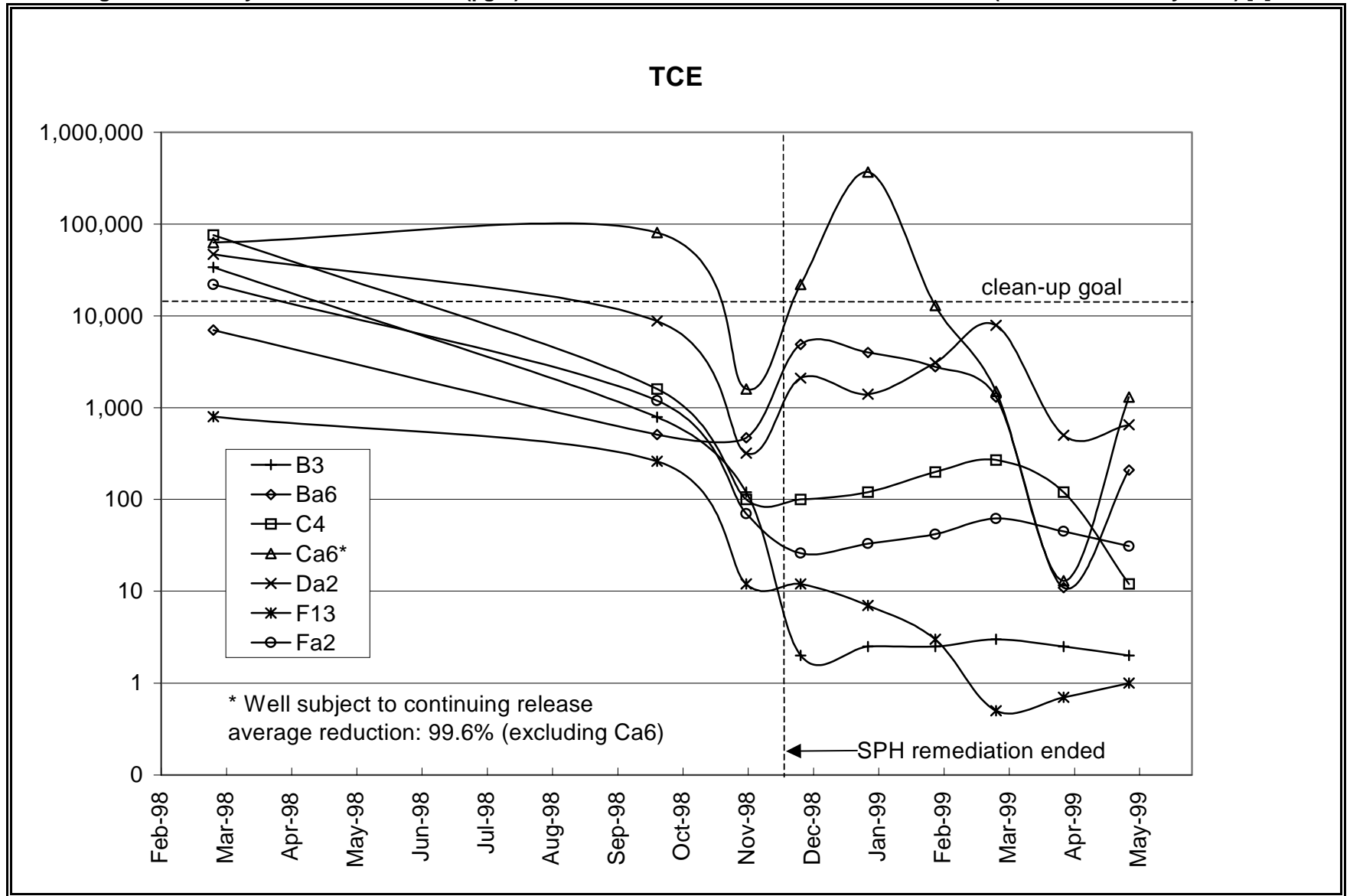


Figure 5. Monthly TCE Concentrations (µg/L) in Groundwater in Initial Area of Contamination (March 1998 to May 1999) [4]



As shown in Table 1, by November 20, 1998, the Tier III cleanup goals were achieved for the three constituents of concern in all seven wells. The reduction in contaminant concentrations ranged from approximately 470 to 48,000 $\mu\text{g/L}$ for DCE, 10,000 to 88,000 $\mu\text{g/L}$ for TCA, and 800 to 81,000 $\mu\text{g/L}$ for TCE. In addition, as of November 1998, concentrations of constituents 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 SPH operation, elevated levels of TCE (81,000 $\mu\text{g/L}$) were detected in well Ca6. According to ENSR, the source of the high concentrations of TCE was not known. Two solutions were implemented simultaneously by ENSR: 1) well Ca6 was converted to an electrode to improve heating in its vicinity; 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. Concentrations of TCE subsequently decreased.

Table 2 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 2, concentrations of DCE and TCE were higher than the Tier III cleanup levels in Well Ca6 in January 1999, but were subsequently lower than the cleanup levels by February 1999. As of April 1999 constituent concentrations in all wells were below the cleanup goals and the system was shut down. Groundwater monitoring data for May 1999 showed that constituent concentrations remained below cleanup levels.

Table 2. Monthly Groundwater Quality During SPH Remediation of Additional Area of Contamination [11] (December 1998 to May 1999)

Well No.	Constituent	RBCA Tier III Clean-up Level ($\mu\text{g/L}$)	December-98 ($\mu\text{g/L}$)	January-99 ($\mu\text{g/L}$)	February-99 ($\mu\text{g/L}$)	March-99 ($\mu\text{g/L}$)	April-99 ($\mu\text{g/L}$)	May-99 ($\mu\text{g/L}$)
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



Table 2. Monthly Groundwater Quality During SPH Remediation of Additional Area of Contamination [11] (December 1998 to May 1999) (continued)

Well No.	Constituent	RBCA Tier III Clean-up Level (µg/L)	December-98 (µg/L)	January-99 (µg/L)	February-99 (µg/L)	March-99 (µg/L)	April-99 (µg/L)	May-99 (µg/L)
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

PERFORMANCE DATA QUALITY

Thermocouples placed in the soil were used to monitor the heating pattern as a basis for adjusting the distribution of power and also to assist in determining the best electrical configuration for power delivery as the cleanup progressed.

Groundwater samples were extracted monthly and analyzed via head space extraction using an HP 5890 gas chromatograph equipped with an electron capture detector (GC/ECD). Standards for TCE, TCA, cis and trans 1,2-DCE and 1,1 DCE were used to calibrate the instrument. A subset of the sample population was analyzed using a gas chromatograph with a mass spectrometer (GC/MS) following EPA Method 8240. The same techniques were used to periodically monitor contaminant concentrations in the collected condensate.

Off-gas concentrations exiting the condenser were monitored using a flame ionization detector (FID). To correlate the FID signal with total vapor phase contaminant concentrations, grab samples were obtained using Tedlar bags and analyzed using the GC/ECD. The off gas measurements enabled estimates of the rate of contaminant removal and total removed mass throughout the site operation.



COST OF THE TECHNOLOGY SYSTEM

PROCUREMENT PROCESS [3,7,13]

The client was interested in finding a new technology that could enhance or accelerate the remediation of the remaining regions of the site that were determined to be difficult to clean-up with steam injection. The client's consultant, ENSR, performed an evaluation of several technologies for remediating the site and recommended alternatives, including subsurface heating via thermal conductivity from resistive heating elements and SPH.

COST DATA [5,7]

According to the vendor, at the request of the site owner, the total cost of remediation efforts to date could not be disclosed. However, on a per unit basis, the full-scale SPH remediation was completed at a total price of \$32 per cubic yard of treatment area as of November 1998. This cost included the installation and operation of the SPH power system and electrodes as well as vapor extraction and condensate treatment. The costs also included 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 SPH system. At full operation the electrical usage cost was \$14,000 per month plus \$40 per MW-hr. Over the course of the remediation, cumulative electrical costs totaled \$148,000. This corresponded to \$6.40 per cubic yard of treatment volume or 20% of the total cost of \$32 per cubic yard. The only costs not included in this total were final equipment demobilization, as these activities have not been completed.

The unit cost for this technology of \$32 per cubic yard is based on a calculated treatment volume of 23,100 cubic yards of soil and groundwater, or a treatment area of 26,000 square ft and a depth of 24 ft bgs.

The unit cost for the treatment from December 1998 through May 1999 also was \$32 per cubic yard, based on a calculated treatment volume of 11,500 cubic yards. [12]

REGULATORY/INSTITUTIONAL ISSUES

CES has an exclusive license to market the SPH technology in North America and specific markets in Europe and Asia. SPH was developed by Battelle Northwest Laboratories for the U.S. Department of Energy.

OBSERVATIONS AND LESSONS LEARNED

COST OBSERVATIONS AND LESSONS LEARNED

The unit cost of SPH at the Skokie site was \$32 per cubic yard of soil treated, including installation and operation over a 1-year period. Electricity costs accounted for 20% of the total unit cost for this application. This unit cost was the same for both the initial and additional treatment areas.

PERFORMANCE OBSERVATIONS AND LESSONS LEARNED

The SPH system used at the Skokie, Illinois 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.



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