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Thermal Treatment of Eight CVOC Source Zones to Near Nondetect Concentrations

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Abstract

In situ thermal desorption (ISTD) was used for the treatment of eight separate source zones containing chlorinated solvents in a tight loess (silt/clay) above the water table. The source areas were as much as 365 m (1200 feet) apart. A target volume of 38,200 m^3 (49,950 cubic yards) of subsurface material to a depth of 9.1 m (30 feet) was treated in a period of 177 days. Energy was delivered through 367 thermal conduction heater borings, and vapors were extracted from 68 vertical vacuum wells. A vapor extraction and capture system, including a surface cover and vertical vacuum wells next to heater borings, provided for effective pneumatic control and capture of the chlorinated volatile organic compound (CVOC) vapors. A central treatment system, based on condensation and granular activated carbon filtration, was used to treat the vapors. Approximately 5675 kg (12,500 pounds) of contaminants was recovered in the extracted vapors. Forty-seven soil samples were used to document remedial performance. Based on these, the concentrations of the target contaminants were reduced to below the target remedial goals in all eight areas, typically with concentrations below 0.01 mg/kg in locations that had had CVOC concentrations higher than 1000 mg/kg. Turn-key costs for the thermal remediation were \$3.9 million, and the unit treatment cost, including all utilities, was \$103 per cubic meter treated (\$79 per cubic yard).

Introduction

The release of man-made chemicals in the form of dense nonaqueous phase liquids (DNAPL) to the subsurface has created great environmental concerns. Soil and ground water contaminated with DNAPL are relatively slow to remediate naturally, with typical plume life expected to be hundreds or thousands of years. The longevity of DNAPL source zones is primarily caused by the environmental stability of the DNAPL, its immobility in the subsurface, low dissolution rate into moving ground water, and its low vaporization rate when located below the ground water table (Hunt et al. 1988; Mercer and Cohen 1990; Pankow and Cherry 1996).

Conventional in situ remediation techniques have used fluid injection and extraction at ambient temperature, and therefore often suffer from mass-transfer limitations (Hunt et al. 1988). Flushing with water and air has limited effect, because the DNAPL is relatively immobile, and the constituents dissolve and vaporize slowly at ambient temperature.

Thermal conduction heating, also named in situ thermal desorption (ISTD), uses simple heater elements hung in vertical borings to heat the subsurface by thermal conduction, while generated vapors are extracted under vacuum (Stegemeier and Vinegar 2001). Heating the subsurface to temperatures around the boiling point of water leads to dramatic changes in the thermodynamic conditions and makes the DNAPL much more mobile. The vapor pressure of the DNAPL increases markedly with temperature. As the subsurface is heated from 20°C to an average temperature of 100°C, the vapor pressure of the contaminants will increase by between 10-fold and 30-fold (Udell 1996). The Henry's law constant also increases dramatically during heating (Heron et al. 1998a). For chlorinated solvents such as trichloroethene (TCE) and tetrachloroethene (PCE), vaporization is therefore the dominant removal mechanism during thermal remediation (Hunt et al. 1988; Davis 1997; Imhoff et al. 1997; Heron et al. 1998c; Sleep and Ma 1997). Contaminants such as 1,1,2,2-tetrachloroethane (PCA), which are also subject to hydrolysis, can be completely removed at lower temperatures, as they mineralize (Jeffers et al. 1989). Figure 1 shows the half-life of PCA in aqueous solution as a function of temperature, based on Arrhenius' equation with an activation energy of 92 kJ/mol and a half-life at 25°C of 0.4 years (Jeffers et al. 1989). At temperatures above 70°C, the half-life is on the order of days or less.

The effectiveness of ISTD for site restoration of CVOC DNAPL sources to acceptable levels has been documented for several sites (Vinegar et al. 1999; LaChance et al. 2004, 2006; Heron et al. 2008). At these sites, typical target concentrations were in the range of 1 to 5 mg/kg for contaminants such as TCE and PCE, but the soil concentrations

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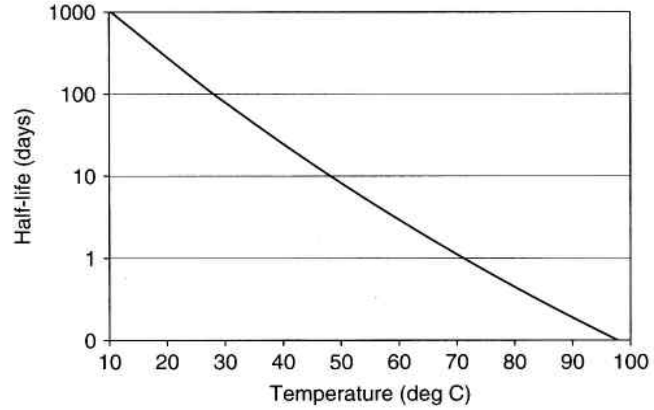

Figure 1. Theoretical temperature dependency of the half-life of PCA in solution and subject to hydrolysis (Arrhenius' equation used with an activation energy of 92 kJ/mol and a half-life at 25°C of 0.4 years).

achieved, based on confirmatory sampling, were in the range of 0.1 mg/kg or lower. Such results led to expectations that even lower CVOC goals can be met using ISTD.

At the Memphis Depot, eight CVOC source areas, extending to depths between 6 and 9 m, with starting concentrations in the range of 100 to 2850 mg/kg of CVOCs, had to be reduced to concentrations around 0.01 mg/kg (PCA) to 0.18 mg/kg (TCE and PCE). The reduction in soil concentration at several locations needed to be better than 99.99% to achieve the remedial goals and site closure. Thermal treatment was identified as the prime candidate technology. Among the options, ISTD was selected based on the high level of confidence in the results and the moderate treatment costs.

This paper presents the results of a full-scale ISTD remediation of eight CVOC-impacted source areas with stringent treatment goals. A mixture of CVOC contaminants was present in the different areas, but the extracted vapors were treated simultaneously using one process system, resulting in complete site restoration and favorable treatment costs.

Memphis Depot Site Description

The Memphis Depot is located in southeastern Memphis, Tennessee. The depot originated as a military facility in the early 1940s. Its initial mission and function was to provide stock control, materiel storage, and maintenance services for the U.S. Army. In 1995, the depot was placed on the list of Department of Defense (DoD) facilities to be closed under the Base Reenactment and Closure (BRAC) program. Storage and distribution of materiel for all U.S. military services and some civil agencies continued until the depot closed in September 1997. Dunn Field is approximately 64 acres of undeveloped land, previously used for storage and stockpiling of materials, including hazardous chemicals. Approximately two-thirds of Dunn Field is covered with grass, and the remaining area is covered with crushed rock and paved surfaces. All of Dunn Field is zoned for light industrial (I-L) use.

Figure 2 presents a schematic cross section of the site. The impacted vadose zone at Dunn Field consists of two distinct geological units: (1) a shallow, relatively low-permeability loess, and (2) a deep, relatively high-permeability alluvium composed of sands, sands and gravels, and discontinuous layers of silt and clay that collectively have been referred to as the fluvial deposits. The loess, a semicohesive aeolian deposit composed of silt, silty clay, silty fine sand, and mixtures thereof, extends from the ground surface to a

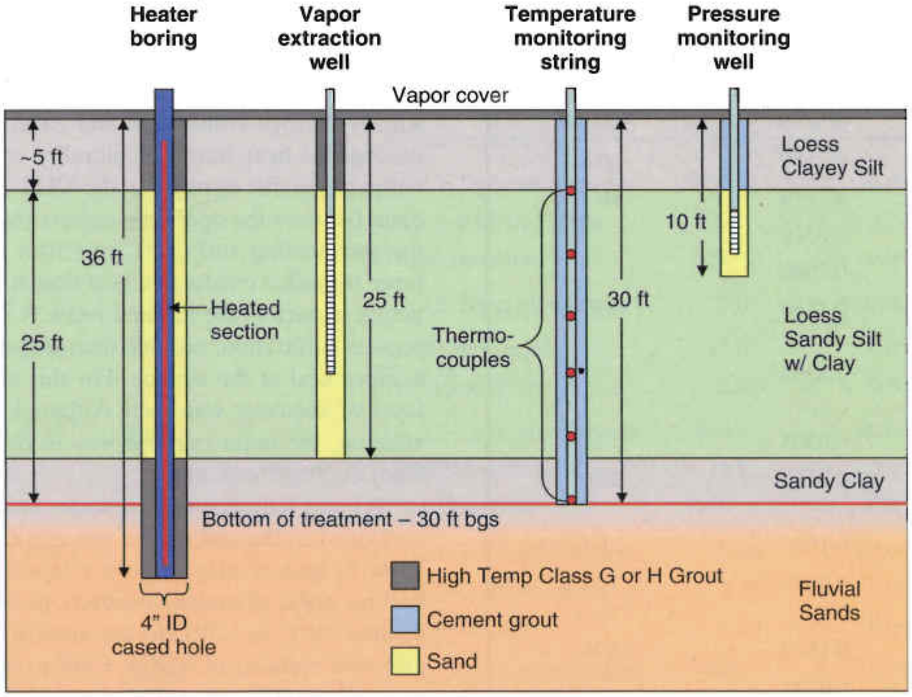

Figure 2. Schematic cross section showing stratigraphy and ISTD borings and wells for an area treated to 30 feet depth.

depth of about 30 feet below ground surface (bgs). Underlying the loess are several feet of sandy clay, followed by 30 to 75 feet of the fluvial sands, silt, and gravel. The upper 10 feet of the fluvial deposits represents a transition zone between the silt-dominated loess and the sand and gravel of the fluvial deposits. The ground water table is found in the fluvial deposits at approximately 23 m (75 feet) below grade, deeper than the CVOC impacts addressed by the ISTD remedy. The shallow ground water is not used as a source of drinking water.

Subsurface soil samples collected at Dunn Field have shown significant levels of CVOCs, including PCA; 1,2-dichloroethane (DCA); 1,2-dichloroethene (1,2-DCE); carbon tetrachloride (CT); chloroform (CF); methylene chloride; PCE; TCE; and vinyl chloride. The highest CVOC concentrations were detected in the northwest corner of Dunn Field: PCA at 2850 mg/kg; TCE at 671 mg/kg, *cis*-DCE at 199 mg/kg, and PCE at 35.7 mg/kg. The contaminants of concern (COCs) and remedial goals are listed in Table 1 along with the maximum concentrations detected.

Several source areas were identified for remediation of subsurface soil. A remedial design investigation (RDI) was performed in 2005 and 2006 to increase soil data density in the four soil treatment areas to delineate CVOC soil contamination laterally and down to a depth of approximately 30 feet, where the loess deposits transitions to the fluvial sands. The RDI included a membrane interface probe (MIP) investigation to characterize the magnitude and extent of elevated CVOCs in the loess using a 40-foot × 40-foot grid. Soil samples were collected from select MIP locations for laboratory analysis to correlate the data sets and adequately delineate the areas with CVOC concentrations below the MIP detection limit but above the established Dunn Field remedial goals (RGs). More than 160 locations were investigated with the MIP and more than 80 soil samples were collected. The collective interpretation of available data led to identification of the eight source areas shown in Figure 3. The MIP and soil sample data clearly delineated the areas requiring treatment; each treatment area was surrounded by MIP or sample locations below RGs. Table 2 shows the surface area, depth, and volume of each of the eight treatment areas. The total surface area is 4950 m^2 (1.25 acres), and the total treatment volume is 38,200 m^3 (49,900 cubic yards).

Table 1

Contaminants of Concern and Remedial Target Concentrations

Parameter	Remedial Target Concentration (mg/kg)	Maximum Starting Concentration (mg/kg)
Carbon tetrachloride	0.2150	6.8
Chloroform	0.9170	96.2
Dichloroethane, 1,2-	0.0329	
Dichloroethene, 1,1-	0.1500	
Dichloroethene, *cis*-1,2-	0.7550	199
Dichloroethene, *trans*-1,2-	1.5200	
Methylene chloride	0.0305	
Tetrachloroethane, 1,1,2,2-	0.0112	2850
Tetrachloroethene	0.1806	21.1
Trichloroethane, 1,1,2-	0.0627	
Trichloroethene	0.1820	671
Vinyl chloride	0.0294	

For the contaminants that exceeded the remedial goals before treatment, the maximum concentration is shown.

Description of Field Implementation

ISTD is the simultaneous application of heat by thermal conduction and vacuum to contaminated soil. Soil is heated using a network of thermal wells installed throughout and immediately surrounding the target treatment zone (TTZ). Figure 4 shows the layout of heater and extraction wells for one of the treatment areas. The heaters were spaced between 15 and 18 feet apart in the different treatment areas, customized based on the presence of contaminants, their boiling point and hydrolysis rates, and the shape of each area. Areas such as Area 3, which has relatively modest starting concentrations, have heater wells spaced the farthest apart, whereas small areas such as Area 1B with high concentrations of PCE and TCE have closer well spacing. Areas dominated by PCA had a larger spacing, because hydrolysis facilitates degradation of PCA at temperatures below the boiling point of water, such that heating to around 90°C is sufficient for effective treatment. Because the potential by-products of the hydrolysis include TCE, the area was heated and treated such that TCE also would be effectively removed.

Figure 2 contains a schematic of the borings and well installed. Electrically powered heating elements suspended vertically within the thermal borings deliver 1.15 kW/m (0.35 kW/feet) over their entire length, when at full power. The heat front moves away from the heaters through the soil by thermal conduction and convection, and the superposition of heat from the plurality of heaters results in a temperature rise throughout the TTZ. The high thermal gradient between the operating heaters (600°C and 800°C) and the surrounding soil (10°C to 15°C) serves as the driving force for radial conductive heat flow to occur over the entire length of each of the thermal wells. A vapor cover is used to prevent infiltration, provide thermal insulation, and provide a vapor seal at the surface. For this site, a simple sprayed layer of shotcrete was used. Although it provided some insulation, the main purpose was to divert rain water away from the treatment areas.

As soil temperatures increase, contaminants and water contained in the soil matrix are vaporized. While locations close to heaters may achieve temperatures well above the boiling point of water, locations in between heaters must achieve 90°C to 100°C to accomplish steam distillation for effective removal of VOCs. Concurrently, hydrolysis leads to mineralization of contaminants such as PCA.

The vacuum applied to the extraction wells from the process system draws vapors through the hot soil around

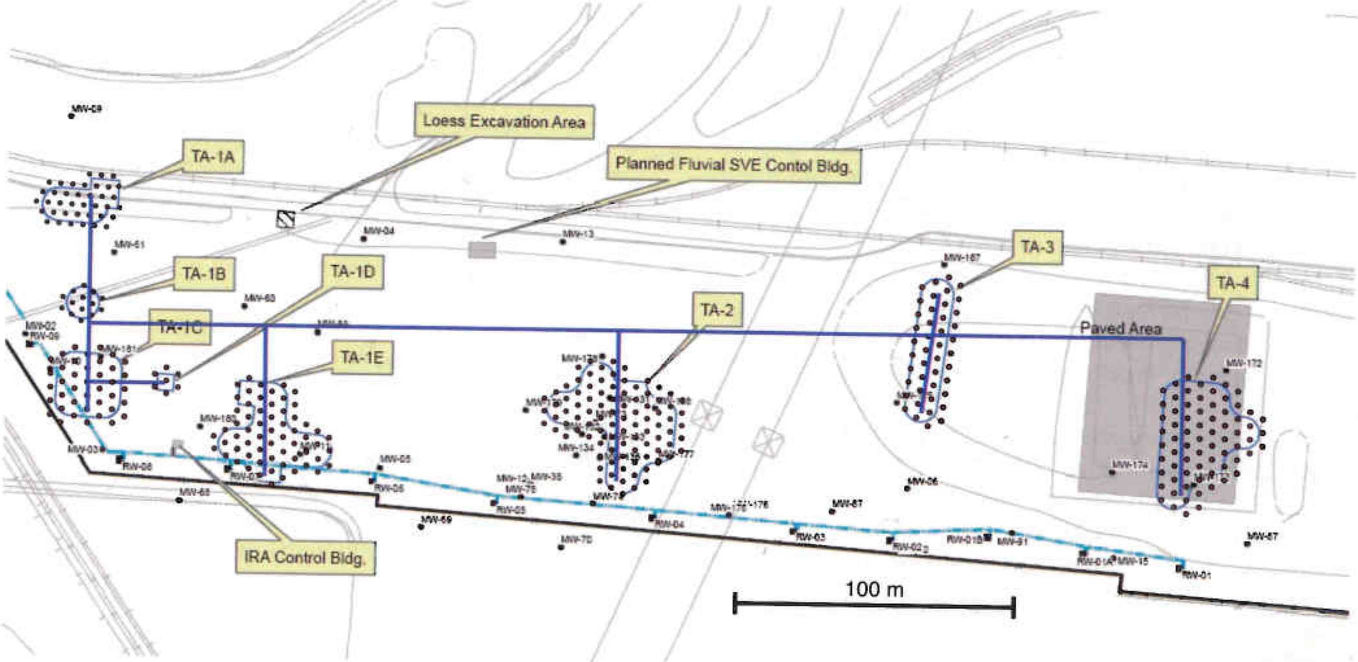

Figure 3. Location of the eight source areas at Dunn Field in Memphis, Tennessee. ISTD heaters are shown as red dots; conveyance piping for extracted vapors is shown in blue.

Table 2

Areas, Depths, and Treatment Volumes for the Eight Source Areas, with Primary Contaminants and Maximum Concentrations before and after Treatment, and Percent Reduction

Source Area	Area (m²)	Treatment Interval (m)	Volume (m³)	Number of Confirmatory Samples	Primary Contaminants	Max Soil Concentration Before (mg/kg)	Max Soil Concentration After (mg/kg)	Percent Reduction (%)
1A	345	1.5–6.1	1578	3	Carbon tetrachloride	6.8	<0.005	>99.93
					Chloroform	14.0	0.053	99.62
1B	117	1.5–9	890	1	cis-1,2-Dichloroethene	123.0	0.005	100.00
					Tetrachloroethene	20.8	0.010	99.95
					Trichloroethene	21.5	0.009	99.96
1C	563	1.5–9.1	4288	4	1,1,2,2-Tetrachloroethane	2850	0.005	100.00
					cis-1,2-Dichloroethene	199	0.132	99.93
					Trichloroethene	671	0.044	99.99
1D	37	1.5–9.1	283	1	1,1,2,2-Tetrachloroethane	0.03	<0.0027	>91.56
1E	861	1.5–9.1	6560	6	1,2-Dichloroethene	17.0	0.017	99.90
					Trichloroethene	2.42	0.031	98.72
2	1233	1.5–10.7	10899	8	1,1,2,2-Tetrachloroethane	1850	<0.003	>99.99
					Tetrachloroethene	21.1	<0.005	>99.98
					Trichloroethene	170	0.417	99.75
3	631	1.5–9.1	4805	5	1,1,2,2-Tetrachloroethane	3.11	<0.003	>99.90
					cis-1,2-Dichloroethene	3.35	0.006	99.82
					Trichloroethene	1.56	0.041	97.37
4	1163	1.5–9.1	8864	7	1,1,2,2-Tetrachloroethane	190	<0.016	>99.99
					Chloroform	96.2	0.929	99.03
					Trichloroethene	4.28	0.082	98.08

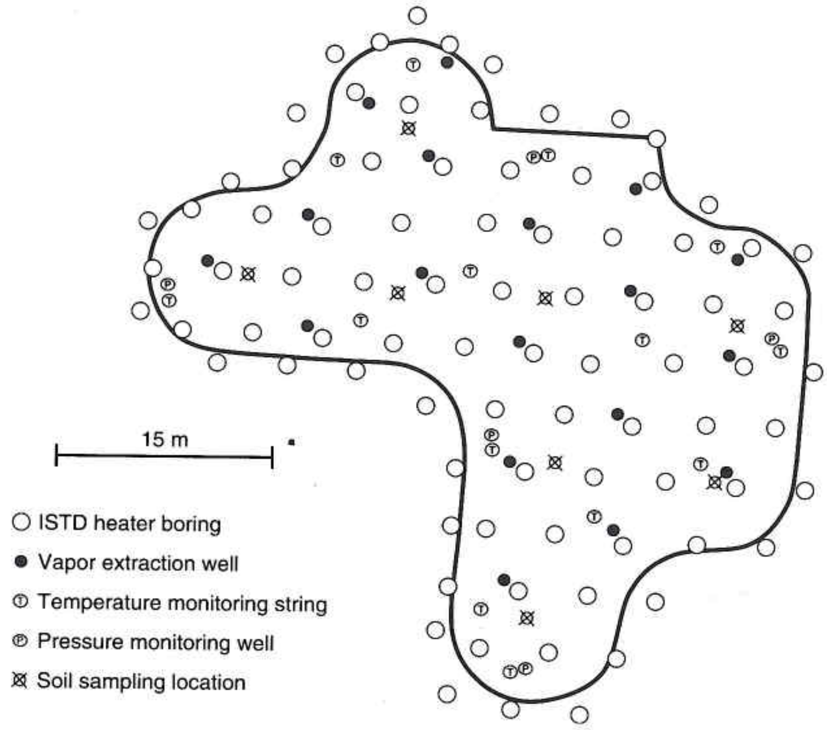

Figure 4. Detailed well-field layout for treatment Area 2. Locations for temperature and pressure monitoring, as well as performance sampling, are also shown.

a subset of the thermal borings (68 locations out of 367 heaters). Vapor treatment is completed within an off-gas treatment unit. The unit consisted of cooling, condensation, phase separation, and granular activated carbon (GAC) filtration. Emissions and discharges met all local and regional requirements as specified in the proper permits.

The heater-only wells are 7.6-cm (3-inch) diameter steel-cased wells housing thermal conduction heaters. Each of these contains a stainless steel heater that is controlled using thermocouples and a silicon controlled rectifier (SCR), allowing the power delivered to the heating elements to be adjusted as needed. The vacuum wells are 5-cm (2-inch) diameter screened wells, set in a sand pack.

The TCH heating system consisted of step-down transformers, energy distribution gear, and the SCR controllers that regulate power to each heater circuit. A total of 4500 kW of power could be delivered to the 367 heater borings (between 9 and 12 kW per heater well).

Heating progress was measured using 63 temperature monitoring strings, each with electronic temperature sensors located at 1.5-m (5-foot) intervals from depths from 1.5 m (5 feet) to the total treatment depth (typically 9 m [30 feet]). In addition, 26 shallow pressure monitoring wells were used to document negative pressure in the formation during heating. Subsurface pressures were recorded using pressure gauges installed at the top of the steel risers connected to a buried screen.

The remedial action objective (RAO) for thermal treatment of the loess required that the average concentration for each CVOC in each treatment area (defined as TA-1 areas combined, TA-2, TA-3, and TA-4) be below the remediation goal, and that no individual sample result exceeds the remediation goal by a factor of 10 or more. For samples that were nondetect, the average was calculated using one-half the laboratory reporting limit.

Soil confirmation samples were collected in a phased approach. The sample locations were selected based on previous sample results and included the locations with the highest reported CVOC concentrations. Samples were planned at multiple depths from several locations with a total of 47 samples from 35 borings. The initial confirmation samples were collected when soil temperatures in the treatment areas approached 90°C on Days 83 to 85 of treatment operations. Round 2 soil samples were collected at the completion of the planned treatment period on Days 106 to 108. After Round 2, sample results demonstrated that CVOC concentrations were below remediation goals at 33 of the 47 locations. Treatment operations were focused in the recalcitrant areas, and locations were resampled at 2- to 3-week intervals until the final sample was collected on Day 174 and the RAO was met in all areas.

Soil samples were collected by direct-push sampling with a Geoprobe 6620DT. Soil cores were collected in a 24-inch steel sampling tool with a Teflon disposable sleeve. The Teflon sleeve was removed from the sampling tool, capped at both ends, placed in a shallow basin containing ice, and cooled until the sample reached ambient temperature as determined by an infrared thermometer. At each sample depth, three EnCore® samples were collected for analysis of volatile organic compounds by EPA Method 8260. Borings for repeat samples were located 1 to 3 feet from the previous location(s).

Vapor monitoring of the thermal treatment system included field measurements and laboratory analyses. Photo-ionization detector (PID) readings were collected 6 days/week at the vapor treatment area. Measurements were made at four locations: the well field influent prior to any treatment; the influent to the granular activated carbon (GAC) treatment vessels; between the two operating carbon treatment vessels; and at the vapor discharge. PID readings were also collected at the vapor extraction header pipe from each treatment area; the frequency was increased from every two weeks to every other day on Day 108.

At the well-field influent and the loess treatment area headers, a vacuum pump was used to overcome the vacuum of the soil vapor extraction (SVE) system. The vacuum pump was connected to the individual sampling ports with short Teflon tubing and allowed to purge for 2 to 3 min; the sample was then collected from the outflow of the vacuum pump. At the three locations in the vapor treatment system, a vacuum pump was not required. A short piece of Teflon tubing was connected to the sampling port and allowed to purge for 2 to 3 min. The samples for PID readings were collected in a 1-L dedicated Tedlar sample bag. After filling, the bag was connected directly to the PID through a moisture trap and the peak value was recorded. The PID was calibrated daily to a 100 ppmv isobutylene standard.

Vapor samples were collected monthly at the influent to the GAC treatment vessels and at the vapor discharge. Samples were collected in 6-L Summa canisters and submitted for VOC analysis using EPA Method TO-15. The results were used with the daily PID readings to estimated CVOC mass removed in the vapor stream.

Energy balance calculations were based on simple heat transfer equations and enthalpy of vaporization for water at 100°C. Energy flux in the extracted steam was calculated as the mass of condensate produced in the condenser times a unit energy content of 2230 kJ/kg (1050 BTU/pounds). The number of pore volumes of steam generated and extracted was estimated from the condensate totals, converted to a steam volume at 100°C using steam table values for steam density (0.60 kg/L), a porosity of 30%, and volume (38,200 m^3 = 49,950 cubic yards) of the treatment zones. The average temperature achieved was estimated from simple averaging of all the thermocouple measurements in each treatment area. It should be noted that this created a bias toward lower numbers, because the majority of the temperature monitoring locations were at the coldest locations in the center of the equilateral triangle formed by three heaters (centroid locations), and the fact that hot zones around each heater well were not accounted for. This provided a safety margin during operations—ensuring that all locations are properly heated before operations were ended in an area.

Mass removal estimates were derived from vapor flow rate data and measured vapor concentrations. Daily fluctuations were recorded using a PID. The PID data were calibrated to the laboratory sampling results, with response factors adjusted over time as the vapor composition would change.

Results

Extraction of vapor began on May 27, 2008. The ISTD heating was started and slowly ramped up to the design power input of between 3500 and 4500 kW over a period of 5 days. The power delivered to the eight treatment areas is shown in Figure 5. The ISTD system operated continuously with minimal downtime, and the treatment areas heated to the target temperature over a period of between 95 and 120 days, with substantial variation from area to area. The calculated average temperatures in each of the eight areas are shown in Figure 6. Interim and confirmatory soil samples were collected on six occasions during treatment to track the progress, until the last area had met the cleanup criteria after 174 days of heating. A period of controlled cool-down followed in each area, with vapor extraction continuing for a minimum of 10 days, until all operation was completed by December 4, 2008. All ISTD equipment was demobilized by February 2009.

Electrical energy delivered and energy removed as steam is shown in Figure 5, and a cumulative energy balance is shown in Figure 7. The power input reached a level between 3000 and 4500 kW after 10 days of operation, and steam extraction became significant after 4 weeks of heating, before peaking between days 90 and 150 at a rate corresponding to 1500 kW, or approximately 50% of the power injection at that time. By the end of operation, 10.6 million kWh of

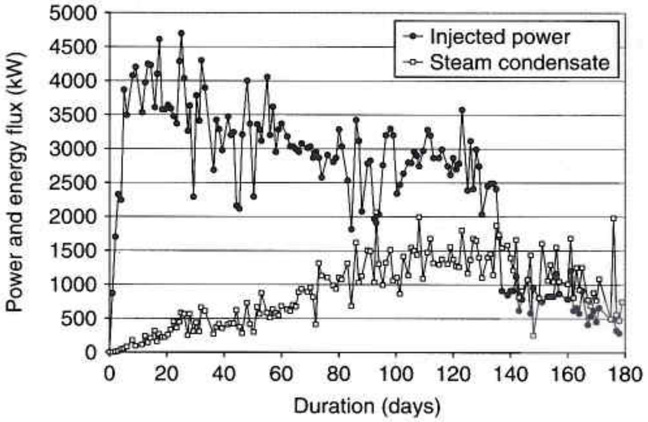

Figure 5. Electrical energy delivered to and energy removed as steam from the eight treatment areas. Note the drop in power supply on Day 135 when two large areas had met the cleanup criteria and were de-energized.

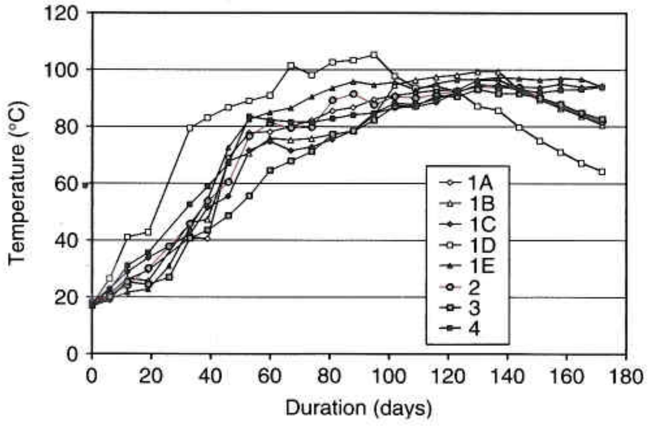

Figure 6. Calculated average subsurface temperature for the eight source areas. After reaching the remedial standards, heating was suspended in each area and cooling started (note the different heating shutdown times).

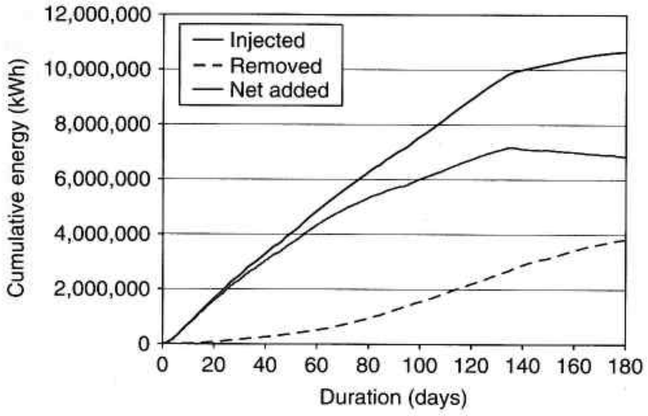

Figure 7. Cumulative energy balance for the ISTD operation.

electric power had been delivered, and 3.8 million kWh of energy in the form of steam had been removed, corresponding to 36% of the injected energy. The energy delivered corresponded to 289 kWh/m^3 (221 kWh per cubic yard) of soil and sediment within the treatment zone.

The vapor extraction system removed approximately 1350 Nm^3/h (800 scfm) of air and steam during operations. When the system was shut down after 180 days of operation, a total of 3.0 million L (793,000 gallons) of steam condensate had been recovered. Based on an average porosity of 30%, the pore volume of the treatment zones is 11,010 m^3 (14,400 cubic yards). With a steam density of 0.62 g/L at atmospheric pressure, the steam removed from the subsurface corresponds to 4.8 million m^3 (6.3 million cubic yards), which is equal to approximately 436 pore volumes of steam generated and extracted from the TTZ. This steam generation, sweep through the subsurface, and extraction is the main mechanism for the physical removal of contaminants.

Contaminant concentrations in the extracted vapors started increasing immediately after start of operations (Figure 8). The concentrations peaked after 90 days of heating and remained high until Day 130, and then declined steadily as the depleted treatment areas were shut down. At the end of ISTD operation, concentrations in the extracted vapors were below 20 ppmv, and an estimated total of 5675 kg (12,500 pounds) of VOCs had been removed in the vapor phase.

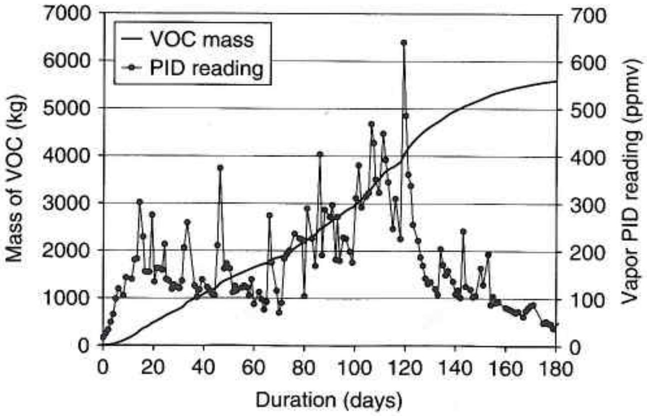

Figure 8. PID readings of extracted vapors and cumulative mass removed in the vapor phase.

Interim soil sampling was conducted on six occasions, with repeat sampling of locations that exceeded the target criteria during the previous sampling round. Forty-seven confirmation soil samples were collected from 35 sample locations and depths. Locations were added to improve spatial distribution within the treatment areas and vertical distribution within the treatment interval. Although the target treatment interval was typically from about 1.6 m to either 6 or 9 m bgs (depending on the source area), three of the confirmation samples were collected from shallower depths of 0.6 and 0.9 m bgs because CVOC concentrations were above RGs at these locations before thermal treatment. The selected sample locations included the locations with the highest CVOC concentrations based on analytical or MIP results. The confirmation sampling program was reviewed and approved by EPA and Tennessee Department of Environmental Control (TDEC) before implementation.

Table 2 summarizes the treatment results, as well as peak concentrations at the sampling locations measured before thermal treatment. At the end of thermal treatment, all CVOC remedial goals were met.

The maximum soil concentration of any of the contaminants after ISTD treatment was 0.93 mg/kg for chloroform and 0.42 mg/kg for TCE, both in Area 4. These values were both flagged by a "J" by the analytical laboratory, meaning that these are estimated values. These results were from samples collected before treatment was completed. The locations were not resampled because the concentrations were only slightly above the remediation goals and did not prevent meeting the remedial action objective.

Table 2 shows the percent reduction in the peak concentrations. Generally, the reduction in concentration was on the order of 99.99% for CVOCs that were present in high concentrations before the thermal treatment. Approximately 5675 kg (12,500 pounds) of contaminants were removed in the vapor stream. An additional quantity was likely degraded by hydrolysis. This dramatic reduction in contaminant mass, and the reductions in soil concentrations at the site facilitated successful closure of the eight source areas.

The project costs are summarized in Table 3. Terra-Therm was hired by engineering-environmental Management (e^{2}M) as the sole contractor, after the successful response to a request for proposal in early 2007. The total thermal treatment cost was $3.9 million, which corresponds to a unit cost of $103/m^3 ($79/cubic yard). This cost is inclusive of all project expenses, including design, utility line protection, power drop, and electricity. The unit costs do no include e^{2}M's oversight and interim/confirmatory sampling.

Discussion

Figure 9 shows a conceptual model of the ISTD process as the heat spreads between two heaters by thermal conduction. Close to the heaters (within 1 m [3 feet]) the pore water is evaporated and the soil dries and heats to above 100°C. The hot and dry conditions provide a zone of elevated gas permeability. As the heating progresses, boiling temperatures are achieved at larger distances from the heaters, and steam

Table 3
Project Costs and Breakdown

Workplan	$25,399
Design & permitting	$131,331
Drilling	$548,003
Construction	$1,230,162
Operations	$660,497
Transformer installation and power usage	$1,009,736
Activated charcoal usage w/disposal	$103,891
Demobilization	$142,795
License fee	$80,582
Total thermal treatment cost	$3,932,396
Oversight, sampling, and utility protection	$816,547
Total project cost	$4,748,943
Treated volume, cubic meters	$38,167
Unit thermal treatment cost, per cubic meter	$103
Unit thermal treatment cost, per cubic yard	$79

is generated deeper into the soil matrix. The generation of steam leads to a 1600-fold expansion of the water (based on water and steam densities at 100°C and 1 atm pressure of 970 and 0.62 g/L). The steam generation at the pore scale is believed to be the major removal mechanism for contaminants during thermal remediation (Udell 1983; Yuan and Udell 1993). It was also the major mechanism identified during a laboratory-scale demonstration of thermal treatment of a silt layer contaminated with TCE (Heron et al. 1998b). After heating of the zone between heater borings, gas-phase permeability allows for a sweep of steam toward the extraction wells, effectively connecting all the boiling zones via heated pathways, through which the steam can migrate and be captured. For thermal remediation, it is crucial to understand not only how the site is heated, but also how the generated vapors migrate and are captured by the extraction system. At this site, the vapor cover assisted in the capture of the contaminants, preventing rain infiltration, and by providing thermal insulation so the upper few meters of the site could be heated effectively, enabling the steam to sweep through instead of condensing.

Toward the end of the projected duration of the thermal treatment, interim sampling indicated a small subset of locations where the VOC concentrations remained above the remediation criteria. This occurred mainly in the most low-lying areas, where precipitation caused a high water content of the soils prior to and during thermal operations. Treatment of these areas was accelerated by the installation of additional vapor extraction wells around these recalcitrant areas. These wells were alternated between air injection and vapor extraction during the final weeks of operation to increase the flow and exchange of vapors in these areas, and resulted in the remedial goals being met. Similar modifications were used previously at the Young-Rainey STAR Center, where thermal remediation was challenged by the presence of a low-permeability layer (Heron et al. 2005).

At every site, the number of samples and the resolution of the sampling grid will limit the certainty with which conclusions can be drawn. Confirmatory sampling was biased high at this site by selection of the locations that had the

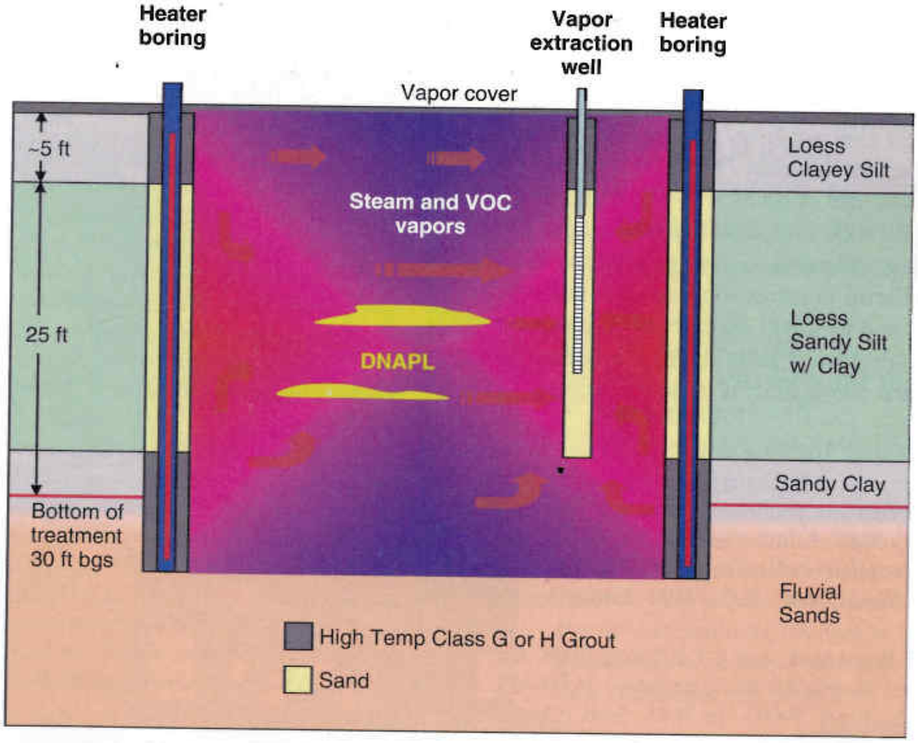

Figure 9. Conceptual model showing heating, migration, and capture of steam and VOC vapors. Note that the upper part of the unsaturated zone was heated to near steam temperatures, allowing steam to flow through to extraction wells without condensing.

highest pretreatment concentrations. The ISTD treatment was applied uniformly across all eight source areas with the same level of treatment. The 47 soil samples collected for confirmatory sampling all showed concentrations of the target contaminants below the RGs. This data indicates that final concentrations in areas with less contamination would have been even lower. However, few samples were collected outside and above or below the target treatment volumes, where the concentrations were below RGs to begin with. The nature of the thermal technology applied here, combined with experience from other similar CVOC sites treated using ISTD, suggested to the authors that low concentrations would have been measured if more sampled had been collected in such areas. The combined evidence of the substantial hotspot reductions in concentration and the mass recovery curves indicating that the sites were depleted in COCs at the end of thermal treatment was taken as an indication that all areas had met the remedial standards at this site.

Conclusions

In situ thermal desorption was shown to be highly effective for treatment of chlorinated solvents in eight CVOC source zones. The eight areas were heated in a period of 177 days, and 5675 kg (12,500 pounds) of CVOC contaminants were recovered. Soil concentrations of all contaminants were reduced from concentrations over 1000 mg/kg (indicating the presence of DNAPL) to below 1 mg/kg in all 47 confirmatory soil samples, with all remedial goals met. This was accomplished by the use of 289 kWh/m^3 (221 kWh/cubic yard), and a unit treatment cost of \$103/m^3 (\$79/cubic yard).

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