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World's Largest In Situ Thermal Desorption Project: Challenges and Solutions

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Abstract

This paper presents the largest In Situ Thermal Desorption (ISTD) project completed to date. The redevelopment of a former aerospace manufacturing facility adjacent to a commercial airport was the main driver, requiring relatively rapid reduction of several chlorinated volatile organic compounds (CVOC) in a 3.2-acre source zone. The source zone was divided into four quadrants with differing treatment depths, heated simultaneously using a total of 907 thermal conduction heater wells. Five different depths were selected across the area, according to the depth of contaminant impact. Prior to implementation, a risk and optimization study led to placement of a vertical sheet-pile wall around the treatment zone to minimize groundwater flow, and a pilot test of a novel direct-drive method for installation of the heater casings. Because of a shallow water table, a layer of clean fill was placed over the treatment zone, and partial dewatering was necessary prior to heating. A network of vertical multiphase extraction wells and horizontal vapor extraction wells was used to establish hydraulic and pneumatic control and to capture the contaminants. The site was split into four decision units, each with a rigorous soil sampling program which included collecting a total of 270 confirmatory soil samples from locations with the highest pretreatment CVOC concentrations requiring reduction to below 1 mg/kg for each contaminant. Temperature monitoring and mass removal trends were used to trigger the sampling events. Eventually, a small area near the center of the site required the installation of four additional heaters before the soil goals were reached after 238 days of heating. The total energy usage for heating and treating the source area was 23 million kWh—slightly lower than the estimated 26.5 million kWh. Actual energy losses and the energy removal associated with the extracted steam were lower than anticipated. An estimated 13,400 kg (29,800 lbs) of CVOC mass was removed, and all soil goals were met. This paper presents the challenges associated with a project of this scale and describes the solutions to successfully complete the ISTD remedy.

Introduction

In-situ thermal remediation (ISTR) is accepted as an effective alternative for treatment of source zones, based on the high efficiency for mass removal and reduction of source area concentrations (Davis 1997; Heron et al. 2013). Thermal conduction heating, also named in situ thermal desorption (ISTD), uses simple heater elements suspended in vertical borings to heat the subsurface by thermal conduction, while generated vapors are extracted under vacuum (Stegemeier and Vinegar 2001). Two recent papers illustrate the use of ISTD for treatment of NAPL source zones (Heron et al. 2009; Heron et al. 2013). To date, most thermal source zones have been of moderate size (less than one acre) and readily implemented using grid power and other available utilities. This paper presents a larger ISTD site and the associated challenges of constructing and treating it quickly—including:

- The large power demand needed.
- Potential groundwater flow and cooling of the zone to be heated.
- Shallow groundwater, making vapor recovery difficult.
- Drilling and installation costs for more than 1,000 wells/heaters.
- The process of tracking the progress and determining when treatment is complete for a multi-acre site.

Effective reduction of contaminant concentrations requires bringing the subsurface to a temperature at which the contaminants are mobilized in the vapor state, and effectively capturing the generated vapors (steam and volatile organic contaminants; VOCs). For volatile contaminants, the target temperature is the boiling point of water, below which all dense non-aqueous phase liquid (DNAPL) must boil, and at which in-situ boiling causes a steam drive out of the pores on a local scale (Hunt et al. 1988; DeVoe and Udell 1998). This requires an energy input, defined as the energy demand for heating the site to boiling, plus the energy demand needed for boiling a fraction of the pore water. Experience at similar full-scale operations indicates that between 10% and 30% of the pore water must be boiled to reduce concentrations from DNAPL levels to below 1 mg/kg in soils and sediments (Udell 1996).

This demand for energy translates into a demand for power—often totaling between 200 and 400 kWh/m^3 treated, depending on the starting water content, porosity, chemical mass, and remediation targets (Heron et al. 2009). Because typical operational periods are less than 1 year, large sites will require power supplies of several

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doi: 10.1111/gwmr.12115

megawatts, which may be challenging for the local utility company.

At some sites, thermal treatment is staged over multiple operational periods to minimize the size of the equipment used and the utility connections. At this site and others with ample availability of power, multiple source zones have been treated simultaneously, using a central treatment system for extracted fluids (Memphis Depot, TN: Heron et al. 2009).

The site encompassed 3.17 acres with four treatment zones, each with a different power requirement. The total energy added to the subsurface was approximately 23 million kWh over a period of 238 days, averaging approximately 249 kWh/m^3. This required a substantial upgrade of the power delivery to the site.

During the wellfield construction, a sheet pile was installed along the perimeter of the wellfield to minimize the infiltration of groundwater. Groundwater presence and flow may be of great importance for thermal treatment. The water content influences total energy need for heating. However, since the thermal diffusivity is relatively invariant for wet soils, heating rates are less affected for zones where the water hardly moves. It is when the water flows at significant rates that detrimental effects are seen. Where cool water flows into a zone being heated, the heat capacity of the water must be accounted for. For each liter of water flowing in, an additional ~3,900 kJ of energy must be added to heat the zone to a temperature of 100 °C (assuming ambient temperature of 10 °C). If this is not accounted for, the zones where the water flows will heat more slowly than predicted. An example of an ISTD site affected by groundwater flow and cooling was presented in Heron et al. (2010). Examples of sites where other ISTR technologies have experienced similar affects include East Gate Disposal Yard (Truex et al. 2009).

As ISTD for volatile chemicals relies on vaporization of the target compounds and removal of the generated vapors in the steam produced by boiling groundwater, it is important to ensure their recovery (Udell 1996). Extraction screens must be placed such that the steam and contaminant vapors can flow to them and be extracted (Heron et al. 2013). In most cases, this means that the extraction screens must be fully or partially screened in the vadose zone. If the screens are submerged, the vapor flow will not be initiated, and instead of extracting the vapors necessary for establishing pneumatic control, the vacuum will simply lift water in the well and lead to up-welling. Therefore, a critical step in thermal remediation is to ensure that the water table is maintained below the vapor extraction screens before the heating and vapor generation starts.

Drilling costs can affect the feasibility of large-scale thermal treatment, through the drilling costs per se and those for disposal of drill cuttings. Therefore, it is of great interest to select drilling methods that minimize the borehole diameter, optimize production rate, and minimize generation of cuttings. For these reasons, direct-push methods were selected for this site.

Confirmation of treatment completeness is essential for optimizing a thermal project and minimizing its expense. Collection of soil samples during the heating process is used to determine progress. For large sites, regulatory acceptance can be expedited by dividing the treatment zone into smaller decision units—with each required to meet the regulatory standards. Such an approach was selected for this site.

This paper presents a large-scale ISTD project for a 3.2 acre CVOC source zone, the major challenges related to the sheer size of the project, and solutions and decisions used to optimize the remedy and minimize risks and costs.

Teterboro Site Description

The site is located adjacent to Teterboro Airport in Teterboro, New Jersey. The site is generally flat and is bounded by highways and the airport runway (Figure 1).

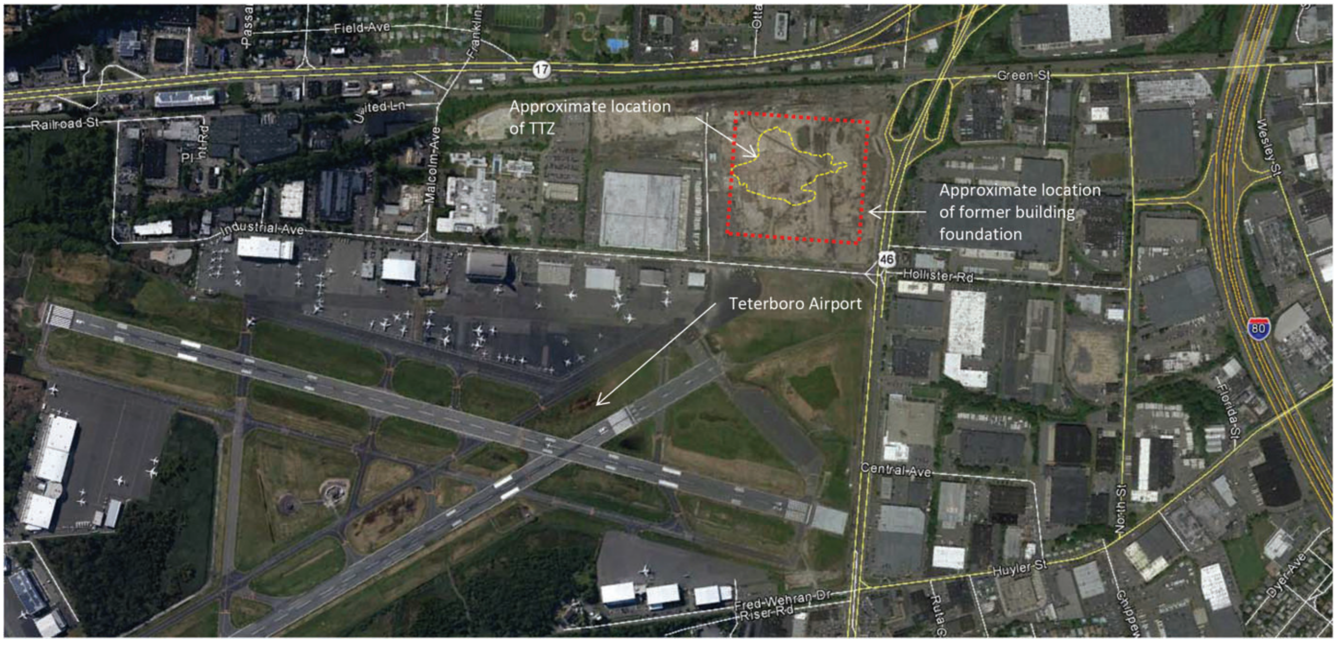

Figure 1. Arial view of the treatment zone and the surrounding area. The target treatment zone (TTZ) is shown in yellow outline.

The site had served as a major aerospace manufacturing facility, which since World War II had produced high-precision metal parts for avionics and space applications. Most of the target treatment zone (TTZ) was situated within the footprint of the former manufacturing building.

The focus of the ISTD remediation effort was a large area with CVOC soil impacts in excess of 10 mg/kg, beneath the groundwater table. The area also contained lenses of dense non-aqueous phase liquid (DNAPL) within the saturated soil. The treatment area was determined based on an intensive remedial investigation effort (O'Brien & Gere 2012), with the outer perimeter delineated by soil sampling locations where the total VOC content was less than 10 mg/kg. The surrounding dilute plume zones were not included in this remedy.

The ISTD TTZ had an area of approximately 12,820 m^2 (137,990 ft^2). The treatment depths were selected based on soil sample data across the site and varied from 3.66 m (12 ft) to 11.0 m (36 ft) as depicted in Figure 2. A small area near the center of the TTZ did not require treatment.

Figure 3 presents a schematic cross-section of the site. An imported construction fill layer of about 0.6 m (2 ft) thickness was formerly present, underlain by a sandy zone which varies significantly in thickness across the site. The sand is relatively permeable and able to conduct water

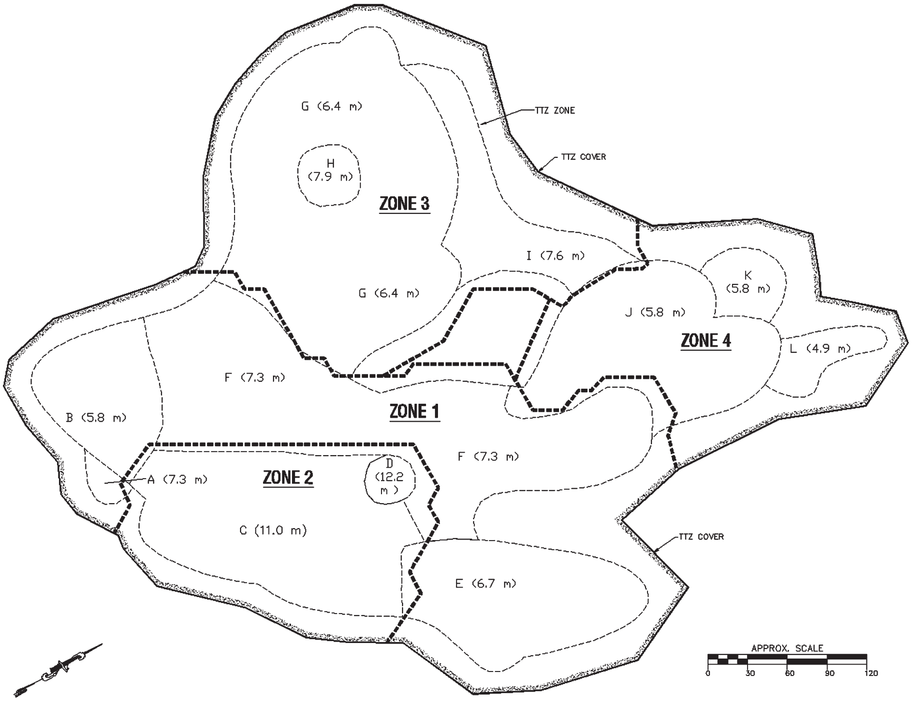

Figure 2. Thermal treatment zone (TTZ) with varying treatment depths and decision zones for confirmatory sampling (Zones 1 through 4).

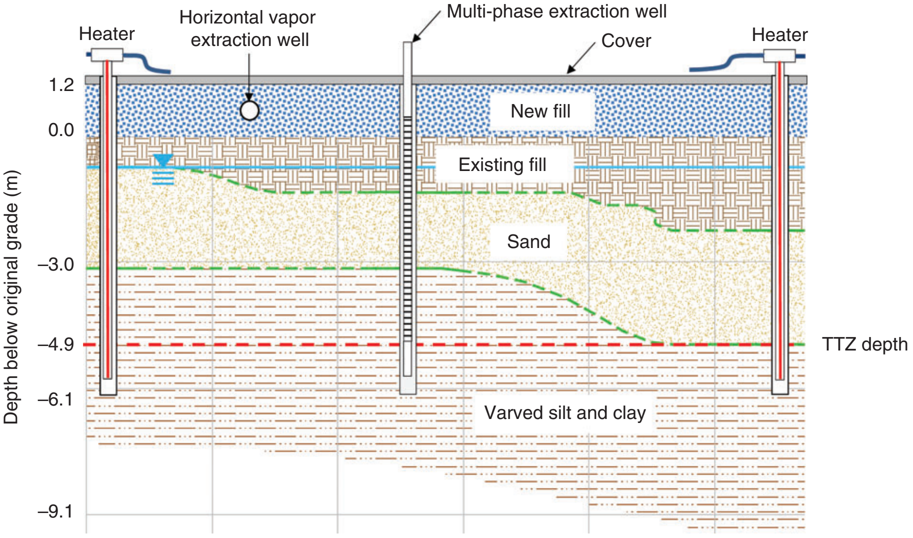

Figure 3. Cross-section showing stratigraphy and location of heaters and extraction wells. Note that 1.2 m (4 ft) of clean fill was placed over the site.

readily. Below the sand zone is a varved silt and clay zone, which extends deeper than the treatment depth approximately 8 to 12 m (26 to 40 ft) below ground surface at the site. The typical groundwater elevation is approximately 3 ft below ground surface and with seasonal variation and severe rainstorms, the site occasionally experiences flooding conditions. Note that a new fill layer (1.2 m; 4 ft) was placed over the site prior to remediation, in order to create a thicker unsaturated zone for extraction of generated vapors.

The chemicals of concern (COCs) in soil at the site are the chlorinated volatile organic compounds tetrachloroethene (PCE), trichloroethene (TCE), chloroethane, methylene chloride, 1,1-dichloroethene (1,1-DCE), 1,1-dichloroethane (1,1-DCA), *cis*-1,2-dichloroethene (*cis*-1,2-DCE), *trans*-1,2-dichloroethene (*trans*-1,2 DCE), freon-113, 1,1,1-trichloroethane (1,1,1-TCA), benzene, and vinyl chloride. Maximum concentrations of the COCs in the treatment area varied from 10 to 10,000 mg/kg. Cleanup goals were established based on New Jersey Department of Environmental Protection (NJDEP) Soil Cleanup Criteria. The subsurface needed to be restored to less than 1 mg/kg for each COC based on 95% UCL in each decision unit. No samples of the treated soil were allowed to exceed 2 mg/kg for any individual contaminant.

Description of Field Implementation

ISTD is the simultaneous application of heat by thermal conduction and vacuum to contaminated soil. During the ISTD process, soil is heated using a network of thermal wells installed throughout and immediately surrounding the TTZ. Electrically powered heating elements suspended vertically within the thermal wells deliver 1.15 kW/m (0.35 kW/ft) over their entire length, when at full power. Thermal energy provided by the thermal wells heats the soil, water, and contaminants. 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 steep thermal gradient between the operating temperature of the heaters (typically between 600 °C and 800 °C) and the temperature of the surrounding soil (10 °C) serves as the driving force for outward radial conductive heat flow to occur over the entire length of each of the thermal wells.

As soil temperatures increase, contaminants and water contained in the soil matrix are vaporized. While locations within 6 to 12 in. (0.15 to 0.30 m) of heaters may achieve temperatures well above the boiling point of water (100 °C), locations in between heaters only need to achieve 100 °C to accomplish steam distillation for effective removal of VOCs (DeVoe and Udell 1998).

The negative pressure applied to the vacuum wells from the process system draws vapors through the hot dry soil immediately adjacent to each thermal well (Heron et al. 2009; Heron et al. 2013). Vapors were also removed from the subsurface via unheated, horizontal soil vapor extraction (SVE) wells.

The heater borings wells were 7.6-cm (3-in.) diameter steel cased pipes housing thermal conduction heaters. Each contained a stainless steel heater that was controlled using thermocouples and a silicon controlled rectifier (SCR), allowing the power delivered to the heating elements to be adjusted automatically based on temperature or manually as needed. The vertical and horizontal vacuum wells were 10.2-cm (4-in.) diameter screened wells. A vacuum was applied to the wellhead.

The features of the ISTD system for the Teterboro Site were as follows:

- The site was graded, and 1.2 m (4 ft) of high-permeability clean fill was placed over the TTZ to provide an effective capture/collection zone for vapors generated during the heating process.
- A vertical sheet-pile wall was installed around the treatment area, tied a minimum of 1 m (3 ft) into the underlying clay at varying depths to provide a hydraulic barrier to groundwater flow.
- A surface cover (of lightweight concrete composite) was installed to insulate the surface and ensure effective heating and treatment of shallow soils, prevent infiltration and provide a vapor barrier to ensure capture and treatment of vapors produced during heating.
- 907 vertical heater borings and 35 multiphase extraction wells were installed. 797 of the 907 heater casings were installed using a custom direct-drive approach, whereby the casing was advanced by a vibratory push device. The remaining heater casings were installed with an auger drill rig due to obstructions (when refusal was observed using the direct-push method). Extraction wells were installed using auger drill rigs.
- 116 horizontal vapor extraction wells were placed in the new fill layer at a depth of 0.6 m (2 ft).
- 80 vertical temperature monitoring strings were installed to depths following the TTZ shape. Depths varied from 5.8 to 12 m (19 to 40 ft). Most thermocouples were installed at the centroids of the equilateral triangles between thermal wells, i.e., the coolest locations within the TTZ.
- Interconnecting piping and manifold system—fiberglass was used for both temperature and corrosion resistance.
- A 26 kV overhead transmission line supplied power to electrical distribution switchboard.
- Electrical distribution gear rated for a maximum of 11,250 kW. Three transformers were placed around the perimeter of the TTZ to facilitate installation of power cables to the heaters.
- A thermal oxidizer with a capacity of 4860 m^3/h (3000 scfm) for vapor, and a liquid treatment system with a capacity of 11.3 m^3/h (50 gpm) for liquids was designed for the site. This system was sized to accept more than 23,000 kg of CVOC, and to tolerate corrosion from hydrochloric and hydrofluoric acid potentially generated by mineralization of the chlorinated and fluorinated compounds, either in situ or within the thermal oxidizer.

Table 1 provides a summary of the design basis for the ISTD system at the Teterboro, New Jersey site. An area of 12,820 m^2 (137,990 ft^2) was treated. After placement of the new fill layer, the treatment depth varied from 4.9 to 12.2 m (16 to 40 ft) below grade, and the treated volume was 93,690 m^3 (122,300 yd^3).

Table 1

Summary of Volume, Heat Capacity, and Energy Balance Calculations for the ISTD Operation

	Zone 1	Zone 2	Zone 3	Zone 4	Total			
Treatment area	4,930	1,948	3,948	1,994	12,820	m^2		
Average depth with fill	6.94	11.04	6.71	5.68		m		
Treatment volume, with fill	34,193	21,504	26,477	11,329	93,500	m^3		
Solids volume	20,697	13,017	16,027	6,857	56,600	m^3		
Water volume	12,559	7,899	9,725	4,161	34,300	m^3		
Air volume	939	590	727	311	2,570	m^3		
Heat capacity, solids	9,372	5,894	7,257	3,105	25,600	MJ/K		
Heat capacity, water	52,574	33,064	40,711	17,419	143,800	MJ/K		
Heat capacity, air	0.9	0.6	0.7	0.3	3.0	MJ/K		
Total heat capacity	61,947	38,959	47,969	20,524	169,400	MJ/K		
Energy to raise temperature to 100 °C	5,885	3,701	4,557	1,950	16,093	GJ	4,470,000	kWh
Energy to boil pore water	12,883	8,103	9,976	4,269	35,185	GJ	9,770,000	kWh
Estimated energy removed in liquids	1,346	846	1,042	446	3,680	GJ	1,020,000	kWh
Estimated heat losses	13,060	8,213	10,113	4,327	35,712	GJ	9,920,000	kWh
Estimated total energy demand	33,174	20,864	25,688	10,991	90,670	GJ	25,200,000	kWh
Budgeted energy demand with contingency					95,400	GJ	26,500,000	kWh
Actual energy delivered by ISTD system					83,668	GJ	23,241,000	kWh
Actual unit energy usage							249	kWh/m^3

The vapor extracted from the wellfield was passed through a series of moisture separators and heat exchangers, which removed entrained and condensed liquids from the vapor stream. The liquids were treated onsite using air stripping before discharge to the sanitary sewer. The vapors were dried and treated onsite using thermal oxidation and acid gas scrubbing for neutralization of hydrochloric and hydrofluoric acid generated by the oxidation of the contaminants. Treated vapors were emitted to the atmosphere. Scrubber discharge water went to the sanitary sewer. Emissions and discharges met local and regional requirements as specified in the approved permits.

Subsurface and heater temperatures were measured using type K thermocouples connected to an automatic data collection system, and posted on a project webpage.

Because of the large area, the site was divided into four decision units for confirmatory sampling. Interim and final soil samples were collected in accordance with the guidelines presented by Gaberell et al. (2002). A total of 270 samples at 56 locations were collected to provide data on contaminant reductions along the vertical profiles. Sampling locations and depths were selected by the use of a random-number generator and covered all of the treatment area. Soil samples were collected using a direct push sampling tool equipped with four 15.2-cm (6-in.) stainless steel inserts. The ends of the recovered sleeved samples were immediately covered with a sheet of Teflon and capped, placed in a shallow basin containing ice, and cooled until the interior of the soil sample had reached ambient temperature as determined by a thermometer placed in a sacrificial sleeved sample. After cooling, one of the undisturbed sleeved samples was placed on ice in a cooler, while another core was split open to enable an examination of the soil type. Delivery of the undisturbed core samples to the laboratory was made within 24 h of sample collection. Samples were analyzed using EPA Method 8260B.

Periodic grab samples from the vapor treatment system were collected and analyzed using EPA Method TO-15. Daily screening measurements of the VOC concentration in the vapor stream were conducted using a portable flame-ionization detector (FID) calibrated to a 100 ppmv methane standard.

Mass removal estimates were derived from vapor flow rate data and measured vapor concentrations. Daily fluctuations were recorded using a FID. The FID data were calibrated to the total VOC concentrations in the laboratory samples (EPA Method TO-15). Note that the FID detects organic vapors which are not among the COCs at this site. Therefore the FID data are only used as screening level data, and to provide recovery trends between the laboratory sampling events.

Uncertainties and Key Decisions

In order for the client to make informed decisions related to the major uncertainties, a risk evaluation matrix was developed, listing the major unknowns with their potential implications, cost impacts, and potential measures to control or eliminate the risk. An abbreviated form of this matrix is presented in Table 2.

For a site of this size, where more than 1000 borings and wells had to be installed, the cost of drilling and waste

Table 2

Risk Evaluation Matrix Used to Optimize Project Performance

Area of Performance Risk	Potential Causes and Effects	Mitigation Approach (Potential)	Impact to Project Cost	Decision
Heater Well installation difficulties—drilling rate and cost	Subsurface Obstructions—refusal Change of drilling method Prolonged drilling phase	Design around known subsurface obstructions (concrete blocks). Well installation pilot (several days) to verify drilling methods	More than $500,000 difference for alternate drilling methods	Client chose to fund a drilling and heater installation test—which showed that the innovative direct-push method was feasible
Groundwater intrusion and impact on heating	Rain and seasonal high water levels—higher groundwater level and flow slows heating—greater potential in areas of higher permeability (such as overlying fill)	Install full-scale barrier to hydraulically isolate treatment zone. Place additional fill to raise grade Install full-scale dewatering system	Large and difficult to predict—shallow groundwater can prevent timely start and finish. Groundwater flow can hamper proper heating and prevent successful closure	Hydraulic barrier (sheet pile wall). Installed 4 ft (1.2 m) of clean fill imported to raise grade. Multiphase extraction wells installed
Utilities Intrusion into/out of Treatment Area	Known/unknown buried utilities (storm, sanitary, fire lines, etc.) can convey water to and from treatment zone—with associated cooling or energy loss	Cut off utilities (can be done in conjunction with barrier wall installation)	Minimal, if done as part of barrier install	Barrier wall selected
Low organic vapor recovery	In-situ vapor condensation at boundary of heating zone, insufficient vapor recovery	Proper insulation and vapor recovery design. Additional shallow horizontal vapor extraction wells	Modest cost increase if implemented before heating starts	A combination of horizontal vapor collectors and vertical multi-phase extraction wells was selected
Mobilization of contaminant mass (downward)	Incomplete heating at deepest portions of target treatment zone(s). Inability to reach goals at depth in certain zones	Install heating equipment to extend beyond deepest known soil contamination. Perform pre-/post-remediation soil sampling to verify contamination removal/distribution at lower intervals.	Large impact if thermal treatment is not successful at depth	Heaters extended 5 ft below deepest known CVOC impact above criteria. Interim soil sampling program adopted
Acid attack on process equipment	Presence of CFC compounds which turn into hydroflouric acid once oxidized—with potential for corrosion of oxidizer and downstream equipment	Select more robust thermal oxidation and acid gas scrubbing system	Potentially large if system goes down during heating	HF-resistant system was selected

disposal was significant. The client agreed to fund a pilot-scale experiment with installation of the heater casings using a vibratory hammer mounted on a direct-push rig (Figure 4). This custom tool proved to be very effective, after a method was developed to protect the carbon steel pipes and the welds. Eventually, most of the 907 heater casings (totaling 8,981 linear meters [29,465 ft] of drilling) were installed using this method, which had an average production rate of 121 m/day (397 ft/day) compared to the traditional auger method, which only produced 18 m/day (59 ft/day). In addition, no drill cuttings were generated, saving transportation and disposal fees.

As the basis for evaluating the influence of shallow water on the project, numerical modeling of the heating process was completed. The delivery of power through the heaters, removal of steam by the boiling of water, and heat losses were simulated (Figure 5). Sensitivity studies were performed, wherein the influence of groundwater flow in particular was evaluated. Inflowing water rates, both from below and horizontally, were tested, with a focus on total energy demand and duration of treatment.

On the basis of the uncertainty associated with the rate of groundwater flow into the treatment zone, a decision was made to install sheet-piling to hydraulically isolate the treatment zone and to install a full scale dewatering system in the form of 35 individual Multiphase extraction wells with pumps. Without the sheet-pile, the water flux to the TTZ comprised a cooling factor that would have negatively impacted both the ability to treat and the power consumption by reducing the heating rate around the perimeter and delayed achievement of target temperatures by several months (Figure 6). Critical water flux characteristics include both surface water infiltration to the site and horizontal groundwater flow within and immediately surrounding the TTZ.


Figure 4. Direct-drive installation of ISTD heater casing.

Groundwater at this site was approximately 0.9 m (3 ft) below the original grade at the time this decision was made. The hydraulic conductivity of the 0 to 2.4 m (8 ft) bgs vertical interval consisting of fill/sand/silt sand was approximately 1×10^{-3} cm/s and the water level could rise significantly during flooding events. The installation of a sheet-pile to serve as a groundwater barrier wall around the perimeter of the site reduced the influx of groundwater to the TTZ to an absolute minimum. Design measures included extending sheet piling a minimum of 5 ft into the underlying clay confining layer. The surface water infiltration was addressed with a lightweight concrete cover with a water resistant coating.

The shallow groundwater posed another challenge. Vapor recovery was deemed to be very difficult with such a thin vadose zone. First, 1.2 m (4 ft) of clean fill was placed over the treatment area, which was intended to create an unsaturated zone of about 2 m (7 ft) thickness—ideal for shallow vapor extraction and capture of the generated steam and CVOC vapors. At the time of operations, the water was observed to be much shallower—essentially flooding the horizontal vapor extraction screens in many locations across the site. The water was less than 0.6 m (2 ft) below the vapor cover at some locations, making it impossible to extract vapor under vacuum. The water was observed during installation of the horizontal soil vapor extraction wells, and the most probable explanation for the presence of water was that the original ground surface had been compacted enough that the rainwater could not easily infiltrate. As a result, the multiphase extraction (MPE) wells were operated for a period of 30 days prior to heating, removing some of

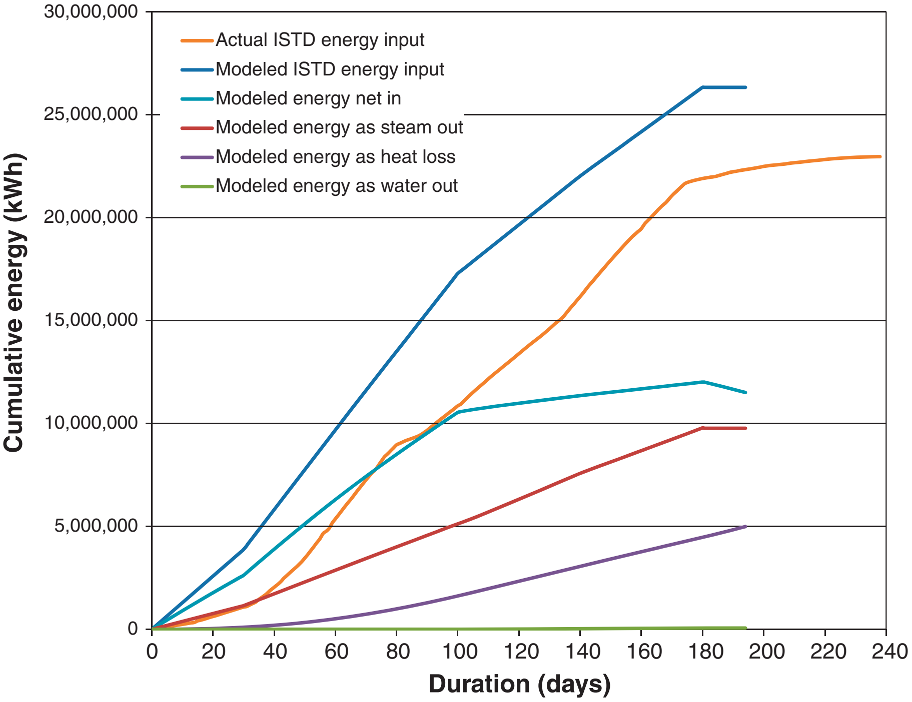

Figure 5. Numerical simulation results for prediction of energy usage and duration of thermal treatment—and actual ISTD energy input measured during operation.

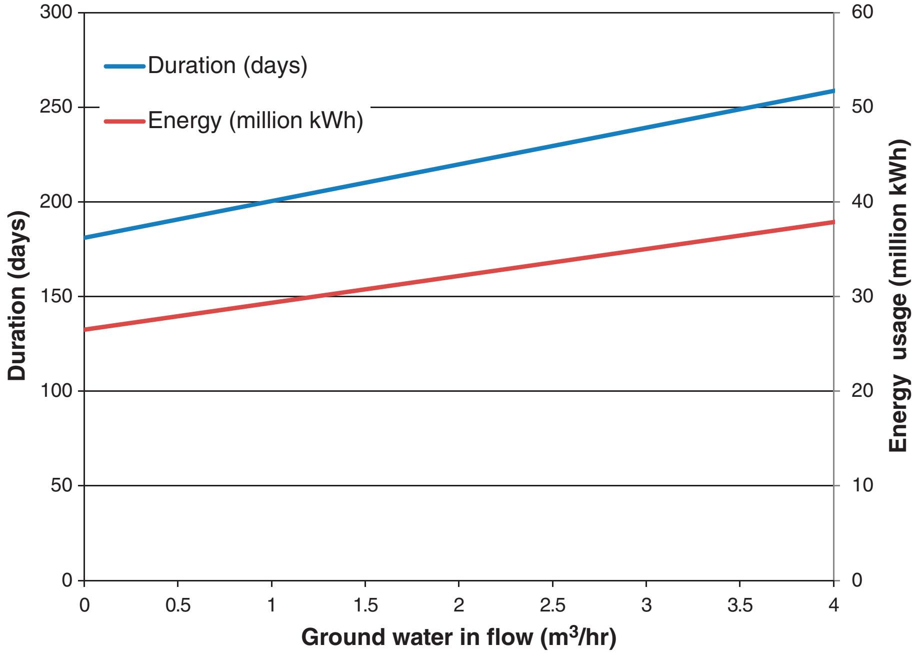

Figure 6. Modeled impact of groundwater flow on treatment duration and energy demand.

the shallow water and prolonging the project, but creating the necessary water table draw-down needed for the vacuum extraction to be effective. The decision to install the 35 MPE wells, and the shallow horizontal vapor extraction wells (as per Table 2) was clearly justified.

Rain-water runoff was addressed by the installation of a sloped vapor cover, designed to be both water-proof and insulating. Rain was directed to swales around the treatment zones and to stormwater sewers.

Another concern was the presence of buried utility lines in the treatment area, and particularly ones that might have carried fluids into or out of the zone. Since it was elected to install a sheet-pile wall around the area, this included utility clearance and cutoff/abandonment of any buried lines, effectively eliminating this uncertainty.

The risk of potentially leaving untreated CVOC near the bottom of the treatment zone, or to have CVOCs condense at depth, was evaluated. As a result it was decided to extend the ISTD heater borings to a minimum of 1.5 m (5 ft) deeper than the deepest known CVOC impact above the treatment goals. This was done to ensure that a temperature near the boiling point of water could be reached at the bottom of the treatment interval. In addition, the interim soil sampling program was developed to ensure that data be collected at different times at locations near the bottom of the treatment zone, such that enhancements could be made in problematic areas.

The presence of flourinated compounds at this site made an analysis of well-field and process system materials crucial. If the flourinated compounds break down, formation of hydroflouric acid can lead to severe corrosion issues. Since the CFC compounds present at this site are volatile, and the site was heated to 100 °C, minor HF formation was expected and observed in the subsurface or conveyance piping. The only corrosion issue was related to the high-temperature section of the thermal oxidizer and scrubber system, where HF-resistant alloys were used. This added to the cost of the system, but the system performed as designed with minimal corrosion and down-time. With proper allowance for these material upgrades, the system can tolerate a large mass of CFC, at this site likely many thousand pounds were extracted and treated. A special refractory lining was required in the thermal oxidizer, and the spray nozzle in the acid scrubber was upgraded to a high grade Hastelloy® material.

Power cables for low-voltage conduction are expensive because of the copper content. Therefore, an economic optimum was chosen where the high voltage lines were extended across the perimeter of the site to multiple transformers. This minimized the quantity of thick copper cables to be used to deliver power to all the heaters. For gas used by the thermal oxidizer, the large amount of gas was conveniently delivered using a simple extension of the existing natural gas lines to the treatment system.

The ISTD system operated 24 h/day, 7 days/week from the start of heating on January 15, 2013 through ISTD system heater shutdown on September 10, 2013, for a total of 238 total heating days. Typically, the ISTD operation was attended by two operators at least 5 days/week (10 h/day). Figure 7 shows the well-field during wintertime operation.

Results and Discussion

Figure 5 shows the energy balance as predicted by numerical modeling, along with the actual power usage during the project. The thermal system operated for 238 days vs. the modeled period of 181 days. The main reasons for the extended operations were (1) the period of water extraction that preceded ISTD heating at the design rates (caused by the shallow groundwater), and identification of a small area near the middle of the site where treatment had to be amended by additional heaters and more heating time.

However, the total amount of energy used (23 million kWh) compares favorably with the estimated usage of 26.5 million kWh. This indicates that the energy removal rates and heat losses presented in Table 1 may have been over-estimated. The energy balance kept during operations showed that the steam extraction and removal accounted for approximately 6 million kWh of energy (data not shown), compared with the estimated 10 million kWh, which explains the difference.

Subsurface temperatures responded well to the heating, with most thermocouple strings exhibiting heating to boiling point temperatures from top to bottom of the TTZ. Figure 8 shows the average temperature profiles in each of the four decision units, representing and illustrating the average of more than 1 million readings. The profile for Zone 4 represents a zone where the heating was slower than average at the top depths. This would be a typical area for interim sampling, which would indicate a need for additional heating time to meet the soil standards.

Another indicator of remedial performance is the temperature of the vapors extracted from across the site. A zone where the horizontal extraction screen is under water, for instance, will not convey any hot air or steam, as the line is cold. Therefore, the temperatures of the risers from all horizontal wells were tracked regularly. Figure 9 shows an example data plot from about day 150, prior to the whole site reaching treatment temperatures, with the color scale representing the temperature of the riser associated with each screen. A process was developed whereby water was pumped from the wells that were cold. The water removal resulted in these screens becoming exposed to steam and air and eventually conveying hot gases. This process ensured that no cool shallow zones were left toward the end of the heating, which could have potentially led to zones with CVOC concentrations above the targets.

The mass removal rates and cumulative totals are shown in Figure 10. The data is based on TO-15 grab samples and

Figure 7. ISTD well-field in operation during New Jersey winter.

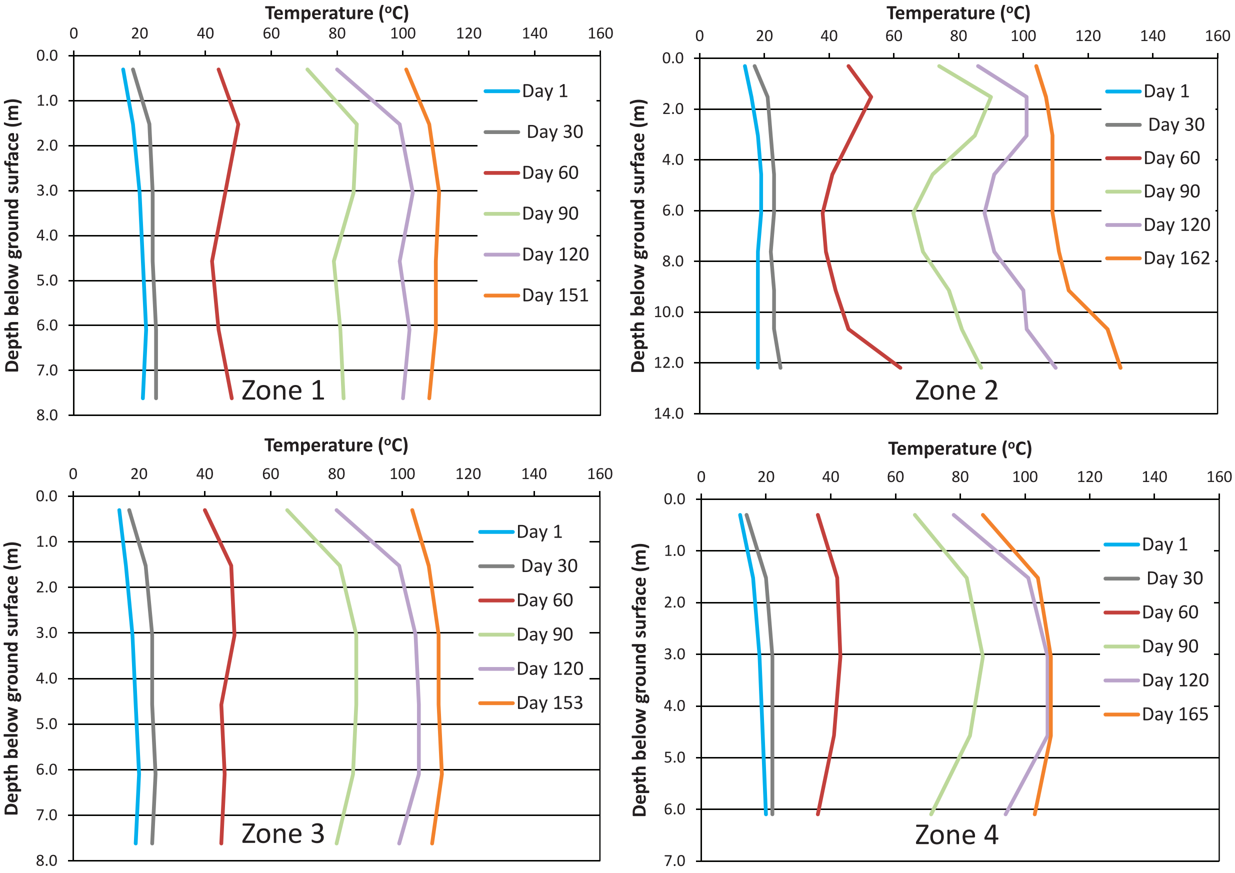

Figure 8. Average temperature profile progression in the four decision zones.

flow rate measurements, with additional trending data from FID screening of the vapor stream. Mass removal peaked after approximately 2 months of heating at 750 kg/day (1650 lb/day), remained high for about 3 months, then declined to low levels near the end of the heating period. An estimated 13,400 kg (29,800 lbs) of CVOC mass was removed.

Following the interim sampling, several final soil sampling events occurred at the end of operations. While most samples met the remedial standards during the first sampling round conducted at approximately 165 to 175 days of heating, a few areas did not. In one of these areas, four additional ISTD heater borings and one additional vacuum extraction boring were installed, and heating and treatment continued until the sampled soils met the criteria. The maximum observed pre- and post-treatment concentrations of the major COCs mentioned in the Teterboro Site Description section are shown in Figure 11. Soil concentrations were reduced from levels of 10 to 10,000 mg/kg to below 1 mg/kg for each of the site COCs (e.g., trichloroethene, *cis*-1,2-dichloroethene, vinyl chloride).

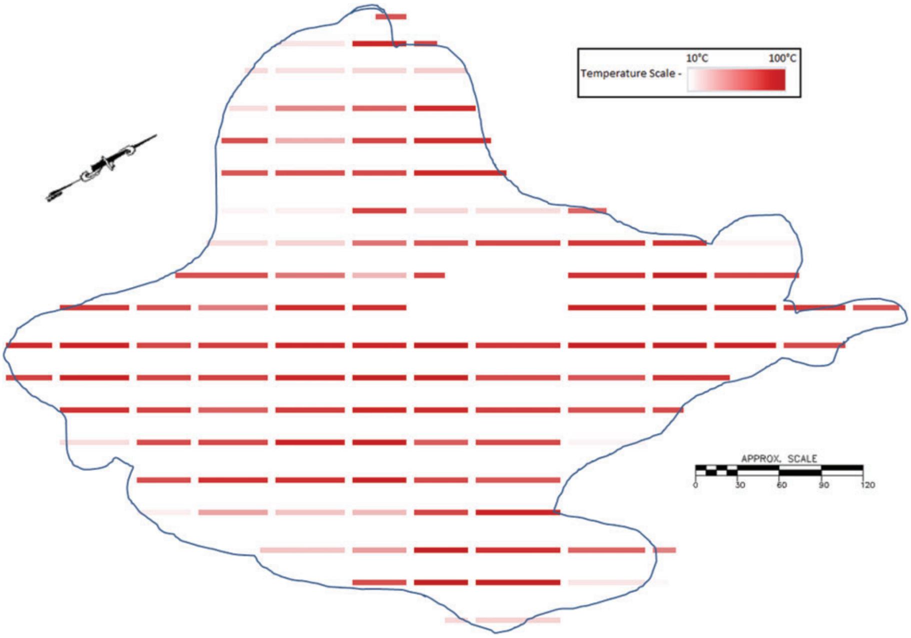

Figure 9. Map of temperatures in extracted vapor from horizontal vapor collectors around day 150.

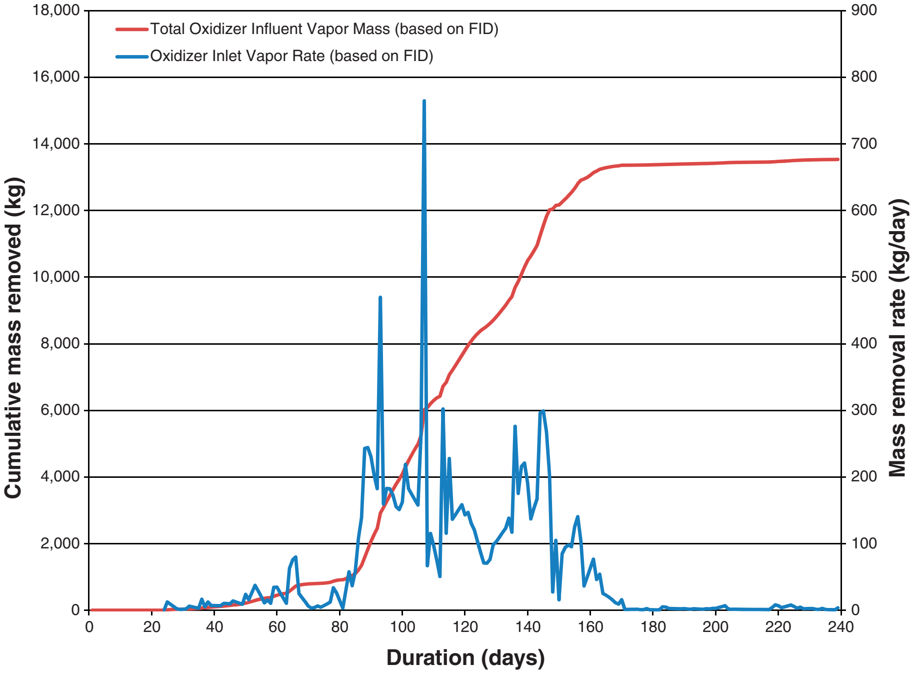

Figure 10. Estimated CVOC mass in extracted vapors and liquids (rate and cumulative).

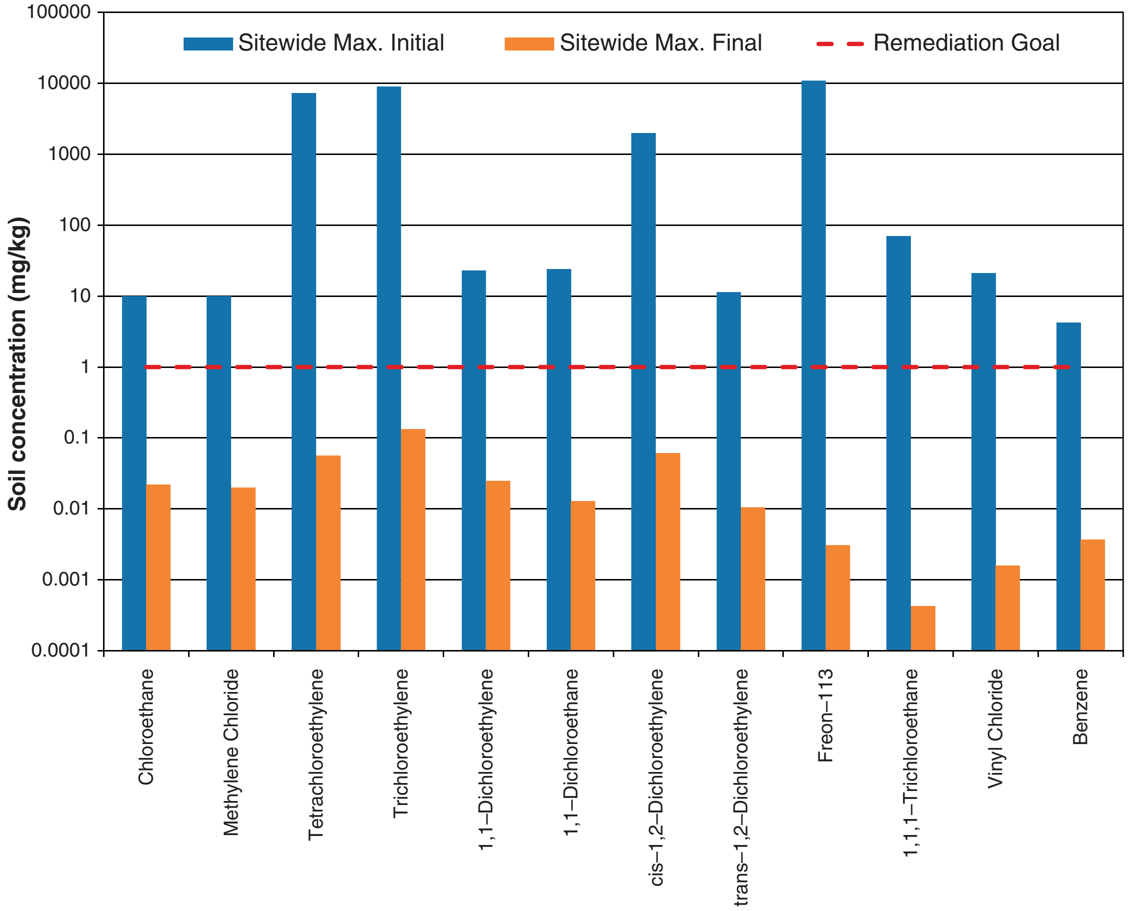

Figure 11. Maximum soil concentrations for selected chemicals before and after thermal treatment.

Conclusions and Recommendations

Large source areas are particularly challenging because the thermal systems needed to properly heat and treat are big and energy-intensive, and the cost of operation is high. Therefore, it becomes important to have reliable predictions of the energy demand and the operational duration.

In this project the value of numerical modeling and the associated sensitivity analysis was demonstrated. This analysis showed a strong influence of groundwater flow on project duration and energy usage. For instance, a horizontal flow of 2 m^3/h (9 gpm) would extend the heating period by 40 days and increase the energy demand by 5 million kWh. The cost impact would be approximately $300,000 for operations cost and $500,000 for electricity. The vertical barrier installed around the treatment area cost less than half of this amount. We recommend that similar project-specific analyses be done as part of the optimization of thermal projects. As a result, the client made proactive decisions to install sheet-piling around the treatment zone, place a layer of clean, construction fill over the site, and to install multiphase extraction wells suitable for lowering the water level, if required. All three decisions proved to be of great importance, since an unusually high water level at the site could have hindered operation.

For ISTD, the value of utilizing direct push technologies to complete over 7,800 m of drilling in 65 days was demonstrated, greatly reducing the time and cost of installing the heaters. Where applicable, direct-push methods are ideal for optimizing the speed of installation and minimizing cuttings for transport and disposal. The cost of the pilot test for this installation method (less than $100,000) was recovered several fold by the savings realized when 797 of the 907 heater casings were installed in this manner. Using traditional drilling techniques, it was estimated that an additional $200,000 to 300,000 would have been spent.

As listed in Table 2, the heaters were installed to a depth of 1.5 m (5 ft) below the treatment zone. This was done to ensure heating to target temperatures, and to minimize cold-spots at the base of the treatment zone, which could lead to condensation of contaminants. Interim sampling was performed, and no apparent increases of COC concentrations were observed. This supports the previous claimed value of heating below the target treatment zone (Heron et al. 2013). It is important to heat the deeper zones, such that condensation and accumulation of COC is not encouraged.

Soil sampling was the main metric for determining when to stop heating and treatment in each of the four decision units shown on Figure 2. In addition, the trend in mass removal rates (Figure 10) and screening of individual manifold legs using hand-held PID/FID instruments were used to determine where concentrations were still elevated, and used to focus the heating and extraction. The sequential shutdown of areas and zones as the remedial criteria were met, rather than operation of the entire well-field until all criteria were met at all locations, saved between 5% and

10% of the total energy spent, and a similar percentage of the total cost to operate the system. Therefore, the splitting of large target volumes into smaller decision units has tremendous value at large sites.

Acknowledgments

The authors would like to thank Ralph Baker of TerraTherm for a careful review of the manuscript.

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