APPLICATION OF "THERMAL CONDUCTIVE HEATING/IN-SITU THERMAL DESORPTION (ISTD)" TO THE REMEDIATION OF CHLORINATED VOLATILE ORGANIC COMPOUNDS IN SATURATED AND UNSATURATED SETTINGS

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ABSTRACT: TerraTherm's patented In-Situ Thermal Desorption (ISTD) process, also termed In-Situ Thermal Destruction, was recently used to remediate three separate source zones contaminated with chlorinated volatile organic compounds (CVOCs) at an active manufacturing facility in the USA. Soils within two of the source zones were unsaturated while soil within the third source zone was saturated with water. The total volume of soil remediated within the three source zones was 10,950 cubic yards (CY) (8,372 m^3). The results indicate that attaining an interwell soil temperature of 210°F (99°C), the boiling point of water at the site, was effective in reducing CVOCs from maximum pre-treatment concentrations for Trichloroethene (TCE) of 4,130 mg/kg to 0.07 mg/kg (average of 54 samples). The post-treatment sampling results were significantly below the remedial goal for TCE of 1 mg/kg and were achieved following 150 days of soil heating. Effective treatment of the source zones provided the basis for a No Further Action (NFA) letter for soils at the site.

SITE BACKGROUND

The site is an active manufacturing facility where chlorinated solvents were used for degreasing tools and manufactured components from 1950 to 1993. According to available information, Trichloroethene (TCE) was the main solvent used at the facility beginning in 1950. The site is located in a rural area, although one side is directly adjacent to a residential neighborhood (Figure 1). Soils beneath the site consist of a surficial silt and clay unit (clayey till), which varies in thickness between 6 ft (1.8 m) and 18 ft (5.5 m). The clayey till varies in silt and clay content and in some locations contains significant amounts of gravel. A sand and gravel unit begins at the base of the clayey till unit and extends to a depth of approximately 100 ft (30.5

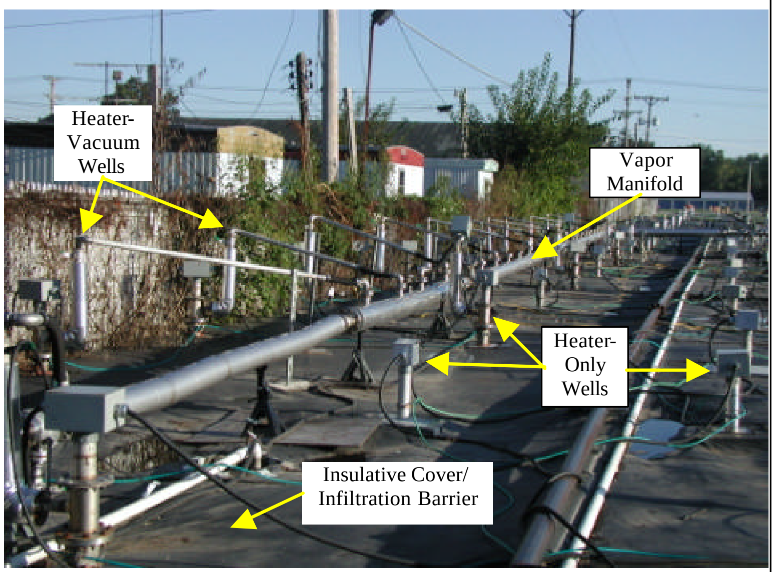

FIGURE 1. Completed ISTD Well Field at the Midwest Site. Note the proximity to the adjacent residences.

m) below ground surface (BGS). The topography across the site is flat. The water table underneath the site is present within the sand and gravel unit at approximately 30 ft (9.1 m) BGS. Perched groundwater has been observed locally within the clayey till unit beneath portions of the site at approximately 2-4 ft (0.6-1.2 m) BGS. The sand and gravel aquifer is used a source of drinking water.

The major contaminant present at the site was TCE, along with lower concentrations of 1,1,1-Trichloroethane (1,1,1-TCA), and Perchloroethene (PCE). Table 1 summarizes the site dimensions and pre-treatment concentrations of the chlorinated solvents in the three source areas/Target Treatment Zones (TTZs). This table also includes the risk-based cleanup objectives established for the site and the boiling points of the chlorinated solvents.

TABLE 1. Site Dimensions and Contaminant Information for the Midwest Site.

Treatment Zone	Parking Lot 1 (unsaturated)	Parking Lot 2 (unsaturated)	Former Waste Water Basins (saturated)	Overall Project
Area (ft^2 [m^2])	14,187 [1,318]	3,115 [289]	2,409 [224]	19,711 [1,831]
Depth (ft[m])	15 [4.6]	15 [4.6]	15 [4.6]	15 [4.6]
Volume (cy [m^3])	7,882 [6,026]	1,730 [1,323]	1,338 [1,023]	10,950 [8,371]
Contaminants of Concern	**Avg./Max. Concentrations (mg/kg)**	**Avg./Max. Concentrations (mg/kg)**	**Avg./Max. Concentrations (mg/kg)**	**Cleanup Goal (mg/kg)/ Boiling Point (ºF [ºC])**
TCE	99.7/4,130	4.9/20.7	1.1/12.6	1.056/189 [87]
1,1,1-TCA	31.7/1,350	0.02/0.08	4.9/39.9	28.6/165 [74]
PCE	1.5/22.2	0.001/0.005	0.005/0.050	5.94/250 [121]

DESCRIPTION OF ISTD TECHNOLOGY

TerraTherm's patented ISTD process utilizes conductive heating and vacuum to remediate soils contaminated with a wide range of organic compounds. Heat and vacuum are applied simultaneously to the soil with an array of vertical or horizontal heaters, under imposed vacuum. Heat flows from the 1200-1500°F (650-800°C) heating elements through the soil primarily by thermal conduction. As the soil is heated, VOCs and SVOCs in the soil are vaporized and/or destroyed by a number of mechanisms, including: (1) evaporation into the subsurface air stream; (2) steam distillation; (3) boiling; (4) hydrolysis; (5) oxidation; and (6) pyrolysis (high-temperature chemical decomposition in the absence of oxygen). The vaporized water and contaminants, as well as some volatilized inorganic compounds, are drawn counter-current to the heat flow into the vacuum extraction wells ("heater-vacuum" wells).

The conductive heating process is very uniform in its vertical and horizontal sweep. This is because thermal conductivity values vary over a very narrow range, regardless of soil type. The very uniform thermal properties of soil result in uniform heating of the TTZ. Thus, it is possible to ensure that 100% of the TTZ becomes heated to or above the target treatment temperature. In addition, the soils immediately adjacent to the thermal wells become superheated. As this occurs, any clays that are present will dry, shrink, and fracture, creating closely spaced airflow paths. This provides additional permeability for vaporized contaminants to migrate toward the heater-vacuum wells, even in very tight clay. The combined effectiveness of both heat and vapor flow yields nearly 100% sweep efficiency, leaving no area untreated.

ISTD is capable of achieving a destruction/displacement efficiency that approaches 100% allowing attainment of stringent levels of treatment. This is a result of the ability to uniformly heat the soil to the boiling points of the contaminants of concern (COCs) and to maintain these temperatures for many days. Laboratory treatability studies and field project experience have confirmed that a combination of high temperature and long residence times results in extremely high overall removal efficiency (>99%) of even high boiling SVOCs. Including this project, every one of the eleven completed ISTD field projects has achieved the required levels of the COCs, even though their initial soil concentrations were often very high (Stegemeier and Vinegar, 2001). The low levels of COCs in the vapor that are not destroyed in-situ are conveyed to the aboveground air quality control (AQC) system for removal.

TARGET TREATMENT TEMPERATURES AND HEATING TIME

The target treatment temperature for the CVOC site was selected by considering the following: 1) the boiling points of the COCs (Table 1); 2) ISTD processes; 3) the remedial goals; and, 4) the desired treatment time. Based on boiling points alone, a temperature of 250°F (121°C) (the highest boiling point of the COCs) would be required to boil off all of the COCs. However, in-situ volatilization, distillation and steam stripping processes can result in significant removal of VOCs and low-boiling SVOCs (both NAPL and dissolved components) at temperatures around the boiling point of water. This process has been demonstrated through research conducted by Udell (1996), which showed that steam distillation is capable of effectively boiling off TCE or PCE NAPL in groundwater at temperatures below the boiling point of water. The remaining dissolved COCs are then effectively removed and stringent cleanup levels achieved via steam-stripping mechanisms by boiling off just a small fraction of the water present in the TTZ (e.g., 5-10%). Therefore, a target treatment temperature of 210°F (99°C), the boiling point of water at the site's elevation, was selected for this project. Very high (>99%) resulting removal rates have been measured for ISTD of CVOCs using this approach (Udell 1996; Vinegar and Stegemeier, 1999; USEPA, 2003).

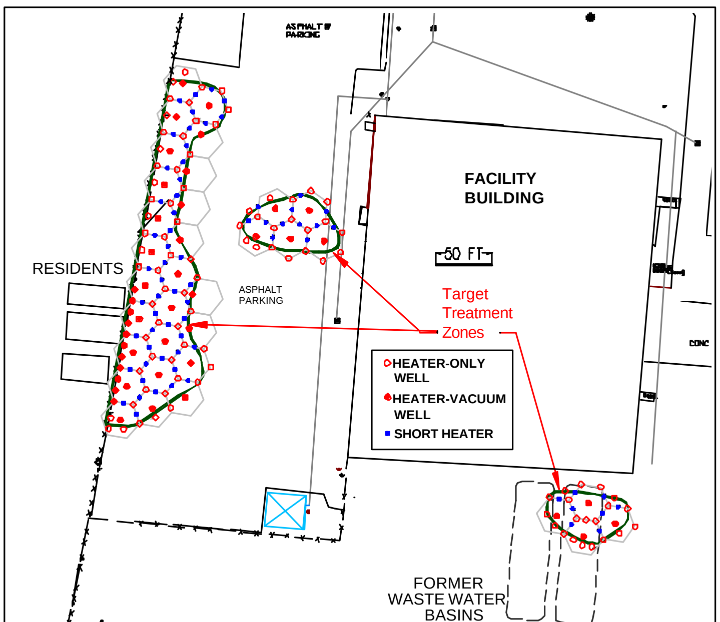

FIGURE 2. Site Map Showing Treatment Areas and ISTD Well Layout

DESIGN DETAILS

Based on site characterization data, three TTZs were identified for remediation using

ISTD. These included two areas beneath the parking lot (Parking Lot Area 1 and Parking Lot Area 2) and a portion of the Former Waste Water Treatment Basins (Figure 2). The ISTD heater-only wells were located at the apex points of the hexagons, with a heater-vacuum (producer) well at the center of each hexagon (Figures 2 and 3). This well pattern arrangement results in a 2:1 ratio of heater-only wells to heater-vacuum wells, with a sub-pattern comprised of equilateral triangles measuring 17.3 ft (5.3 m) on each side, and with a thermal well at each point of the triangle (Figure 3). It is the centroid (middle) of these triangles at which the coolest temperatures can be expected to occur, since the centroid of the triangle formed by three adjacent thermal wells is the furthest point from any one of the thermal wells.

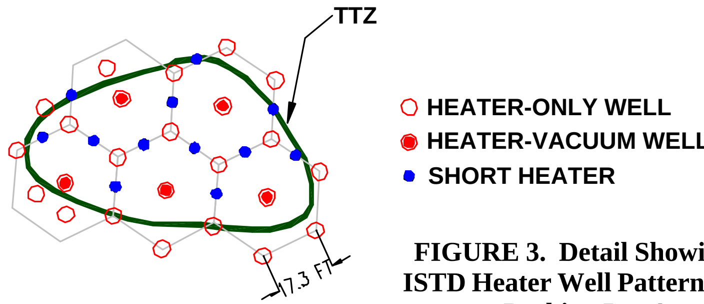

FIGURE 3. Detail Showing ISTD Heater Well Pattern in Parking Lot Area 2.

Detailed simulation modeling was performed for this site using the Steam, Thermal, and Advanced Processes Reservoir Simulator (STARS). STARS is a finite difference simulator that has been in development since the early 1980s by the University of Calgary and CMG, Inc. It is the leading non-isothermal, multiphase oil field model. The STARS model indicated that if a standard thermal well pattern was used, cleanup of the near-surface soils (mainly in the upper 2 ft [0.6 m] of the target treatment zone) would lag behind the deeper soils due to heat losses through the ground surface. In order to address this lag in heating, TerraTherm installed short thermal wells (4 ft in length) at selected locations to ensure effective treatment of near-surface soils (e.g., at locations shown in blue in Figure 3). Based on the results of the simulation modeling, a total of 138 full-length and 68 short thermal wells were installed in the three TTZs.

TerraTherm installed temperature monitoring points equipped with thermocouples near thermal wells and at representative centroid locations to monitor the progress of heating and to ensure that the coolest locations achieved the target temperature. Pressure monitoring points were located throughout the ISTD well fields to monitor the effectiveness of the ISTD vapor control/collection system.

Vapors extracted from the subsurface were directed to an aboveground AQC system (Figure 4) designed to comply with stipulated discharge limits and to treat volatilized organic compounds in the off-gases. The AQC system consisted of six major components. These components were: a heat exchanger, knock-out pot (to separate vapor, liquid, and solids), re-heater, acid gas scrubber bed, two Granular Activated Carbon (GAC) beds, and process blowers.

The total power requirement for the ISTD well field and AQC equipment was approximately 1,000 kVA, of which approximately 850 kVA were delivered to the subsurface for heating. The maximum estimated power usage based on the soil properties provided, the power application rate, and a maximum estimated heating duration of 125 days was approximately 3,000,000 kW-hrs.

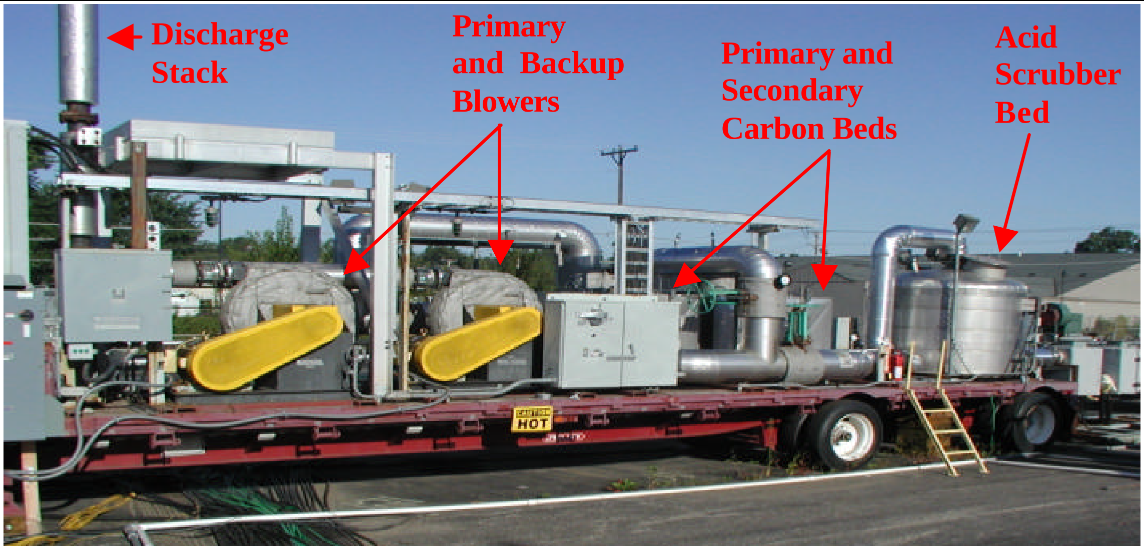

FIGURE 4. ISTD Air Quality Control Equipment

RESULTS

Heating of the three TTZs commenced on May 19, 2003. Heating ceased in the Former Waste Water Basin Area and Parking Lot Area 1 on November 25 and December 2, 2003, respectively. Heating of Parking Lot Area 2 was completed February 17, 2004. Figure 5 presents data from a multipoint thermocouple located at a centroid within Parking Lot Area 1. Data from this location indicate that although temperatures increased steadily and were relatively uniform with depth, the rate of increase was slower than expected. One possible reason for the slower than expected rate of heating was a

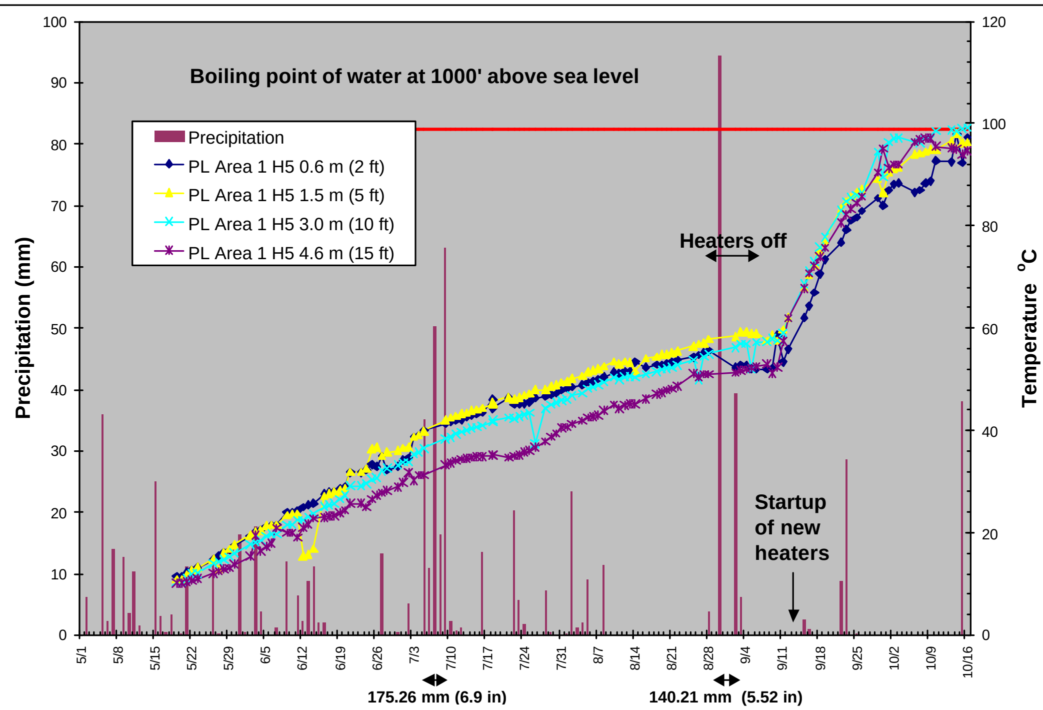

FIGURE 5. Subsurface Temperatures at a Centroid Location in Parking Lot Area 1

greater than expected flux of surface infiltration into the TTZs due to the presence of fractures within the clay till. In order to increase the rate of heating, the short heaters were replaced with full-length heaters the beginning of September 2003. Figure 5 shows that the rate of heating was substantially greater after in-stallation of the additional full-length thermal wells. Figure 5 also indicates that the centroid locations within Parking Lot Area 1 reached the target treatment temperature of 210°F (99°C) by the middle of October 2003, approximately 150 days following commencement of heating.

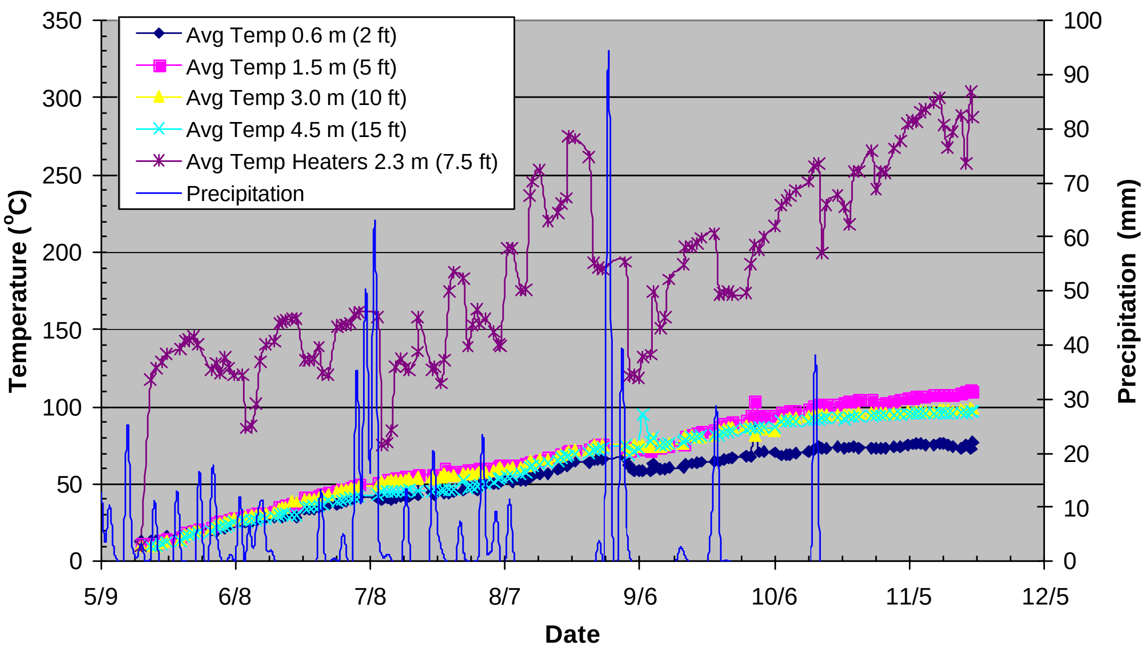

FIGURE 6. Average Temperatures of Interwell Soil and Soil Adjacent to Heaters in Parking Lot Area 1.

Figure 6 presents average temperatures for the Parking Lot Area 1 TTZ for both centroid locations (2, 5, 10, and 15 ft [0.6, 1.5, 3.0, and 4.6 m] BGS) and for soil immediately adjacent to heater wells (7.5 ft [2.3 m] BGS). These data indicate that despite numerous heavy rains, for depths greater than 2 ft (0.6 m), the target treatment temperature of 210°F (99°C) was achieved by the middle of October 2003, after 150 days of heating. The shallow soils were more adversely affected by the influx of cool groundwater into the TTZ than the deeper soils. The impact of groundwater flux into the TTZ can be seen by examining the correlation between the significant temperature variability and periodic cooling of the soil immediately adjacent to the heaters and the major precipitation events.

Based on the results of the Clients' confirmatory soil sampling program, all three areas achieved the remedial goals for TCE of <1,056 µg/kg; for 1,1,1- TCA of < 28,600 µg/kg; and for PCE of < 5,940 µg/kg. Figure 7 presents the pre-treatment, interim and post-treatment soil sampling results for the largest and most contaminated of the three areas, indicating that the mean pre-treatment concentration of nearly 100,000 µg/kg TCE (based on 48 discrete soil samples) was reduced to a mean concentrations of only 4 µg/kg (based on 26 discrete soil samples) by the October interim sampling (~150 days of heating). The Client's post-treatment sampling in November produced a mean concentration of 70 µg/kg TCE (based on 54 discrete soil samples) and confirmed attainment of the remedial goal for TCE and the other COCs. These results represent a 99.93% reduction in the mean concentration of TCE for the largest and most contaminated TTZ.

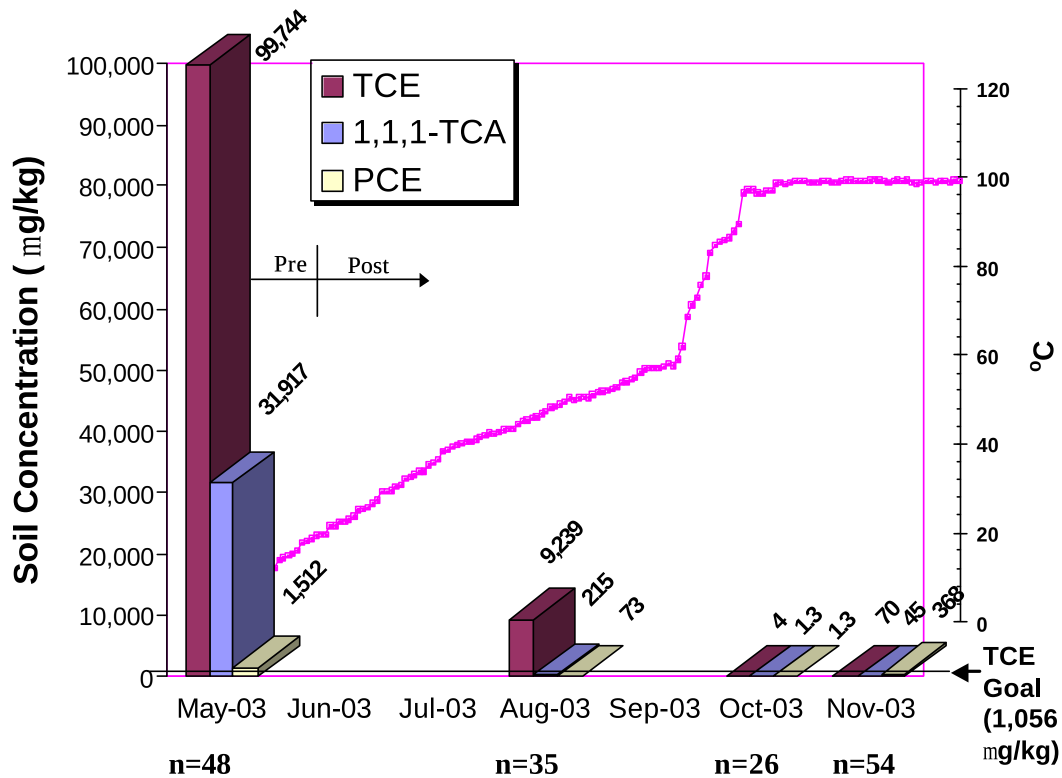

FIGURE 7. Mean Concentrations Measured during Pre-Treatment, Interim and Post-Treatment Soil Sampling Events, Parking Lot Area 1 and Representative Inter Well Temperatures.

It is interesting to note, that although inter well temperatures ranged between 130 and 180 ^{o}F (54 and 82 ^{o}C) in August, mean TCE and TCA concentrations were reduced by 90.7% and 99.4%, respectively. These substantial reductions were achieved because: 1) temperatures near the thermal wells were at the boiling point of water thereby producing steam stripping conditions, 2) the vapor pressures of TCE and TCA were substantially increased (>100 mm Hg at 140 ^{o}F [60 ^{o}C]), and 3) the hydrolysis reaction rates were significantly increased. For example, the hydrolysis half-life of TCA decreases from >1 year at 77 ^{o}F (25 ^{o}C) to 1 day at 176 ^{o}F (80 ^{o}C) (Jeffers et al. 1989). It is also important to note, that the CVOCs were effectively removed by boiling off only a small fraction of the water present in the TTZs.

Similar results were also achieved in the Former Waste Water Treatment Basin treatment area even though saturated conditions existed in that area. For example, the mean concentrations of TCE were reduced from 31,233 µg/kg during the August interim sampling (14 discrete samples) to 132 µg kg during the October interim sampling (14 discrete samples). The Client's post-treatment sampling (18 discrete samples) produced a mean TCE concentration of 102 μg/kg in November.

CONCLUSIONS

TerraTherm's ISTD technology was proven to be effective at achieving stringent remedial goals for CVOCs without complete desiccation of the TTZ. The remedial goals were achieved without having to boil off all of the water within the TTZs. Very hot (400 to 800 ^{o}F (~200 to 400 ^{o}C) and desiccated soil only extended 1-2 feet radially out from the thermal wells. Inter well temperatures of 210 ^{o}F (99 ^{o}C) were sufficient to achieve the remedial goals. Although near surface soil (i.e., 2 ft [0.6 m] below the ground surface) in some areas did not reach 210 ^{o}F (99 ^{o}C), CVOCs were also effectively removed from these soils by steam stripping, volatilization, and in-situ destruction reactions (e.g., hydrolysis). TerraTherm's ISTD technology provided a safe, effective, rapid, and non-intrusive method for remediation of the CVOC source zones in both unsaturated and saturated settings. Effective treatment of the source zones provided the basis for a No Further Action (NFA) letter for soils at the site.

ACKNOWLEDGMENTS

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