Use of Thermal Conduction Heating for the Remediation of DNAPL in Fractured Bedrock

Gorm Heron, (gheron@terratherm.com) (TerraTherm, Inc. Keene, CA, USA)
Ralph S. Baker, John M. Bierschenk, and John C. LaChance
(TerraTherm, Inc. Fitchburg, MA, USA)

ABSTRACT:
This paper presents the first full-scale remediation at a fractured rock site using Thermal Conduction Heating (TCH), also known as In-Situ Thermal Desorption (ISTD). A 90-ft deep TCE source area was treated thermally, including thick zones of saprolite and gneiss bedrock. The thermal treatment used 24 heater borings/wells, and operated for 148 days, after which an average temperature of approximately 100°C was achieved. The ISTD remediation work was highly successful at reducing soil, rock and groundwater concentrations at this confidential facility. Post remediation soil sampling indicated that the 95% UCL of the mean concentration of TCE in soil within the treated area was 17 μg/kg. This was significantly lower than the remedial goal of 60 μg/kg. In addition, groundwater concentrations within the treatment zone were reduced by between 74.5% and 99.7%. The total mass of VOCs removed from the subsurface during the ISTD remediation was approximately 12,000 lbs, almost all of which was TCE.

INTRODUCTION

Prior to this project, there did not exist an effective technology for the remediation of DNAPL in fractured bedrock systems. This is because DNAPL in fractured bedrock presents several significant challenges; including: 1) defining the area to be treated; 2) potential impacts of matrix diffusion within and downgradient of the source zone; 3) discrete nature of fracture pathways and presence of dead-ends; and 4) accessing DNAPL within the fractures and the contaminant mass in the matrix. One technology however, that may be able to overcome many of these limitations is Thermal Conduction Heating also known as In-Situ Thermal Desorption. ISTD is the simultaneous application of heat, by TCH, and vacuum to the subsurface to remove organic chemicals. Heat is applied by installing electrically powered heaters at regular intervals throughout the zone to be treated. The heat moves out into the inter-well regions primarily by thermal conduction. Thermal conduction heating of fractured bedrock sites is capable of: 1) achieving thorough heating of the bedrock (matrix and fractures), 2) preventing unwanted condensation of steam and CVOC vapors, and 3) capture and removal of the CVOC mass liberated from the bedrock and unconsolidated deposits.

In fractured rock settings, a substantial fraction of the contaminant mass may be located in the rock matrix, dissolved in matrix porewater, adsorbed to mineral surfaces and organic matter, or even as tiny droplets or ganglia if the DNAPL has entered the matrix. As a result, it is not sufficient to only apply a remedy to the fracture systems, since back-diffusion and transport of contaminants back out of the matrix can make it impossible to achieve satisfactory plume concentration reductions. Therefore, an effective fractured rock remedy must involve treatment of the contaminants in the matrix.

For thermal treatment of VOC DNAPL and dissolved and adsorbed phases, the dominant removal mechanism is vaporization, as illustrated in Figure 1 for an equivalent porous medium showing how boiling leads to steam formation and gas flow rich in contaminant

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vapors out of the pore matrix. Note the continuous gas phase in the right image where pore fluids are boiling and creating steam, which sweeps out to recovery wells. Boiling occurs at DNAPL-water interfaces and throughout. This mechanism has led to very effective thermal treatment even of thick saturated clay layers (Geomatrix and TerraTherm 2005, LaChance et al. 2004).

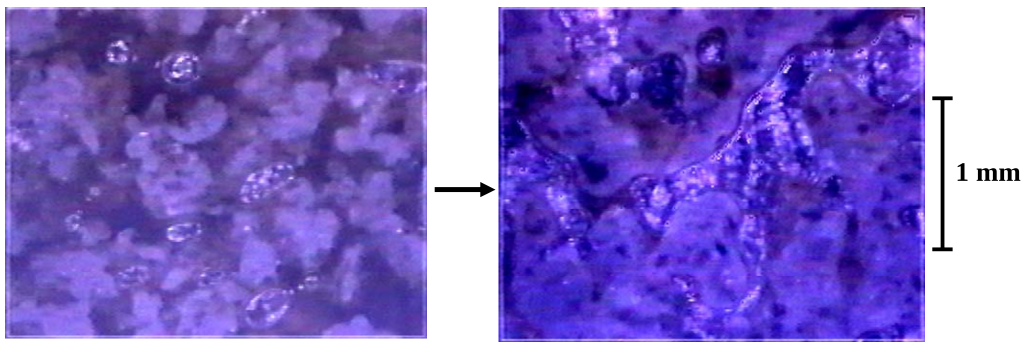

Figure 1. Conceptual illustration of the difference between ambient temperature (left) and boiling temperature conditions (right) at the pore scale for a porous medium.

Figure 2 summarizes the physical property changes occurring during heating for water, trichloroethene (TCE), and tetrachloroethene (PCE). While DNAPL density, viscosity, surface tension, and solubility varies slightly, vapor pressure and Henry's law constants increase dramatically with temperature (Heron et al 2006).

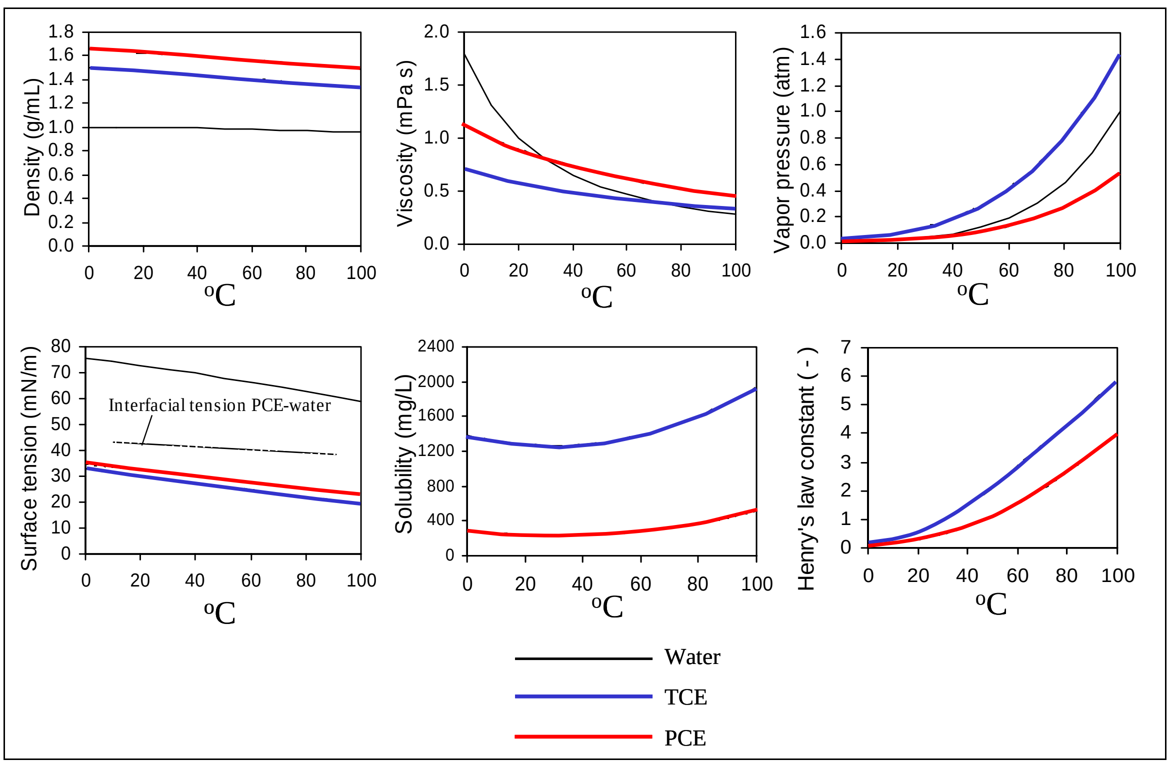

Figure 2. Properties of water, PCE and TCE as a function of temperature (from Heron et al. 2006).

Other mechanisms include enhanced dissolution, hydrolysis, and aqueous phase oxidation. However, vaporization is dominant for most chlorinated solvents.

In fractured rock systems, boiling of fluids in the fractures and the matrix leads to steam formation. The steam will sweep out of the rock towards locations with low pressure. Therefore, vacuum extraction is applied to each heater boring, creating a path for the generated vapors out of the formation. By using each heater boring for extraction, it is ensured that the produced steam can be extracted, and not migrate in unwanted directions. This principle is similar to the one developed for ISTD treatment of tight clay zones (LaChance et al 2006).

SITE DESCRIPTION AND TCH DESIGN

At a site located in the southeastern part of the U.S., TCH was used to remediate a TCE DNAPL source zone that extended 90 ft below the ground surface (bgs). The bottom 15 feet of the treatment zone consisted of fractured gneiss (TerraTherm, 2007). In summary, the Site was underlain by 4 geologic units:

- Fill: The fill was 25 feet thick, had a hydraulic conductivity of 1 x 10^{-4} cm/sec, a porosity of 42 percent and a soil moisture content of 10.8 percent by weight.
- Saprolite: The saprolitic soil (severely weathered granitic gneiss) was 30 feet thick and had a hydraulic conductivity, porosity, and soil moisture content of 5 x 10^{-5} cm/sec, 40 percent, and 14 percent, respectively.
- Partially Weathered Bedrock: Partially weathered rock (PWR) was present immediately beneath the saprolitic soil. It also had a hydraulic conductivity and porosity of 5 x 10^{-5} cm/sec and 40 percent, respectively. This layer was 20 feet thick.
- Fractured Bedrock: In general, the bedrock was assumed to be fractured, with a hydraulic conductivity of 1 x 10^{-5} cm/sec and a fracture porosity of 0.5%. The bedrock surface undulated with a typical depth to the bedrock surface of between 75 and 80 ft. There was a possibility of a highly fractured zone beneath the target treatment zone (TTZ) oriented north-to-south. The hydraulic conductivity of the highly fractured zone was assumed to range between 1 x 10^{-4} and 1 x 10^{-3} cm/s and the porosity was assumed to be 2%.

The water table at the Site was at the bottom of the saprolitic soil at approximately 55 ft bgs, resulting in a total saturated thickness of approximately 25 feet of soil and partially weathered bedrock overlying the fractured bedrock.

The primary contaminant of concern (COC) present in the subsurface) at the Site that the ISTD system was designed to treat was TCE. The TCE at the site was apparently released via a sump/catch basin system associated with an aboveground TCE storage tank and a TCE reclamation unit (Tank Area). The amount of TCE released to the subsurface was unknown. The source area, i.e. the TTZ that the ISTD system was designed to treat was located adjacent to the southwest corner of the existing manufacturing building. The TTZ was selected in order to encompass the highest soil concentrations and the most likely locations of TCE present as DNAPL and included an area approximately 33 ft wide by 76 ft long (2,554 ft^2) with the long axis oriented north-to-south. This alignment also coincided with the axis of the highest groundwater concentrations. The design basis for the bottom of the TTZ was 87 feet below ground surface (bgs) to encompass variations in the top of the bedrock and to ensure that all fill, saprolite, and weathered bedrock within the horizontal limits of the TTZ were treated. The heated interval extended to approximately 90 ft bgs to ensure uniform heating of the bottom of the TTZ. The average depth to the top of bedrock observed based on the installation of the heater-only and heater-vacuum wells was approximately 79 ft. Thus all of the fill, saprolite, and weathered bedrock within the horizontal limits of the TTZ were treated. This amounted to approximately 8,230 cubic yards (cy) of soil and weathered bedrock.

The primary remedial action objective for the ISTD installation was to remove TCE and other CVOCs present from the unsaturated and saturated portions of the TTZ (i.e., above and below the water table within the TTZ) and to attain remedial standards. Although final remedial standards were not established site-wide, the ISTD design was based on the achievement of 60 μg/kg of TCE for soil in the unsaturated zone. Although similar treatment levels for soil beneath the water table were feasible, the possibility that TCE present below the water table outside of the TTZ could migrate back into the TTZ following treatment necessitated that no specific remedial standard be set for the saturated portion of the TTZ. Instead, the ISTD system was designed to operate until the 60 μg/kg remedial standard for unsaturated soil was believed to have been achieved based on measurements of temperature and concentrations of CVOCs in the well field vapor stream and interim soil and groundwater data. At that point, the ISTD system was to be shut down and the soil and groundwater present in the saturated portion of the TTZ would be sampled and monitored to determine the level of cleanup achieved below the water table.

Numerical simulations of the application of ISTD at the Site were performed prior to ISTD system design to provide a basis for development of the conceptual design. As a result of the numerical simulations, a target treatment temperature of 212°F (100^{o}C) achieved in the interwell regions and the removal of a small fraction (i.e., 20%) of the water from the TTZ was found to be sufficient to achieve the remedial standards for TCE. Because the other CVOCs present in the TTZ had similar physical and chemical properties (e.g., boiling points) as TCE, they were also found to be effectively removed from the TTZ by achieving 212°F (100^{o}C) in the interwell regions. Thus, a target treatment temperature of 212°F (100^{o}C) was selected for the project.

A secondary remedial action objective of the ISTD installation at the Site was to minimize the potential for contaminant mobilization during treatment. Given the information available for the site at the time of the ISTD design, high concentrations of TCE and DNAPL were thought to be present in the subsurface. Thus, the ISTD system was designed to minimize the potential for contaminant mobilization outside of the TTZ both vertically and laterally. Specific aspects of the design that were added to minimize the potential for contaminant and DNAPL mobilization included:

Hot Floor: Extension of the heaters into the upper approximately 10 to 15 ft feet of the bedrock and boosting the power output of the bottom portion of the heaters in order to establish a "hot floor." The objective of the hot floor was to provide a barrier to vertical migration of the contaminants as the contaminants would be volatized and extracted from the subsurface when coming into proximity with the hot floor.[1] As described above, this resulted in the heating and treatment of the upper 15 to 20 ft of the fractured bedrock.

Establishment of Upward Vertical Gradients: A low-flow extraction system was designed to slightly lower the groundwater table within the TTZ, thereby creating upward hydraulic gradients across the bottom of the TTZ. The creation of upward gradients across the bottom of the TTZ was designed to offset the downward forces acting on the

[1] TerraTherm holds exclusive license to several patents for implementation of a hot floor during remediation to prevent vertical mobilization (U.S. Patent No. 5,997,214 and international patents granted and pending).

DNAPL and to provide an added level of security to ensure that the DNAPL did not migrate downward.

Perimeter Heater-Vacuum Wells: Because there was a potential that COCs existed up to the edge of the TTZ, heater-vacuum wells were placed around the perimeter of the TTZ to ensure that vapors were pulled back towards the TTZ and not pushed outward. The well-field is shown in Figure 3. Figure 4 shows the completed system, with fiberglass pipe manifold and a concrete vapor cover. A total of 24 heater wells/borings were used, ten of which were also used for vapor extraction.

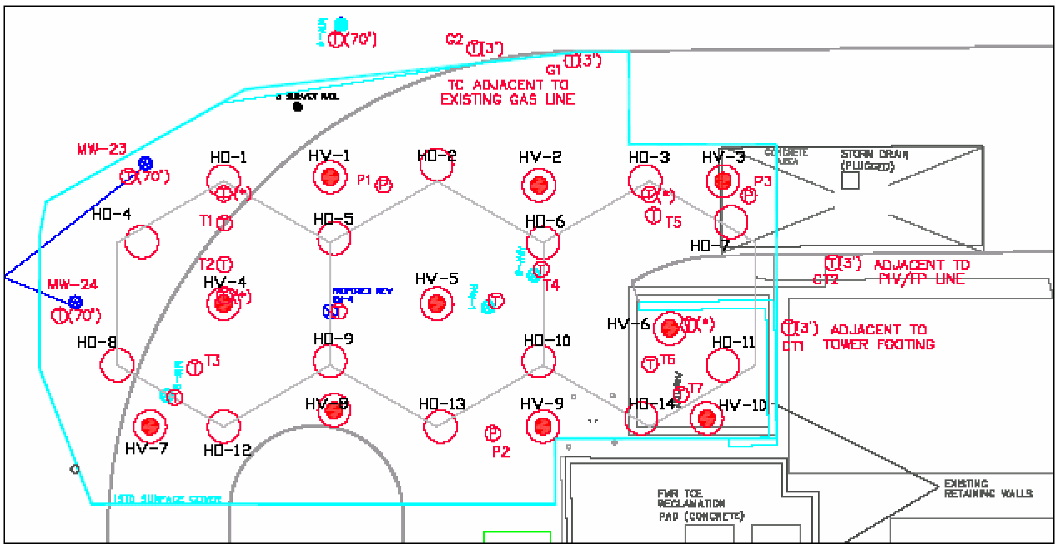

Figure 3. Heater boring/well locations and thermocouple locations at the Site. Heater wells are open circles. Heater wells with applied vacuum and circles with a red center. Thermocouples are denoted by a red "T" within a circle.

Figure 4. Completed ISTD system.

Electrical power (1,500 kW) for the ISTD remediation project was supplied from the existing plant building electrical service. TerraTherm's electrical distribution panels and all downstream equipment, which was configured for 480V, 3-phase, 4-wire service, was wired to the secondary side of the transformer provided by the host facility.

The vapor collection system at the Site consisted of a moisture knock-out pot and a vacuum blower to draw the heated vapors from the ground and convey them to the existing stack via a fiberglass manifold piping system that was constructed by TerraTherm. The liquid condensate from the manifold piping system and the liquid extracted from the recovery wells was piped to the existing groundwater treatment system at the host facility.

RESULTS

ISTD operations ran continuously 24 hours per day, 7 days per week from the start of heating on January 29, 2007 through the end of the heating period on June 20, 2007 and the final ISTD system shutdown on June 25, 2007.

Thermocouples (TCs) were installed at 7 locations between the thermal wells throughout the ISTD well field to monitor the soil heat up. These TCs were used to determine when the target treatment temperature was attained within and at the top and bottom of the TTZ. Attainment of the target treatment temperature was used to gauge when the ISTD treatment could be stopped. Each temperature monitoring location consisted of an array of thermocouples located at selected vertical intervals (e.g., 18, 40, 68, and 83 feet bgs). This vertical array of thermocouples enabled evaluation of the ISTD system treatment progress in the various geological layers found at the Site. Figure 5 shows the thermocouple temperature readings at the 83 feet bgs depth, which is in the bedrock. Similar or higher temperatures were achieved at the shallower depths as well.

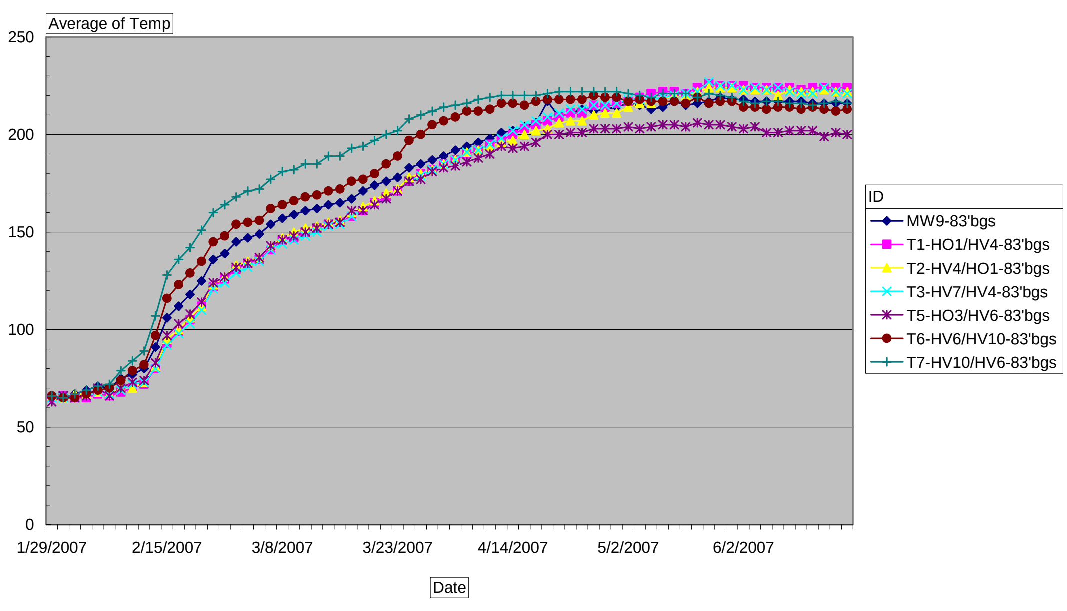

Figure 5. Thermocouple temperature readings (°F) at the Site over the duration of operations at 83 feet bgs (representative of temperatures in the bedrock).

The target temperature of the boiling point of water was generally achieved in the entire treatment volume after approximately 100 days of heating. Since the mass removal continued to be measureable and the power usage was lower than expected, the client chose to extend the operational period by approximately 7 weeks after the initial heat-up. Figure 6 shows the cumulative mass removal curve along with the projected and actual energy usage.

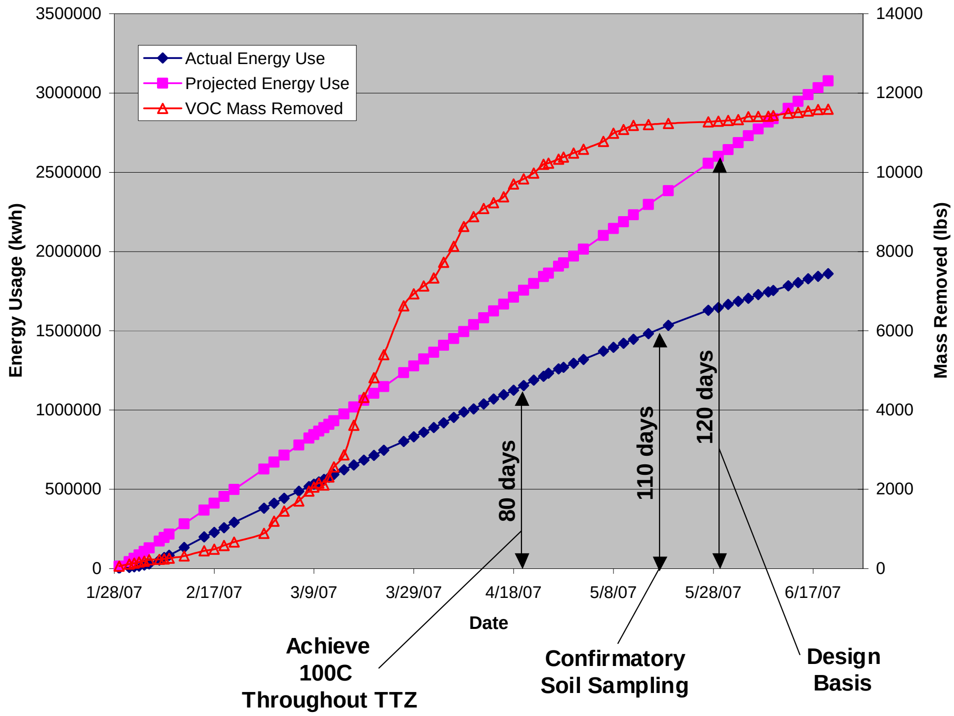

Figure 6. Mass removal and energy usage at the Site.

The total mass of VOCs extracted from the subsurface in the vapor phase during the course of the project was approximately 11,590 pounds (5.8 tons). The total mass of VOCs extracted in dissolved liquid phase was approximately 92 pounds. In addition to the VOCs extracted through volatilization and the dissolved phase, it is expected that some additional mass of VOCs would have been eliminated in situ due to hydrolysis or other in-situ degradation processes such as direct oxidation or pyrolysis.

The total amount of energy used to reach the remedial goal after 110 days of heating was 1,500,000 kWh. The amount of electrical energy expended per volume treated, was 182 kWh per cubic yard. The total operating time and amount of energy that was estimated to be required to heat up the TTZ and attain the remedial goal was 120 days and 2,600,000 kWh, respectively. Thus, the amount of energy actually used to heat up the TTZ was 60% less than the design. This indicates that subsurface heat losses to areas surrounding the TTZ were lower than anticipated, and the applied energy was used efficiently to raise the temperature inside the TTZ. This is great news for thermal remediation in fractured rock.

After 110 days of heating, a total of 66 discrete soil samples were collected and of these, 10 were duplicates. All of the duplicates showed agreement indicating very little sample variability. Soil and rock samples from within the treatment zone show a very thorough removal of contaminants. Measured starting concentrations of TCE were as high as 81,000,000 µg/kg and 1,100,000 µg/L in soil and water, respectively, and DNAPL was visually observed in soil and water samples. The post-remediation 95% Upper Confidence Limit (UCL) of the mean TCE soil concentration for the entire treatment zone, above and below the water table (based on 56 discrete soil samples), was 17 μg/kg (TerraTherm, 2007). The post-treatment concentration of TCE in groundwater samples from a monitoring well within the treatment zone that had starting TCE concentrations at saturation levels (1,100,000 μg/L) was reduced to <5 μg/L.

CONCLUSIONS

In summary, the ISTD remediation work was highly successful at reducing soil and groundwater concentrations at the facility. Post remediation soil sampling indicated that the 95% UCL of the mean concentration of TCE in soil within the treated area was 17 μg/kg. This was significantly lower than the remedial goal of 60 μg/kg. In addition, groundwater concentrations within the treatment zone were reduced by between 74.5% and 99.7%. The total mass of VOCs removed from the subsurface during the ISTD remediation was approximately 12,000 lbs, almost all of which was TCE.

This project demonstrated that ISTD can be very effective for heating and treating fractured bedrock, and that concentrations can be reduced from DNAPL-levels to near non-detect in the rock and groundwater. The mobilized and vaporized DNAPL constituents can be safely extracted and treated using vacuum extraction wells, ensuring capture. This is very promising news for fractured rock sites, where conventional wisdom has been that DNAPL problems are too complex and difficult to solve with available remediation techniques.

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