IN SITU THERMAL DESORPTION OF REFINED PETROLEUM HYDROCARBONS FROM SATURATED SOIL

Denis M. Conley. Haley & Aldrich of New York, Rochester. NY. USA
Kirk S. Hansen, Ground Technology, Inc., Houston, TX, USA
George L. Stegemejer. GLS Engineering Inc.. Houston. TX. USA
Harold J. Vinegar, Shell E&P Technology Company. Houston. TX. USA
Frank R. Fossati. Shell Oil Company, Lake Forest, CA. USA
Fred G. Carl, Shell Technology Ventures, Houston, TX, USA
Herbert F. Clough. Hart Crowser, Inc., Lake Oswego, OR. USA

Abstract: In Situ Thermal Desorption (ISID) is a remediation process in which heat and vacuum are applied simultaneously to subsurface soils to vaporize and destroy contaminants in situ or transport them to the surface for additional treatment. The paper presents the largest commercial application of ISTD to date (covering about 3/4 acre) and was the first project to remediate contaminated soil underneath buildings by inserting thermal wells through the building floor. This was also the first ISTD application to specifically target the removal of free product from atop groundwater in addition to soil remediation. The site was treated with 761 thermal wells containing electric heaters installed to depths of 10 to 12 feet below ground surface on a triangular grid pattern with 7-foot well spacing. Heating of the soil continued for nearly 120 days, during which time 6134 5tons of hydrocarbons were removed from the soil and groundwater. All free product was removed and concentration of benzene, the primary constituent of concern, was reduced to below state regulatory levels in both soil and groundwater. Quarterly groundwater monitoring has confirmed the remedial effectiveness of the technology, and site closure is pending.

INTRODUCTION:

The site was a former bulk fuel terminal located within a mixed commercial-residential neighborhood in Eugene, Oregon. The site was used for the storage and sale of bulk petroleum fuels from the 1920s through early 1970s (PEG, 1996). The facility was equipped with several above and underground storage tanks. Prior to implementation of the ISTD system, all tanks were excavated and removed. Soil and groundwater were impacted by refined petroleum hydrocarbons. Site characterization delineated areas of the site that contained free product identified as gasoline- and diesel-range organics (GRO/DRO). Soil concentrations ranged up to 3500 mg/kg GRO and 9300 mg/kg DRO (PEG, 1996). Groundwater concentrations ranged up to 25 mg/L BTEX and 15 mg/L DRO (PEG, 1995). In addition, free product had been observed as light non-aqueous phase liquids (LNAPL) in monitoring wells located on roughly two-thirds of the site. Thickness of free product ranged from trace to several feet.

Hydrogeology: The site geology consists primarily of consolidated and semi- consolidated, marine and non-marine sediments overlain by unconsolidated alluvium. A gravel layer consisting of primarily crushed and/or pea gravel covers the surface of the site to a depth of 1 to 4 feet (0.3 to 71.2 5m) below ground surface (bgs). A silt layer underlies the gravel and extends to approximately 11 to 16 feet (3.4 to 4.9 m) bgs. In some areas, at typical depths of 7 to 8 feet, there is a zone of silty sand or silty gravel (PEG, 1996). Beneath the silt layer is a lower gravel layer consisting of gravels in a sand-to-clay matrix underlain by a permeable gravel layer at 18 to 19 feet (5.5 to 5.8 m) bgs. Depth to groundwater at the site exhibited seasonal fluctuations ranging from less than 2.0 feet (0.6 m) bgs in early spring (February-April) to below 10 feet (3.0 m) bgs in late summer (August-September). Hydraulic permeability was determined to range from 1 to 10 millidarcy (md) (0.1 to l.OE-10 cm^2) within the upper silt layer. A confining layer was identified at approximately 14 to 17 feet (4.3 to 5.2 m) bgs with permeability less than 1.0 md. However, a second water- bearing unit was identified between 18 and 19 feet (5.5 and 5.8 m) bgs with a measured permeability of approximately 5000 md (5.OE-08 cm^2) (Core Petrophysics, 1997). The two aquifers were not hydraulically connected. Groundwater flow within the upper unconfined aquifer was affected by groundwater mounding in the northwest and southeastern portions of the site (PEG, 1996). The center of the site formed a groundwater trough that may have been affected by the past extensive excavation activities.

MATERIALS AND METHODS

The ISTD remedial system was designed with 761 thermal wells installed to depths of 10 to 12 feet (3.0 to 3.7 m) bgs on a triangular grid pattern of 7-foot (2.1-m) spacing (Figure 1). A total of 277 wells were configured as thermal vapor extraction wells to deliver heat while evacuating contaminant vapors and process gases. The spacing of vacuum extraction or heater/vacuum wells was approximately 7 to 12 feet (2.1 to 3.7 m). The heater/vacuum wells were connected to a central pressure blower capable of 3000 standard cubic feet per minute (SCFM) (85 m^3/min) total flow. Extracted contaminant vapors and process gases discharged from the blower received additional treatment from a regenerative thermal oxidizer (RTO) and one granulated activated carbon (GAC) bed. Remedial system monitoring included in situ thermocouples for recording soil temperatures; process piping vacuum measurements; and effluent stack monitoring of carbon monoxide (CO), carbon dioxide ($C0_2$), and total hydrocarbons (THC) using a CEM system.

Thermal Well Design: Thermal well design for the Eugene site introduced innovations in the selection of well patterns and spacing, in the well completion design, and in the methods of installation. The basic unit of heating was a triangular array of wells, which in previous studies proved to be the most efficient arrangement for heating soil. In previous projects, however, all heater wells were equipped to produce vaporized products by vacuum. Field experiments at Shell's Gasiner Road Test Facility in 1996 (Vinegar et al., 1997) demonstrated that some wells could be heated without being produced, provided that other vacuum wells

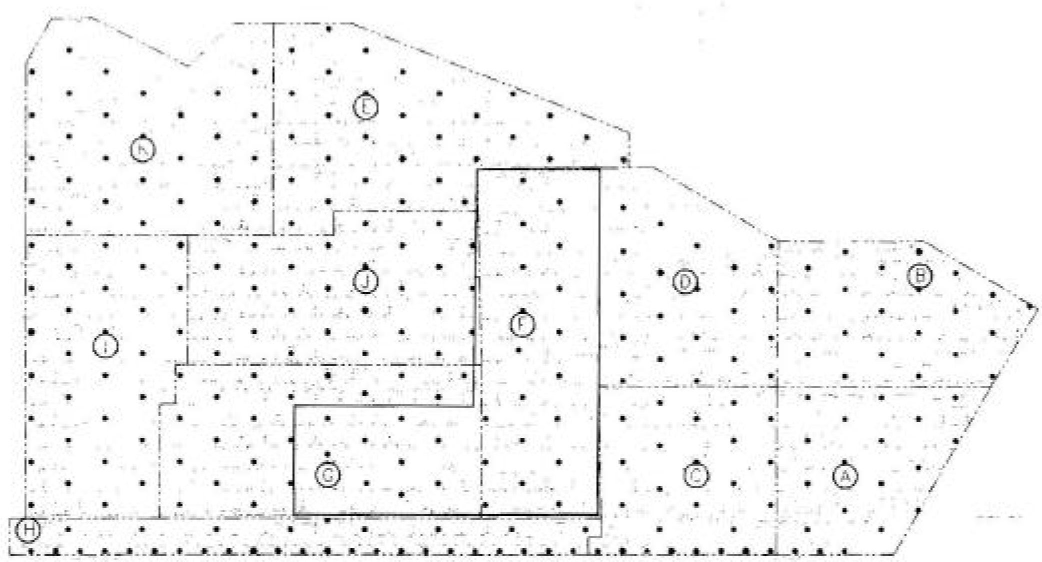

FIGURE 1. Locations of heater (open circle) and vacuum/heater (closed circle) wells on 7-foot triangular spacing. Heavy line shows L-shaped office (left) and warehouse (right). Light lines delineate property boundaries. Dashed lines indicate separate process control areas A-I for ISTD well fields.

nearby captured all the vaporized products. Subsequently, the heater-only well concept was demonstrated at a project site located in Portland, IN in late 1997 (Vinegar et al., 1999). At Eugene, triangular spaced wells were arranged into about 250 contiguous hexagonal patterns, each with a heater/vacuum well at the center surrounded by six heater-only wells. Except at the edges of the project, the heater-only wells were shared by the six surrounding hexagonal patterns, making a nominal ratio of two heater-only wells to one heater/vacuum well. Heater/vacuum wells were used in the outer locations of some of the peripheral patterns to assure complete capture of the vaporized products. A total of 102 thermal wells were drilled inside buildings through the concrete floors. Other wells were installed adjacent to the site straddling a sewer line located at a depth of 7 to 8 feet (2.1 to 2.5 m) bgs.

Energy Balance: The optimum spacing of wells in the triangular units was based on considerations of the time required for heating (operating costs) vs. the number of wells (capital costs of wells and facilities). The time needed for heating is dependent on the minimum average soil temperature required to meet the site remedial objectives, and the rate of movement of the thermal conduction heat fronts. The well spacing determines how much soil each well must heat, which includes the latent heat and the heat capacity of the fluids and the soil minerals. Since heat is supplied by electrical power, the amount of heat that can be injected depends on the power that can be injected per linear foot of heater (KW/ft; 1 KWH = 3413 BTU). Closer well spacing increases the number of wells, which nearly linearly increases the rate of heat injection. At Eugene, a 7 foot (2.1 m) spacing between heater elements was anticipated to require 60 days of heating at an injection rate of 0.3 KW/ft of heater or approximately 12,000 BTU per hour per well.

Groundwater Control: The need for site dewatering and groundwater control was recognized early in the planning and design phase. Field hydrology tests and laboratory measurements on core plugs recovered from soil borings identified two separate aquifers, as discussed previously. The initial groundwater volume in the treatment zone was estimated to be 800,000 gallons (3.03 x 10^6 L) using a surface area of 32,000 square feet (2,970 m^2), an average saturated thickness of 7.5 feet (2.29 m) with porosity 0.35, and an average vadose-zone thickness of 4 feet (1.22 m) with water saturation 0.50 and porosity 0.35. Based on well recovery tests, significant recharge was anticipated from rainfall directly on the site and shallow lateral flow. The vacuum/heater wells were installed with ports that permitted liquids to be pumped from the wells prior to heating. During the 4 months prior to heating (January 19 to May 20, 1998), a total of 257,000 gallons (970,000 L) of groundwater was pumped from the targeted treatment zone, representing 32% of the estimated in-place volume. Higher pump rates were achieved during and after rainstorms, confirming significant recharge of the surface aquifer. The underlying aquifer was dewatered prior to and during thermal treatment to prevent recharge from below by using 39 perimeter wells screened from 14 to 19 feet (4.3 to 5.8 m) bgs. During mid December 1997 to mid July 1998, over 1.5 x 10^6 gallons (5.7 x 10^6 L) of water was pumped from the confined aquifer. This maintained potentiometric surface of the lower aquifer at 14 to 15 feet (4.3 to 4.6 m) bgs throughout the period, about 4 feet (1.2 m) below normal.

Thermal Well Installation: Heater/vacuum well design consisted of a 5.5-inch (14-cm) diameter steel well screen. The wells were drilled to depths of 10 to 12 feet (3.0 to 4.7 m) bgs to avoid the underlying high-permeability gravel bed. Inside each well screen, a 3.5-inch (8.9-cm) heater can, welded shut at the bottom, isolated the heater elements from the flow of product in the annular space. A small-diameter tube (1/4-inch; 0.64-cm) was placed in the annular space for pumping off liquids before and during initial heating. These tubes were later used to monitor vacuum pressure in the wells. The heater-only wells consisted of a simple steel casing (3.5-inch, 8.9-cm diameter) with welded bottom into which the heaters were inserted. The cans were installed by direct push methods to depths ranging from 10 to 12 feet (3.0 to 3.7 m) bgs.

Process Control System: The process and control system was designed to control electrical energy applied to the heating elements; to monitor contaminant vapor and process gas concentrations; and to collect and treat vapors extracted from the treatment area. The thermal well field and Air Quality Control (AQC) system were monitored by a programmable logic controller (PLC) manufactured by Allen-Bradley. The PLC displayed the operating status of each thermal well heating element and the AQC system components through a personal computer (Figure 2).

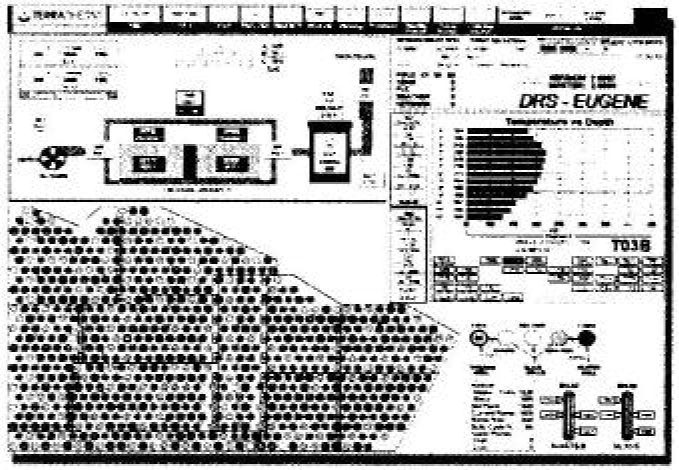

Figure 2. View of Process Control Screen after 45 days of Heating

Process Vapor Extraction & Treatment: The vacuum blower system pulled the process gas stream from the thermal well field manifold system and discharged into a regenerative thermal oxidizer (RTO) manufactured by Airex Corporation. Effluent from the RTO passed through a granulated activated carbon (GAC) bed prior to atmospheric discharge through an elevated small-diameter stack. The process effluent was monitored using a calibrated continuous emission monitoring (CEM) system manufactured by Rosemount Analytical. The quantification of carbon monoxide (CO) and carbon dioxide ($C0_2$) was performed with a non-destructive infrared analyzer prior to the analysis of total hydrocarbons (THC) using a flame ionization detector (FID). Total THC emissions were calculated every 30 minutes during treatment to demonstrate compliance with local air permit criteria. Emission samples collected from the stack were representative of the final atmospheric discharge.

RESULTS AND DISCUSSION

Initial Groundwater Production: Beginning in January 1998, groundwater was produced from approximately 150 heater-vacuum wells that were equipped with the small-diameter dewatering tubes. Initially, each of these wells produced over 10 gallons/day (38 L/day) for a total production of approximately 2000 gallons/day (7600 L/day) from the soil zone targeted for heating. As the target zone was dewatered, the rate fell to about 500 gallons/day (1900 L/day).

Electrical Heating: The heaters were energized on May 7. 1998. Heat was initially applied to the heater/vacuum wells, and then slowly applied to the heater-only wells. Start up was accomplished without evidence of escape of process vapors. During the next two weeks, the wells were brought up to a total energy use of approximately 2.5 megawatts of power or an average injection rate of 290 watts/foot for the 8625 linear feet (260 m) of well heaters in place. With the exception of a nine-day shut down from July 25 to August 3 for interim soil sampling, injection was continued at 2.5 megawatts for approximately 120 days. The energy input was fairly evenly distributed between the west and the east sides of the site (Figure 3). A total of 5.76×10^6 kilowatt hours (KWH) of electrical energy, or 19.7×10^9 BTU of heat, was injected into the soil during the project.

Production Response: Liquid Water: During heater testing in the first two weeks of May, heavy rains increased the liquid water production from the heater/vacuum wells to about 2000 gallons (7600 L) per day. The rains continued during the next month of heating, and precipitation continued to recharge flow into the heating zone. Vapors: The vacuum blower and vapor treatment facility were designed to handle 3000 SCFM (85 m^3/min) from the heater/vacuum wells. Figure 4 represents the total process vapor flow rate maintained during heating. A short interruption in withdrawal occurred during the nine-day heating shutdown for soil sampling. No escape of vapors or pressure build-up was observed. The vapor stream was analyzed for water content, and carbon dioxide (CO_2) to monitor the removal of water and hydrocarbons. The fraction of water in the flowing stream (f_{H2O}) was calculated from analysis of the wet oxygen content (f_{Owet}) and the dry oxygen content (f_{Odry}): (f_{H2O} = f_{Odry})/ (f_{Odry}), see Figure 5. The fraction of $C0_2$ in the flowing stream is shown in Figure 6. Carbon monoxide (CO) was negligible, therefore, the amount of hydrocarbons represented by the $C0_2$ can be calculated approximately from the stoichiometric ratio

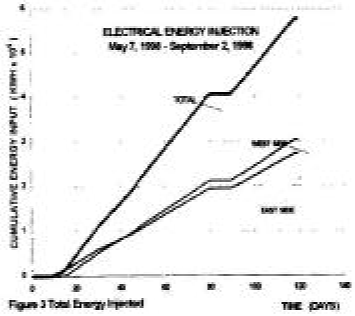

Figure 3 Total Energy Injected

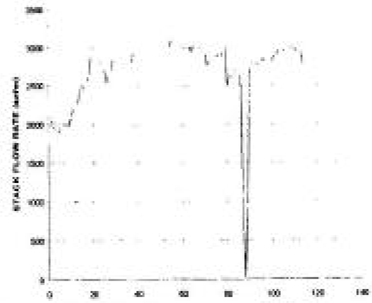

Figure 4 Total Process Flow

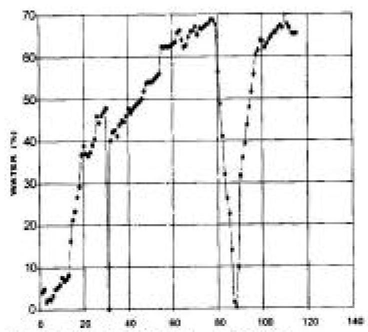

Figure 5 Water Vapor Production

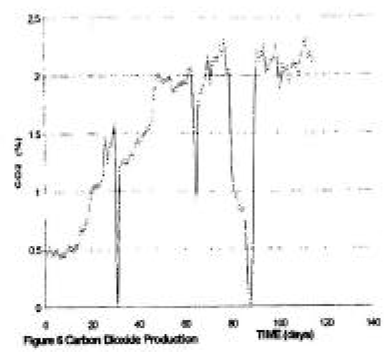

Figure 6 Carbon Dioxide Production

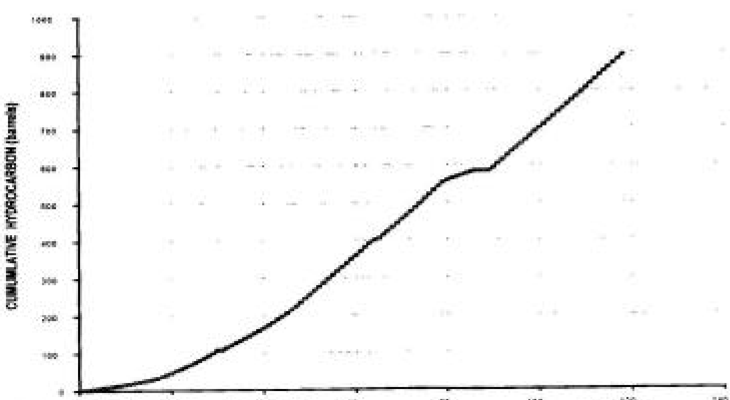

Figure 7 Hydrocarbon Production

of CH_2/CO_2, (Stegemeier and Vinegar, 2000). Masses and equivalent liquid volumes of hydrocarbons produced can be calculated from molar volume (379 cubic ft/mole), molecular weight (14 lbs/mole), and liquid density (280 lbs/bbl) of the product as diesel fuel. This calculated volume is based on petroleum barrels (1 bbl = 42 gallons) and includes any connate organic materials originally in the soil. The amount of connate $C0_2$ is small. The material balances can be derived from the component parts of the total vapor stream. Briefly, if all of the pore fluids are produced, the cumulative production in the vapor stream equals the amount of fluids initially in place plus the amount of convected air and water that passes through the heated region during operations. Table I summarizes amount of soil and fluids initially in place.

TABLE 1. Calculation of initial in-place water volume and soil masses.

Heated Area	of Site =	32,000	sq ft		
Average Soil	Porosity =	0.35			
Average Dry	Density =	107.5	lbs/cu ft		

Zone	Depth (ft bgs)	Water Saturation	Water (bbl)	Dry Soil (tons)	HC in Soil (tons)
Vadose	0-4	0.5	3,990	6,880	4.2
Upper	4-11.5	1.0	14,970	12,900	18.0
Total Target	0-11.5		18,960	19,780	22.2
Lower	11.5-14	1.0	4,990	4,300	1.3
Total Heated	0-14		23,950	24,080	23.5

T 1

Cumulative volume of produced vapor was0. approximately 0.464×10^9 SCF of vapor was produced. This nearly half-billion cubic feet of vapor represents over 14,600 tons of material removed from the soil, of which 9200 tons was convected air. Total water produced as vapor was approximately 30,400 barrels or 5300 tons. Total equivalent liquid hydrocarbons produced was approximately 957 barrels or 134 tons (Figure 7). The energy balance can be used as an independent check of the production estimates. About 19.7×10^9 BTU of heat was injected into the soil during the project, and an additional 5.0×10^9 BTU was released by the thermal conversion of hydrocarbons to $C0_2$, assuming that 90% of this conversion occurred within the soil. The amount of injected plus released heat equals that required to (1) heat the soil pore fluids and mineral grains, (2) heat the inflow water, (3) heat the inflow air, and (4) boil pore fluids plus inflow water. Table 2 gives the distribution of heat, based on the total amounts of soil and fluids removed.

TABLE 2. Heat balance calculations for Eugene, Oregon, ISTD Project

Source of Available Heat				Heat (10^9 BTU)
Injected heat				**19.70**
Heat Released by HC				**5.0**
Total Available Heat				**24.70**
Thermal Process (Initial T = 59°F, ΔT = 400 F°)	**Heat Capacity or Enthalpy (BTU/lbs/F°)**	**Initial Weight (tons)**	**Produced Weight (tons)**	**Heat Used (10^9 BTU)**
Heat Target Soil	**0.21**	**19,780**		**3.32**
Heat Liquid Water	**1.00008**		**5,300**	**1.62**
Latent Heat	**969.0234**		**(As Above)**	**10.27**
Superheat Steam	**0.48**		**(As Above)**	**1.26**
Heat Produced Air	**0.25**		**9,200**	**1.85**
Heat Produced HC	**0.50**		**134**	**0.05**
Heat Loss (Lower)	**0.21**	**4,300**		**0.72**
Heat Loss (Top/Sides)	**(28% of Heat**	**Injected)**		**5.62**
Total Heat Used		**24,080**	**14,634**	**24.71**

This balance shows that over half of the heat was used to boil and superheat the large amount of water as needed to dry the soil. About 10% of the heat was used to heat the air, and very little heat was needed to vaporize the hydrocarbons.

Soil Data: Soil samples were analyzed for total hydrocarbons using ODEQ Method NWTPH-Dx, BTEX by EPA Method 8020, and polyaromatic hydrocarbons (PAHs) by EPA Method 8270. Pre-treatment analyses indicated the presence of DRO as high as 9,300 mg/kg and concentrations of noncarcinogenic PAHs greater than 1.0 part per million (PEG. 1996). Post-treatment soil sampling was conducted by Hart Crowser (1999a) in September-December of 1998; composite soil samples were collected using a push-type soil sampler. A summary of the pre- and post-treatment soil analysis data is provided in Table 3 together with representative post-treatment groundwater analyses (Hart Crowser, 1 999a). Groundwater BTEX and TPH values have remained below regulatory requirements for three subsequent quarters of monitoring (Hart Crowser, 1999b).

TABLE 3. Summary of representative soil and groundwater sample results.*

Parameter	TPH-DRO	TPH-GRO	cPAHs	Benzene	Toluene	Ethyl-benzene	Xylenes
Pre-treatment Soil Analyses (mg/kg)			1994-1995				
MW-5 (8)	9,300	3,500	NA	3.3	3.6	11	21
GP-2 (5)	2,300	380	NA	0.16	<0.025	0.65	1.7
GP-3 (3)	3,300	490	NA	<0.025	0.51	4.6	25
SGP 11(13)	2,600	150	NA	0.13	0.11	0.24	0.30
SGP-13 (3)	1,200	1,100	NA	0.53	1.9	8.4	14
MW-11 (5)	1,100	660	NA	0.11	<0.025	2.0	2.5
MW-12 (5)	1,200	120	NA	0.033	<0.025	0.42	0.65
Post-treatment Soil Analyses (mg/kg)			September-December 1998				
VGP-7A	280	NA	<0.06	<0.03	<0.03	<0.03	<0.009
VGP-11	5,600	NA	<0.06	<0.03	<0.03	<0.03	<0.009
VGP-14A	990	NA	<0.06	<0.03	<0.03	<0.03	<0.009
VGP-16A	1,100	NA	<0.06	<0.03	0.19	0.29	0.35
MW-13	510	NA	<0.06	<0.006	<0.006	<0.006	<0.006
Post-Treatment Ground-Water Analyses (mg/L)			December 1998				
MW-13	NA	<0.1	<0.0001	<0.0005	<0.0005	<0.0005	<0.0015
MW-14	NA	0.27	<0.0001	0.0025	0.0016	<0.0005	0.0027
MW-15	NA	<0.1	<0.0001	<0.0005	<0.0005	<0.0005	<0.0015
MW-16	NA	0.14	<0.0001	0.0021	0.00074	<0.0005	<0.0015

*TPH- DRO/GRO – Total petroleum hydrocarbons, diesel range/gasoline range organics, cPAHs – carcinogenic polyaromatic hydrocarbons (i.e. benzo (a) pyrene).

CONCLUSIONS

The Eugene project successfully demonstrated extension of ISTD technology to several new areas of application, including:

1. Thermal treatment of impacted groundwater and soil below the water table;
2. Use of heater/vacuum wells for partial dewatering prior to thermal treatment;
3. Remediation of groundwater and soil underneath an existing building by placing thermal treatment wells through the concrete building floor;

4.Removal of all free product and reduction of benzene in groundwater to below regulatory requirements;
5.Reduction of BTEX and carcinogenic PAHs to nondetectable levels in the soil and significant reduction of diesel-range TPH;
6.Reduction of manufacturing, installation, and operation costs by using one (1) heater/vacuum well in the center of each hexagon surrounded by six heater-only wells.

REFERENCES

Core Petrophysics, 1997, *Liquid Permeability Study, Soil Remediation Project, Eugene, Oregon*, File No. 2-970909-2SC.

Hart Crowser, 1999a, *Quarterly Activity Report, Former Jackson Street BulkTerminal, Eugene Oregon*, January 27.

Hart Crowser, 1999b, *Proposal for Site Closure, Former Jackson Street Bulk Terminal, Eugene Oregon*, DEQ File No. 20-94-4004, December 2.

Pacific Environmental Group, 1995, *Environemntal Site Assessment Remedial Status Report, Former Shell Bulk Fuel Facility, Eugene Oregon.*

Pacific Environmental Group, 1996, *Site Characterization Report, Former Shell Bulk Fuel Facility, Eugene, Oregon.*

Stegemeier, George L. and Vinegar, Harold J., (2000), "Thermal Conduction Heating for In-situ Thermal Desorption of Soils", *Handbook of Mixed Waste Management Technology,* CRC Press, L.L.C., in review, to be published in 2000.

Vinegar, H. J, Menotti, J.L., Coles, J.M., Stegemeier, G.L., Sheldon, RB., and Edelstein, WA. (1997), "Remediation of Deep Soil Contamination Using Thermal Vacuum Wells", SPE 39291, 1997 Soc. Pet. Eng. Annual Technical Conference, San Antonio, Texas, October 5-8.

Vinegar, Harold J., Stegemeier, George L., Carl, Fred G., Stevenson, Jeffery D., and Dudley, Ronald J., (1999), "In-Situ Thermal, Desorption of Soils Impacted with Chlorinated Solvents", Paper #99-450, presented at the Air and Waste Management Association Annual Meeting, St. Louis, June 22.