LNAPL REMEDIATION USING ELECTRICAL RESISTANCE HEATING

TRS Group, Inc.

ABSTRACT

An Electrical Resistance Heating (ERH) pilot test was conducted in the fall of 1998 to determine the effectiveness of using ERH in combination with soil vapor extraction (SVE) for the remediation of benzene and light nonaqueous-phase liquids (LNAPL) at an island location on a river in the Midwest.

Hydrocarbon-stained soils were discovered on an island in Ohio in May 1993 during the installation of a monitoring well. The stained soils may have resulted from a past release from a pipeline system that was formerly operated to convey petroleum products from a former refinery to a terminal on the river. The pipeline system consisted of five, six-inch diameter steel pipelines that were buried at depths ranging from two to four feet below ground surface (bgs). Each pipeline was typically dedicated to conveying a separate refined product (e.g., jet and aviation fuel, diesel fuel, and three grades of gasoline). Additional test borings and monitoring wells were installed to characterize and delineate the petroleum hydrocarbons on the island.

A soil vapor extraction (SVE) system was installed in the summer and fall of 1995. The SVE system consisted of sixteen-vapor extraction wells installed at depths ranging from nine to 19 feet bgs. The wells were connected to a 25-hp vacuum pump via a network of buried 2- to 6-inch diameter PVC collection piping. Extracted soil vapor was treated via a catalytic oxidation unit capable of handling up to approximately 700 cubic feet per minute (cfm). The vacuum pump, moisture separator, and catalytic oxidation unit were mounted on an elevated platform above the 100-year flood elevation. The SVE system has been operated seasonally during lower groundwater levels since October 1995. Seasonal operation generally has occurred between July and December.

Previous site work had shown that volatile organic compound (VOC) contamination extended from approximately six feet bgs to a depth of approximately 30 bgs. For the purpose of the pilot test, a treatment zone covering a diameter of approximately 50 feet was selected between three existing extraction wells.

SUBSURFACE CONDITIONS

The site generally consists of clayey silt and silty clay from grade surface to a depth of three to six feet bgs. Fine to medium grain sand, mixed with gravel fills the region from approximately six feet bgs to 23 feet bgs. Below this depth, the soil consists of medium to coarse grain sand to a bedrock formation at nearly 60 feet bgs. The vadose zone soils have an organic carbon content of 0.7 percent. Grade surface in the pilot study area is at approximately 474 feet above mean sea level (msl).

The water table at the site fluctuates seasonally from between 460 feet above msl to greater than 480 feet above msl, with the greatest elevations occurring during the late winter and early spring seasons.

This fluctuation causes periodic intermittent flooding of the island to levels as high as 12 feet above grade surface. Groundwater levels during the pilot study remained approximately 15 feet below grade surface. The groundwater beneath the site flows toward the south and southeast, at a velocity of approximately 1 ft/day.

ERH PROCESS

ERH is a multi-phase electrical technique that uses readily available 60 Hz electricity to resistively heat soil and groundwater. Heating between the ERH electrodes creates an *in-situ* source of steam to strip volatile and semi-volatile contaminants from the subsurface. Soil vapor extraction (SVE) is then used to capture the off-gases for aboveground treatment.

ERH operates under the principal that electrical current passing through a resistive component (i.e. soil) will generate heat. By heating to the boiling point of water, an *in-situ* source of steam is created which strips contaminants from the soil. The steam serves two purposes. First, its physical action drives contaminants out of portions of the soil that tend to lock in the contaminants via capillary forces. Second, the steam acts as a carrier gas for the contaminants, enabling the contaminants to be swept out of the soil into the vacuum vent by increasing the permeability of the soil. The subsurface temperature rise also aids in the volatilization of contaminants in the treatment area by increasing the vapor pressure of the VOCs trapped in the subsurface. Each of these actions is unaffected by the heterogeneity of the soil, since the difference in soil conductivity between various soil types is relatively minor.

In this pilot test, the ERH system used conventional single-phase transformers to convert standard three-phase electricity into six-phase electricity. This power was then delivered to an electrode array consisting of six (6) steel electrodes arranged in a hexagonal pattern, with one neutral electrode placed in the center.

Each electrode is connected to a separate transformer to provide it with an individual electrical phase. The physical spacing of the electrodes, as well as the electrical phases, are both 60 degrees apart, which results in a uniform ratio of physical distance to potential difference between all electrodes in the array. This uniform ratio helps balance the delivery of power to the subsurface based on the electrical resistivity of the soil between electrodes, since each electrode will conduct electricity to every other electrode. This even distribution of power results in thorough heating of the subsurface throughout the treatment area as indicated in following infrared photograph.

SITE SPECIFIC APPLICATION

For the purpose of conducting the pilot study, the ERH process was operated using a single hexagonal electrode array. The array was installed with a 35-foot diameter pattern, with each electrode being installed to 24 feet below grade surface (bgs). Each of the electrodes was constructed to focus the electrical power input to depths of between five and 12 feet bgs, and between 19 and 24 feet bgs. In addition, the electrodes were electrically insulated from grade surface to a depth of 3.5 feet bgs. The actual heated region extended outside the array diameter, to an area approximately equal to 50 feet. The total heated volume for the pilot study was about 1,800 cubic yards.

A central SVE well was installed approximately two feet to the northeast of the neutral electrode in the array. The well was installed to a depth of 14 feet bgs and was constructed of 4-inch diameter

CPVC with a 10-foot long screen. The screen extended from a depth of 4 feet bgs to 14 feet bgs. The central vapor extraction well extracted steam at a rate of about 350 scfm, which was then delivered to an air-to-air heat exchanger.

A 21,000-gallon steel water storage tank was installed on site to collect condensate generated during the ERH operation. The condensate collected by the condenser was pumped to the storage tank where it was periodically removed via a vacuum truck for disposal at the facility's wastewater treatment plant.

A 480-volt power feed for the ERH system was supplied from a portable 750kW-diesel generator. The diesel generator was supplied fuel via gravity feed from an external diesel-fuel storage vessel with a capacity of 2,300 gallons.

Subsurface temperatures were measured to monitor the status of the site heating. These measurements were taken at intervals from grade surface to 26 feet bgs. The thermocouples were installed within a 3/4" CPVC probe located equidistant between two power electrodes and the neutral electrode. Once the thermocouples were installed, the pipe was filled with sand to minimize airflow channels within the pipe.

REMEDIATION GOALS

Based on existing data from the site, maximum initial concentrations of benzene in the soil and groundwater in the pilot test area were estimated to be 24 mg/kg and 2 mg/l, respectively. The average initial concentration of benzene in the soil was determined to be 2,700 parts per billion (ppb), with a high of 24,000 ppb measured in one well. Average benzene concentration in groundwater was 300 ppb, with a high of 2,000 ppb measured in one well. Since the area to be remediated was located near the center of the overall site contaminant plume, the target area was subject to renewed contamination throughout the project. For the purpose of determining the effectiveness of the ERH pilot study, cleanup goals of 98% removal of benzene were established for both soil and groundwater. This goal was based on operating the ERH system to reach the boiling point of water in the subsurface, and maintaining this temperature for a period of 60 days.

Groundwater monitoring probe clusters were installed at three locations along a transection on the island in the area of the ERH electrode array. The purpose was to monitor groundwater concentrations up gradient, within, and downgradient of the remediated area. Each cluster consisted of four probes placed in separate borings at depths of 1, 4, 7, and 10 feet below the water table, with depth to water at approximately 15 feet bgs. Two additional vacuum monitoring probes were installed at right angles to the transection on the approximate edge of the remediation area. The purpose was to permit monitoring of soil vacuum, and adjustments of vapor removal rates during vapor sampling.

During installation of the monitoring probes, soil samples were collected for headspace screening and select samples were submitted for chemical analysis. The purpose of sampling and analysis was to provide a baseline for comparison with post-treatment data to evaluate the effectiveness of the ERH field test. In addition, select samples were submitted for microbial enumeration and evaluation to provide background information, prior to the field test, for comparison with recovery of the microbial population after testing.

Groundwater samples were collected from the probes via polyethylene tubing and a peristaltic pump. In order to provide sufficient baseline data to evaluate natural variability in the various constituents of interest at the site, a total of four rounds of groundwater sampling were performed prior to initiation of the field test. One round of sampling was performed approximately two weeks before the field test and the three remaining rounds were collected every other day during the week prior to the field test.

OPERATIONS

Power was applied to the soil and groundwater on October 19, 1998. The off gas temperature at the head of the SVE well was used as the basis for determining when the site had reached boiling. By October 29th, the off gas had reached 93 degrees Celsius, where it stabilized for the remainder of the test. This stabilization of the off gas temperature was an indication that the majority of the site had reached the boiling of water.

In addition to monitoring off gas temperature, the subsurface temperature was monitored using thermocouples installed in a temperature monitoring well. This well was located equidistant from the neutral electrode and two electrodes located on the eastern side of the array. Data from this well indicated that the entire site was boiling within 15 days of startup, at depths from 7 to 14 feet bgs. Temperatures deeper in the water table, at 20 to 26 feet bgs, rose to nearly 30 degrees C, then remained relatively constant throughout the heating period. A graph of temperatures versus time is included as Figure 1.

Review of the data seems to indicate that as the temperature in the deeper water zone rose, the warmer water rose toward the surface. It was then replaced by cooler water from outside the treatment area, in a "natural circulation" pattern. A groundwater temperature reading taken from monitoring well MW-67 during the study further supports this theory. This temperature had risen to almost 30 degrees C, despite being located more than 30 feet outside the perimeter of the treatment area, in a direction perpendicular to the natural direction of groundwater flow. A larger scale application of the ERH process would be more efficient, since there would be less mixing of cool water in the heated region.

Once temperatures in the subsurface reached the boiling point of water, they were maintained there for a period of 31 days. On November 30th, the power supply was turned off and groundwater samples were taken from three groundwater monitoring point clusters. In addition, soil samples were obtained from locations immediately adjacent to these sample points two days after shutdown. Table 1 compares the results of pre-test and post-test analyses.

Table 1. Analytical Comparison for Benzene

		SOIL	**GROUNDWATER**
	Preliminary Goal	**300 ppb**	**50 ppb**
AVERAGE	Pre-test	2,700 ppb	300 ppb
CONCENTRATION	Post-test	72.9 ppb	8.8 ppb
	Percent C/U	**97%**	**97%**
HIGHEST	Pre-test	24,000 ppb	2,000 ppb
CONCENTRATION	Post-test	490 ppb	43 ppb
	Percent C/U	**98%**	**98%**

While the data indicates that the ERH pilot test fell just short of achieving the predetermined goal of 98% average cleanup, all groundwater samples taken were below the preliminary cleanup goal of 50 ppb. We feel that had the system continued to operate for an additional 7 to 10 days, the preliminary cleanup goal for soil would also have been achieved. Cost considerations, as well as the threat of flooding on the island dictated a somewhat reduced operating schedule. This total operating period was 42 days from date of first application of power to the subsurface. The original intent had been to raise the temperature of the site to the boiling point of water, then hold at that temperature for 60 days.

In addition to the time consideration, other factors are believed to have played a part in the slow removal of benzene from the site. A key factor is the effect of diesel components in the treatment area. As given by Raoult's Law, the presence of semi-volatile diesel components in solution tends to inhibit the removal of benzene by reducing its vapor pressure and limiting its ability to volatilize in the presence of steam and vacuum. However, this same phenomenon may be responsible for the extraction of some diesel components that otherwise wouldn't be anticipated. By combining the volatile component benzene with the semi-volatile diesel, the diesel will have a higher vapor pressure than it would in its pure state.

Samples taken at the conclusion of the test reveal that total petroleum hydrocarbons, as diesel, (TPH-DRO) were reduced in soil by as much as 66%, and in groundwater by as much as 98%, with average concentrations being reduced by 80% in groundwater and 7% soil. Contaminant reduction graphs showing the average reduction of contaminants in soil and groundwater are included as Figures 2 and 3.

Throughout the pilot study, steam was extracted from the central VE well and passed through the heat exchanger for condensing. The condensate was then pumped to the water storage tank for disposal. Prior to removing condensate from the storage tank, a discriminating liquid sensor was lowered into the tank to measure the amount of free-floating hydrocarbons on the surface. A total of 51,154 gallons of water was removed during the test, as well as approximately 265 gallons of free product. This product had the general consistency and odor of a kerosene-type fuel. However, no laboratory analysis was performed to quantify its specific composition.

Civil & Environmental Consultants, Inc. (CEC) has calculated mass removal rates prior to, during, and after the application of ERH. Their data shows that the vapor extraction system alone had removed a total of 280 pounds of contaminants over the 10 week operating period preceding application of ERH. Over the ensuing 12 weeks, the combined system had removed an additional 3,890 pounds of contaminant. This is an increase in mass removal of nearly 1,400%.

CEC also compiled data comparing pre- and post-test soil microbial counts at the site. General indications are that heterotrophic counts remained relatively constant throughout the study, at approximately 1.E+07 to 1.E+08 cells/ml. Petrophilic microbial counts increased by as much as a factor of 1,000, as measured three months following shutdown of the ERH system. Average petrophilic counts increased by a factor of 100. This data shows that heating of the site was highly beneficial to the overall petroleum hydrocarbon degraders. The increase in degraders will increase the natural biodegradation of the site, resulting in continued reduction of contaminants at the site long after ERH operations have ceased.

SUMMARY

The results of the pilot study indicate that the ERH technology is a highly successful mechanism for removal of LNAPL. The results clearly indicate:

- A significant increase in mass removal rates over straight SVE (~1400%)
- A 98% reduction of overall benzene concentrations
- The successful removal of 80% of diesel components (TPH-DRO) from GW
- A significant increase in petroleum hydrocarbon degraders
- The rapid removal of contaminants, with the above results achieved with only 42 days of ERH application

Based on these results, the client is currently evaluating the full-scale application of ERH throughout the site to achieve proposed cleanup goals. It was anticipated that the next phase of this project would begin in the second half of 1999.

Figure 1.
Temperature Vs Days of Operation

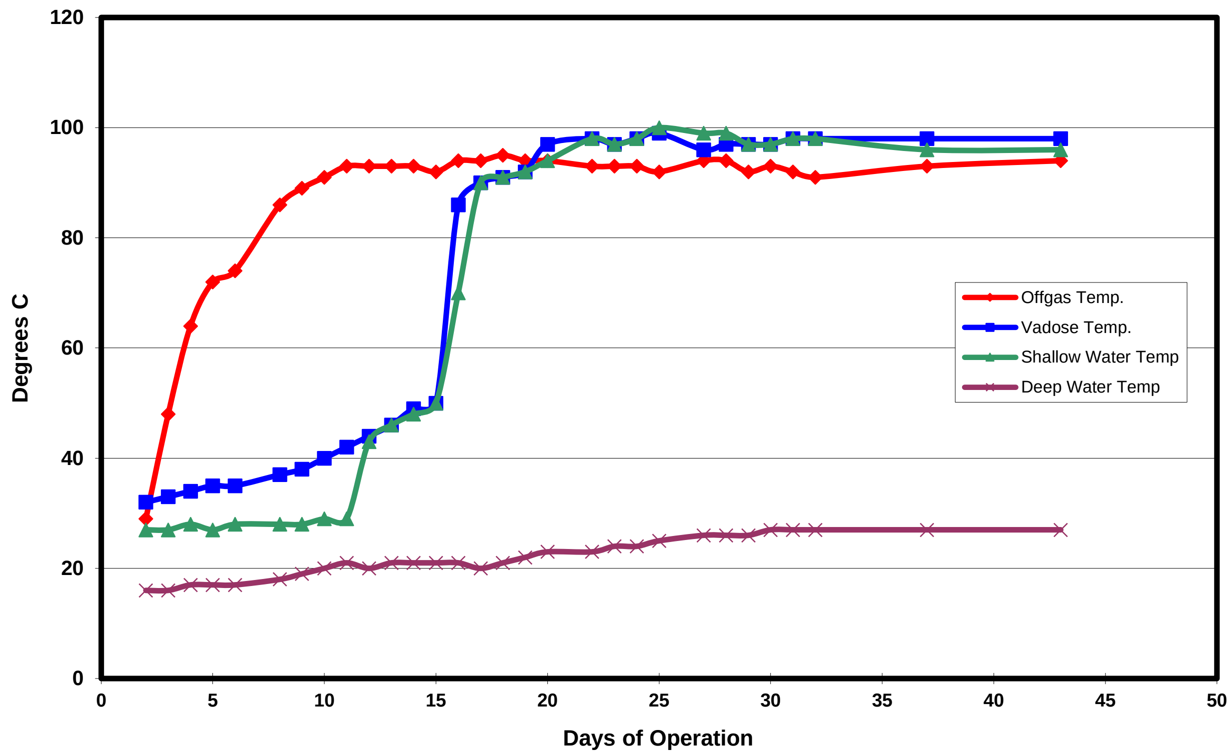

Figure 2.
Average Soil Contaminant Reduction

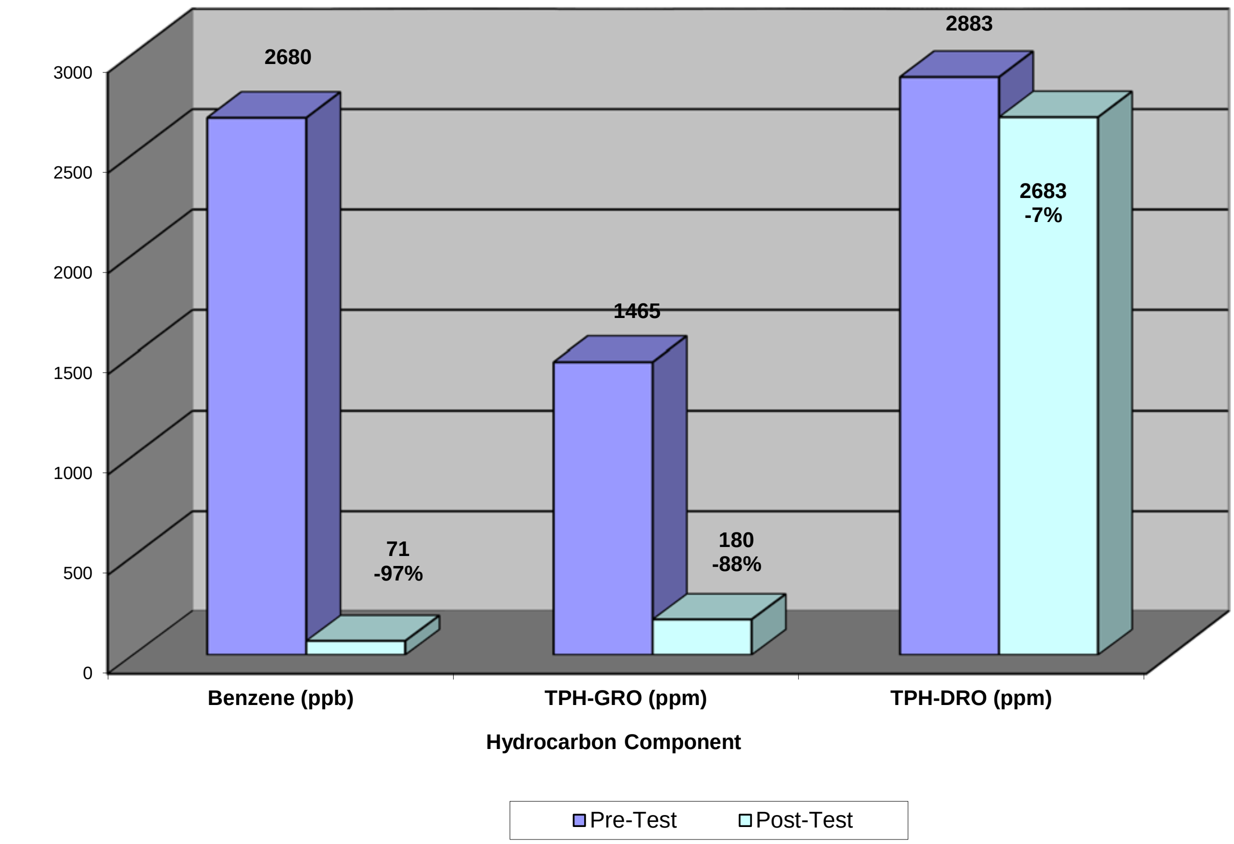

Figure 3.
Average Groundwater Contaminant Reductions