ET-DSP^{TM} FOR IN-SITU REMEDIATION UNDER AN OCCUPIED RESIDENTIAL APARTMENT BUILDING

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ABSTRACT

This paper presents the implementation and results of ET-DSP^{TM}, an in-situ electrical soil heating technology, in combination with high vacuum dual phase extraction, to achieve the removal of vapour pressure sensitive BTEX compounds from under an occupied residential apartment building. Operating within several engineering, environmental, and safety constraints, a design was developed in order to conduct electrical heating and in-situ extraction operations unobtrusively to the day to day living of the residents within the apartment complex and general area.

To place electrodes and extraction wells beneath the building into the contaminated volume of soil required that an entire apartment suite be converted into an operational site where drilling operations could be conducted in conjunction with the placement of surface facilities. The extraction facilities and ET-DSP^{TM} system were designed in such a manner that noise levels were reduced to well below acceptable levels and induced surface voltages were virtually eliminated. The standard operating procedures were also produced so that onsite activities of field personnel were kept to a minimum. One of the objectives of this paper is to present in detail the implementation strategy and economic factors.

This is the third implementation of ET-DSP^{TM} by Shell Canada Products Ltd in Canada. In a typical application of the process, electrodes are strategically placed into the contaminated zone. The pattern of electrodes is designed so that conventional three-phase power can be used to heat the soil. Also, the distance between electrodes and their location is determined from the heat transfer mechanisms associated with vapour extraction, electrical heating and fluid movement in the contaminated zone. Without consideration of all the heat transfer mechanisms, a less effective heating process will result. To determine the ideal pattern of electrode and extraction wells, a multi-phase, multi-component, three-dimensional thermal model is used to simulate the process. Operational data were monitored and compared to the numerical simulation of the process. Excellent agreement between field temperature, electrical operating, and energy consumption data and the numerical simulation predictions was observed. An additional objective of this paper is to present the results of the numerical simulation for this project in light of the field measured performance data.

During the remediation process several confirmatory samples were extracted from the target soil. The results consistently showed a significant reduction in the concentration of the hydrocarbons with non-detect levels being achieved in all of the samples that were tested. This is a direct result of a substantial temperature increase of the soil and concurrent increase in the hydrocarbon vapour pressure. The operations of the high vacuum dual phase extraction system were optimized to

recover the hydrocarbon vapours and dissolved phase concentrations from the soil as they were created. A final objective of this paper is to present the remediation performance achieved at this site with confirmatory drilling data and vapour concentration levels over time.

INTRODUCTION

Objective. The objectives of this paper are to:

1. Describe a method for the in-situ remediation of volatile hydrocarbon compounds that combines electrical heating technology with high vacuum dual phase extraction.
2. Present the results of the implementation of this technology for the remediation of a soil contaminated with volatile organic compounds that leaked from an underground storage tank and migrated to under an apartment building complex**.**
3. Give the results of the numerical simulation for this project in light of the field measured performance data., and
4. Summarize the remediation performance achieved at this site with confirmatory drilling data and vapour concentration levels over time.

Introduction to ET-DSP^{TM} and the Extraction Method Removing contaminants in-situ can be a long and costly operation. It has been demonstrated that heating the soil can greatly accelerate the removal of volatile hydrocarbon compounds (Buettner et. al., 1992, Scientific American, 1999). Thermal techniques for removing volatile organic compounds from soils include *in-situ* vapor stripping, dynamic underground stripping (Buettner and Daily, 1995), hot air injection, electromagnetic (Dev et. al., 1988) electrical heating, and **ET-DSP^{TM}** (DOE, 1995, McGee et. al., 1995).

The *Electro-Thermal Dynamic Stripping Process* uses three-phase line power and water injection at *electrode wells* to heat the soil *in-situ*. The process works to enhance other remediation technologies such as high vacuum dual phase extraction, bio-remediation, and natural attenuation. The features of the process are to minimize the heating time, bring about uniformity of heating, and maximize the remediation of contaminated soils. Three-phase electrical energy is delivered to contaminated soils by way of a Power Delivery System connected to a pattern of several electrode wells. The electrode wells are placed around the perimeter and adjacent to the volume of contaminated soil. Several extraction wells are located within the perimeter of the electrode wells. The extraction wells are positioned to optimize the convective heat transfer and maximize the rate that contaminants are removed. An example of the **ET-DSP^{TM}** system used at a previous Shell Canada site is shown in Figure 1.

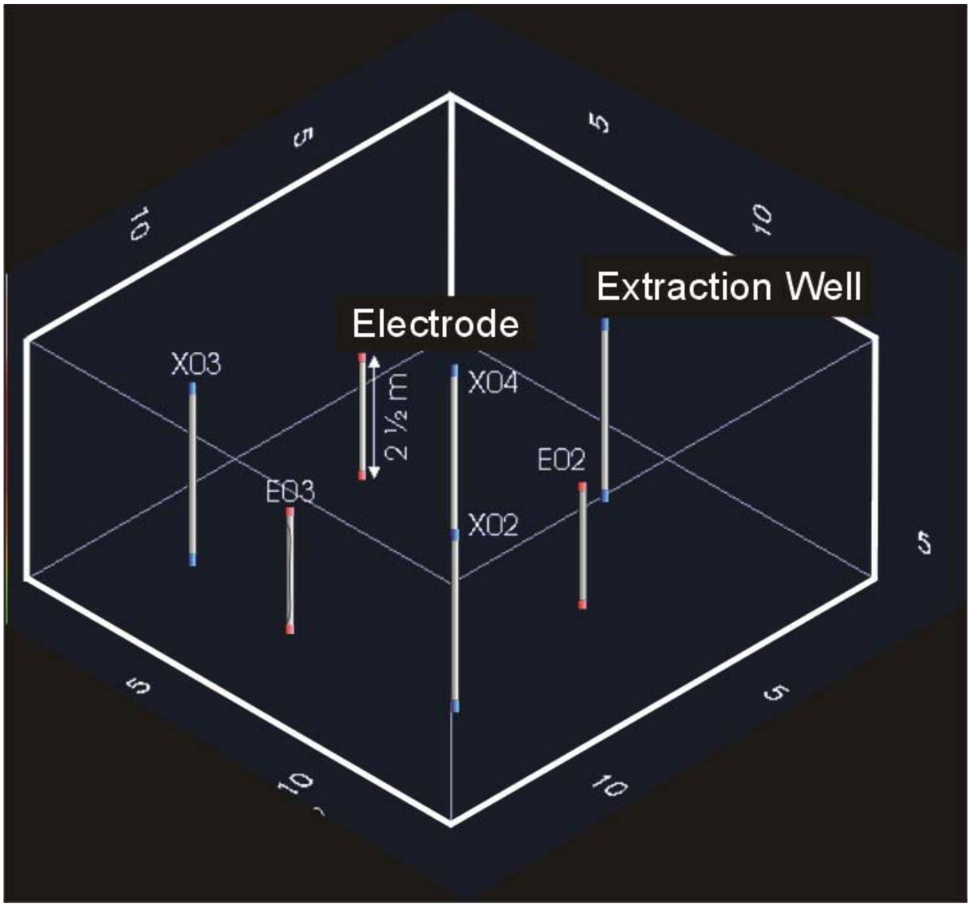

FIGURE 1. Electrode and extraction well layout used at the Crowchild Three Electrode pilot test. There are three electrodes and four extraction wells shown in the figure. The extraction wells are screened from top to bottom and are about twice as long as the electrodes.

Each electrode well is connected to a phase on the Power Delivery System, a flow-line from the water injection pump, and a return flow line to the water handling facilities. The Power Delivery System is controlled by a Computer Controller, which controls the relative phase and voltage of each electrode at instantaneous moments of time. This is referred to as Time Distributed Control and Inter-phase Synchronization and these features make it possible for the preferential heating of the soil with varying electrical properties throughout the zone of contamination.

Electrical heating increases the temperature of the soil by conducting current through the resistive connate water that fills the porosity of the soil. The increase in temperature raises the vapor pressure of volatile and semi-volatile contaminants, thus increasing their volatilization and removal from the soil using vapour extraction. For example, Figure 1 shows the vapour pressure relationship for benzene (C_6H_6). The curve represents the phase boundary of benzene. Above the curve, benzene naturally exits in liquid phase and in the gas phase for conditions below the curve. An increase in temperature from standard conditions of 15 ºC to 80 ºC changes the phase of benzene from liquid to gas at atmospheric pressure. Normal operating conditions of the process are indicated on the plot. The average pressure in the soil is reduced as a result of the vapour extraction wells. The average temperature in the soil is increased to 80 ºC as a result of electrical heating. Under these conditions, the benzene goes preferentially into the gas phase. Once the contaminant is in the gas phase, it is easily removed from the soil by the extraction system. The heating will also tend to dry the soil by producing steam vapour, which will result in an increase in the permeability and dynamic stripping of the contaminants that may not be removed using primary soil vapor extraction.

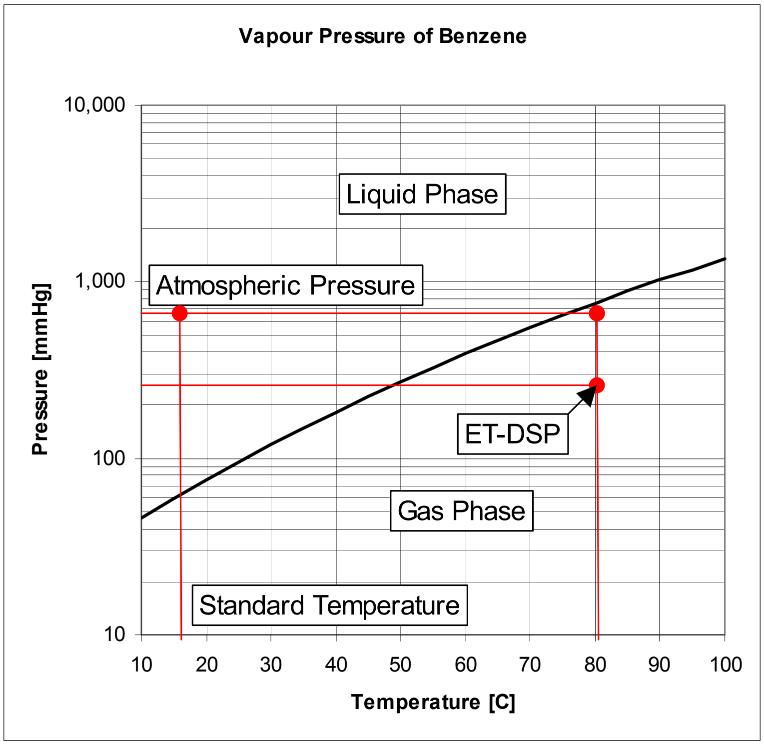

FIGURE 2. Vapour pressure plot of benzene (Hirata et. al., 1975)

The extraction system consisted of multi-phase extraction capability. Based on prior experience using thermal remediation, the size of the extraction was designed to handle both an increase in concentration of hydrocarbon vapours, dissolved phase concentrations, as well as an increase in the production rate of sediments. Extracted vapour and liquids are pretreated in a 4,000 litre free knockout separator. The purpose of this tank is to remove the suspended solids from the liquids prior to processing the fluids through the extraction and treatment facilities. Experience with thermal processes has shown that with increased soil temperature there will be an increase in the sediments produced from the soil. These sediments are typically silts and fine grained sands. This was observed at this project. The processed fluids are pumped through a vapour-liquid separator. The vapour emissions are vented and the water is treated through granular activated carbon and discharged to the sanitary sewer system.

DISCUSSION

Statement of the Problem: The remediation site was located beside a redeveloped service station and included volumes of soil located beneath an apartment building as shown in Figures 3 and 4. The soil was contaminated with benzene and volatile organic compounds making up gasoline that leaked from an underground storage tank. The primary contaminant of concern was benzene. The area encompassed approximately 125 m^2 and targeted 850 m^3 of soil of which approximately 350 m^3 were contaminated with gasoline. Benzene was adsorbed to an organic layer approximately 1½ meters thick, 3½ meters below grade. The depth to groundwater was measured within the organic layer at approximately three meters below grade. Approximately half of the contaminated soil was located beneath the apartment complex. Figure 3 shows the layout of the in-situ electrodes and extraction wells used in the project.

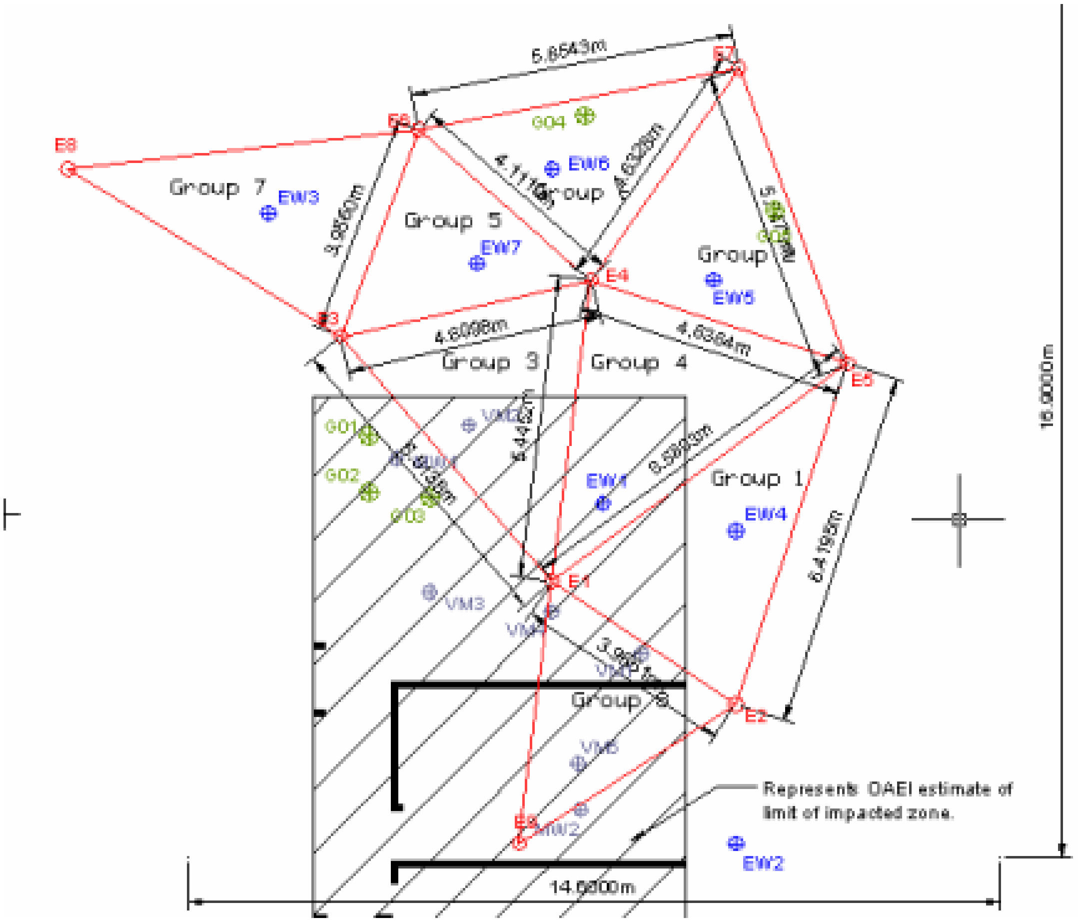

FIGURE 3. This figure shows the layout of electrodes and extraction. Extraction wells are shown in blue and electrodes are shown in red. Patterns of electrode and extraction wells were grouped to optimize the load on the surface facilities.

To save the building from excavation an in-situ remediation technology was considered necessary. The client also required that the remediation process achieve clean up criteria within six to nine months. Conventional in-situ technologies such as soil vapour extraction and pump-and-treat are limited by the slow vapourization process of the hydrocarbons at low temperatures and retardation of the contaminants in-situ, especially in fine sediments and clays. To achieve remediation using conventional methods may require up to ten years. In-situ thermal methods have demonstrated that soils can be remediated in months as opposed to years.

In addition to characterization of the site for concentration levels of contaminant, electrical conductivity of the soil and its distribution was measured. These involve measurements of the electrical properties of the soil as a function of temperature and water saturation. The data is important for the design of the Power Delivery System, estimate of the time required heating the soil, determination of the power requirements, and numerical simulation of the heating process.

FIGURE 4. The corner of the apartment building that the soil beneath it is contaminated with benzene and other hydrocarbon compounds. The rig is drilling a well less than one metre from the side of the building where an electrode will be subsequently located.

Several engineering, environmental, and safety constraints are inherently imposed on the design of the remediation strategy in order to conduct electrical heating and in-situ extraction operations unobtrusively to the day to day living of the residents within the apartment complex and general area. To place electrodes and extraction wells beneath the building required that an entire apartment suite be converted into an operational site where drilling operations could be conducted in conjunction with the placement of surface facilities. The extraction facilities and ET-DSP^{TM} system were designed in such a manner that noise levels were reduced to well below acceptable levels and induced surface voltages were virtually eliminated. The standard operating procedures were also produced so that onsite activities of field personnel were kept to a minimum.

Implementation of the Remediation Strategy. The major components of the remediation system were located next the site and facilities were also located inside the apartment. Figure 5 shows the layout of the major surface facilities. The extraction facilities were sized to create significant vacuum in the soil as well as have the capability to produce vapours and liquids at high flow mass rates. During thermal remediation operations the size of the extraction system is an important consideration. The rapid volatilization of the hydrocarbons which is associated with a large increase in temperature requires that they be removed rapidly from the soil to limit lateral and vertical migration of the plume. This introduces the concept of "Radius of Capture" as opposed "Radius of Influence" in the operations of the remediation. The spacing between extraction wells and the rate of recovery are calculated with the simulator to ensure that the rate of volatilization does not exceed the rate of removal.

FIGURE 5. The major surface facilities for the ET-DSP and high vacuum dual phase extraction system were located next to the apartment building. The area was fenced off for safety and operational reasons. Power lines, hoses, and extraction piping were all placed below ground to ensure that the esthetic value of the site was maintained during remediation operations.

As previously mentioned, an entire apartment within the complex was leased and changed into an operational site. Electrodes and extraction wells were drilled through the floor into the soil. A miniature hydraulic drilling rig was used to drill the wells. The small size of the drill rig limited the size of the electrodes that could be used inside the apartment. To ensure that these electrodes were *electrically similar* to the larger electrodes outside the apartment, a mini electrode was designed. Three mini electrodes are electrically similar as one large electrode. This concept is shown in Figure 6. In order to place wells in limited access locations required specialized drilling technology and methods as shown in Figure 7. Figure 4 shows that conventional drilling methods were also used in areas where it was feasible to do so.

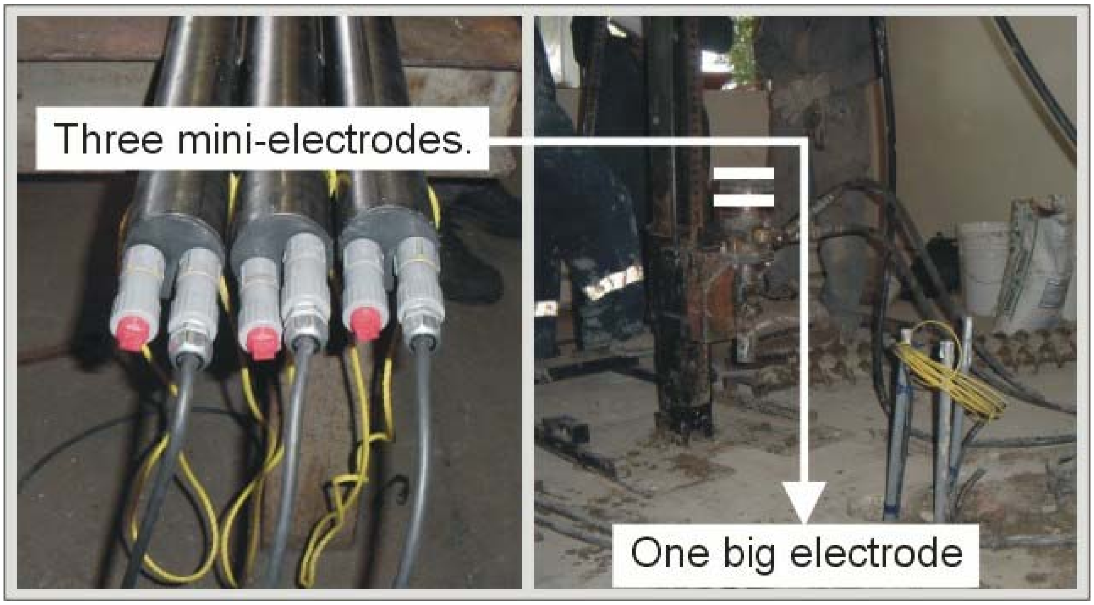

FIGURE 6. Three mini-electrodes are electrically similar to one electrode. The mini-electrodes are placed together as shown in the above figure. This allowed electrodes to be placed in the apartment using a small drill (also shown) while maintaining an electrical balance in the **ET-DSP**$^{\text{TM}}$ process.

FIGURE 7. Specialized drilling methods were used to drill well locations in limited access areas.

Based on the initial site characterization, the remediation process was simulated for the site. The simulation results are used for the design of the overall system and determined the operating strategy and grouping of the extraction and electrode wells. Also, the simulation calculations were used to design the *grounding* system so that voltage potentials on the surface did not exceed safe limits. Based on the simulation results (shown in Figure 8), the following design and operating parameters were used.

1. The distance between electrodes was four to six meters and depended on the grouping strategy,

2. The sequence of groups for electrical heating and extraction. Extraction operations could continue in groups that were not undergoing electrical heating with affecting the efficiency of heating in adjacent groups (see Figure 8).

3. The minimum heating duration for groups is 30 days,

4. Maximum operating current was estimated at 110 amps per electrode and the input power per electrode averaged between 13 and 16 kW, and

5. Some groups may require more than one cycle of heating to achieve target temperatures. An operating contingency of two cycles was built into the operations budget.

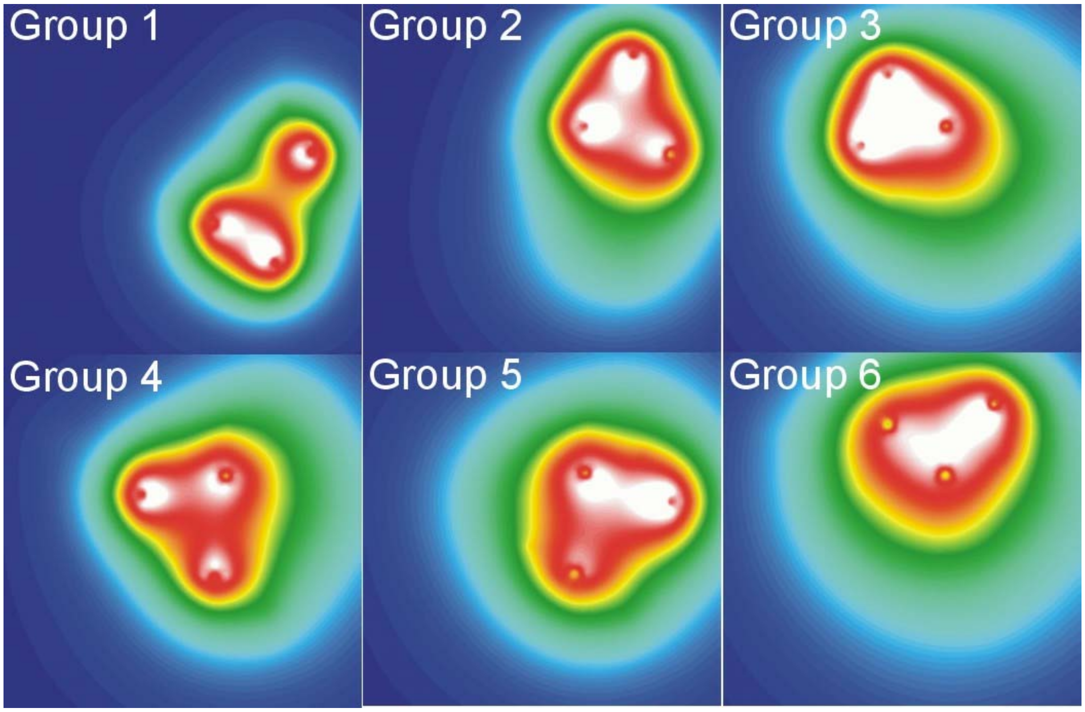

FIGURE 8. This figure shows the numerical results of the temperature distribution during extraction and electrical heating operations. Areas in white are at temperatures above 100 °C. Note that Groups 1, 3 and 4 are beneath the building. Each cycle consists of about 30 days of heating. Not all Groups are shown.

A conventional water handling and vapour recovery system are installed as part of the process. The water handling system is required to provide water injection into the electrode wells to prevent the wells from overheating. The electrode wells are designed with fluid injection capacity. Therefore some of the injected water flows from the electrode wells towards the vapour extraction wells. The heat transported by fluid movement tends to heat the soil rapidly and more uniformly. The produced fluids increase with temperature over time. These fluids are re-injected and the overall thermal efficiency is improved.

The current path is shared between the electrodes connected to the three phase power supply and is through the connate water in the porous soil. The temperature is controlled to minimize drying out of the soil until the latter stages of the heating process. As the soil changes in temperature, the resistivity of the connate water will typically decrease. Also, as the soil dries out, the resistivity will increase. A computer control system is installed to ensure that the maximum current is injected into the electrode wells at all times.

RESULTS

Temperature Results. Substantial temperature increases were measured within the electrode array groups during electrical heating. The average initial in-situ temperatures were 10 ºC and increased to an average of 80 ºC after 31 days. Highest temperatures were observed around the electrodes and confirmed by the production of steam vapours at these locations.

The temperatures of the soil within an electrode group decreased rapidly once electrical power to the group was deactivated. This was due to maintaining extraction operations in groups that were not being heated. The data supports that this approach accelerated the removal of contaminates from the soil.

Towards the end of the project a digital temperature sensing string was installed inside the apartment between Electrode 1 and Electrode 9 (approximately two meters from E1, refer to Figure 3). The vertical temperature distribution taken on April 16, 2002 is shown in Figure 9. The purpose of this data is to show that the majority of the heated volume is vertically contained within the height of the electrodes. It is also noted that the temperature near the floor of the apartment did not reach very high values. The data confirms the numerical simulation temperature calculations.

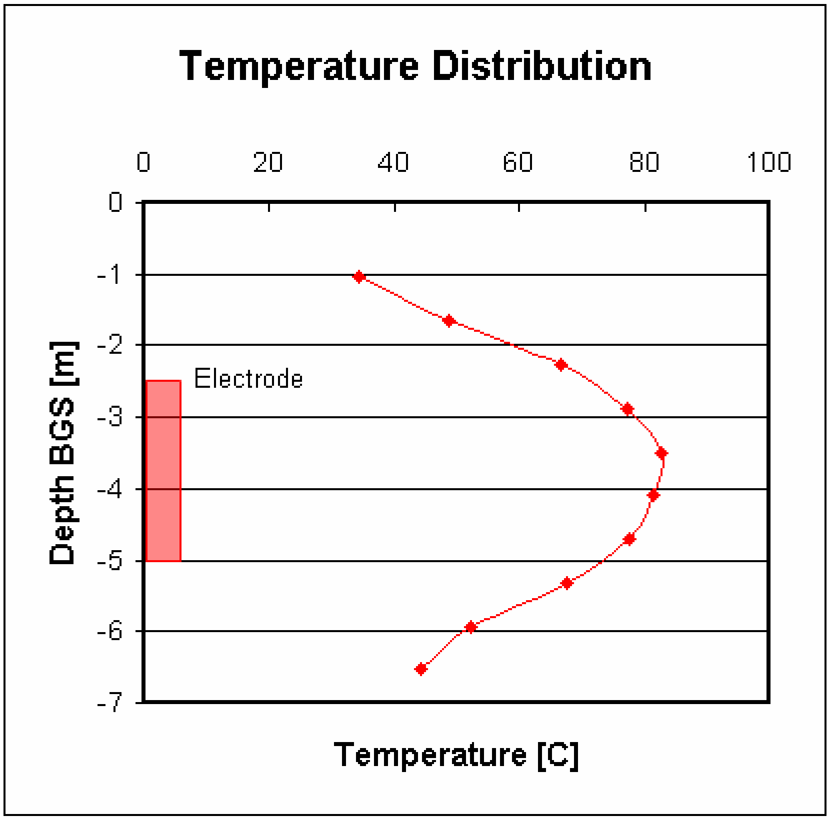

FIGURE 9. This figure shows the vertical temperature distribution in the soil. The temperature sensing string is located between Electrodes 1 and 9, approximately two meters from Electrode 1. The data was taken on April 16, 2002, towards the end of the project.

Petroleum Hydrocarbon Removal. The multi-phase extraction equipment removed a total of 1,800 liters of petroleum hydrocarbon from the subsurface during 220 days of extraction for an average extraction rate of 8 liter/day liquid equivalent. Associated with the recovery of petroleum liquids was 1,500 cubic meters of ground water.

The hydrocarbon recovery rate and cumulative recovery curves during **ET-DSP**^{TM} operations are shown in Figures 10 and 11. Figure 10 shows that the recovery rate declines exponentially as would be expected as more and more hydrocarbons are removed from the soil. The shape of the curve is similar to extraction rate curves for soil vapour extraction with the major difference being the length of time associated with high recovery rates. The conclusions from the data plotted on Figures 10 and 11 suggest that the rate of volatilization was approximately equal to the extraction rate. Also, that heating operations may have been terminated earlier with successful results.

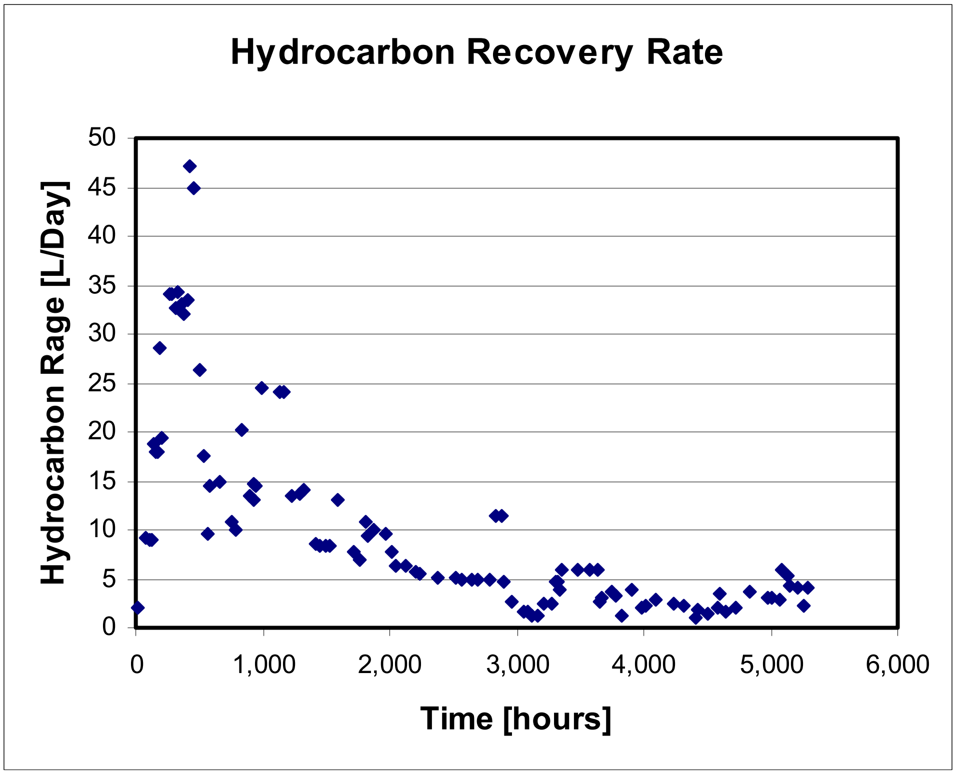

FIGURE 10. This figure shows the rate of hydrocarbon recovery from the soil during electrical heating operations.

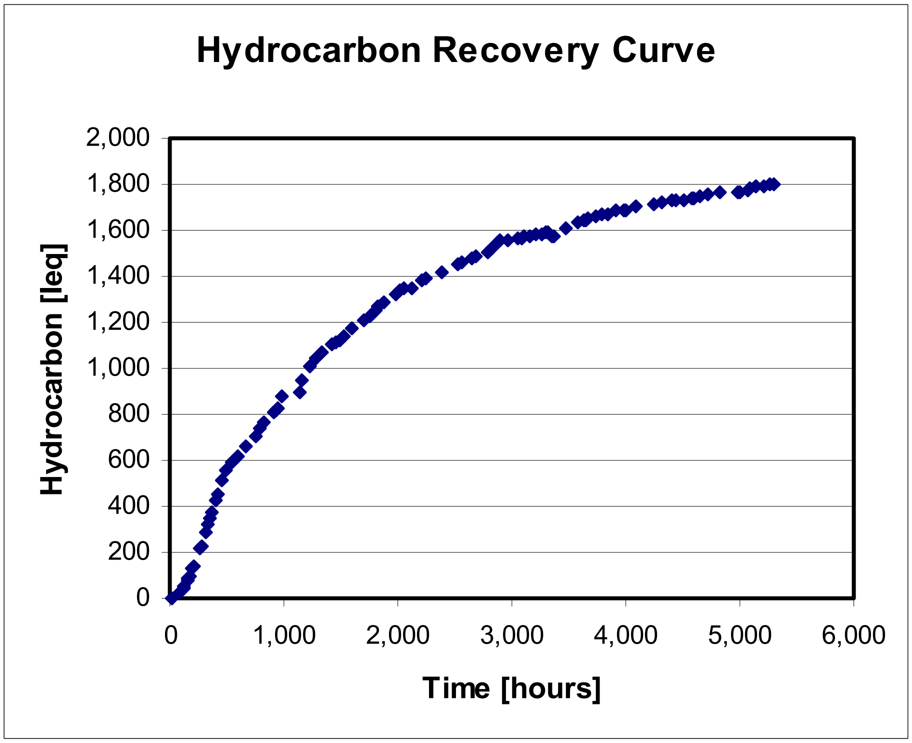

FIGURE 11. This figure shows the hydrocarbon recovery from the soil during electrical heating operations.

Analytical Results. Initial benzene concentrations were in excess of 7.5 ppm from about 1.5 to 5.5 meters below ground surface. Several confirmatory soil samples were submitted to Philip Analytical Laboratories in Calgary for testing. **All soil samples were at or below the laboratory detection limits (0.02 ppm).**

CONCLUSIONS

The following conclusions from the project are made:

1. **ET-DSP^{TM}** combined with high vacuum dual phase extraction technology was successful in the remediation of soils beneath and in the region of an occupied apartment complex, achieving clean results to non-detect.

2. It was possible to safely conduct remediation operations unobtrusively to the day to day living of the residents within the apartment complex and general area.

3. The design of the extraction system was ideal in that it was able to extract hydrocarbons from the soil at a rate at least equal to the rate of volatilization in the soil as a result of **ET-DSP^{TM}**.

4. Based on the hydrocarbon recovery data, it may be possible that **ET-DSP^{TM}** operations could have been terminated earlier with similar successful results.

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