ELECTRICAL HEATING FOR THE REMOVAL OF RECALCITRANT ORGANIC COMPOUNDS

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ABSTRACT: This paper presents a remediation technology that combines electrical heating of the soil with extraction to achieve removal of vapour pressure sensitive compounds, such as chlorinated solvents, volatile and semi-volatile organic compounds, and heavier hydrocarbons. This technology is commercially known as the *Electro-Thermal Dynamic Stripping Process* (**ET-DSP**). As well the results of a Shell operated field test (the **CFB Pilot**) are presented to demonstrate the feasibility and effectiveness of the technology in a commercial environment.

Electrical heating technology has been used in the past (Buettner and Daily, 1995, U.S. DOE, 1995, McGee et. al., 1994). In a typical application of the **ET-DSP** 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. Additionally numerical modeling was used to design the power delivery system, the power requirements from the utility, and the project capital requirements.

Several sites have been remediated using this technology. At all locations removal of contaminates was achieved, typically in less than four months of heating. This is a direct result of a substantial temperature increase in the contaminated soil and concurrent increase in the vapour pressure. The increase in vapour pressure of the contaminants makes it easier to extract them from the soil. Although the data from site to site vary, the typical cost for three phase electrical power is a minor component of the overall cleanup costs for the project. Greater cost reductions are further realized as a result of the significant decrease in time required to complete the remediation for a recalcitrant site.

INTRODUCTION

Objective. The objective of this paper is to:

1. describe a method for the in-situ recovery of recalcitrant compounds that combines electrical heating technology with soil vapour extraction (the technology is referred to as *Electro-Thermal Dynamic Stripping Process*).
2. present the results of this technology for the remediation of a soil contaminated with volatile organic compounds that leaked from an underground storage tank, referred to as the **CFB Pilot.**
3. present the measured thermal response and energy requirements and some numerical simulation calculations, and
4. summarize the economic performance of the technology.

Introduction to the Technology. 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 recalcitrant 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) and electrical heating (DOE, 1995, McGee et. al., 1995).

Most underground storage sites that have leaked are contaminated with non-chlorinated solvents like benzene and acetone, and volatile organic compounds like gasoline. The conventional remediation technology is *soil vapour extraction* for remediation of the soil between the surface of the land and the aquifer water table and *pump-and-treat* for contaminated zones within the ground-water system. These processes are limited by retardation of the contaminants in-situ, especially in fine sediments and clays. Therefore, primary technologies must be operated for long periods of time and may not achieve cleanup standards in low-permeability soils or where the vapour pressure of the contaminant is low.

Electrical heating increases the temperature of the soil by conducting current through the resistive connate water that fills the porosity of the soil. Maximum temperatures are limited to the boiling temperature of the connate water otherwise the electrical path is boiled off. 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 **ET-DSP** process are indicated on the plot. The average pressure in the soil is reduced to one third of an atmosphere 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 exists in the gas phase. *The average temperature only has to exceed 50 ºC for benzene to occur in the gas phase during soil vapour extraction operations*. Once the contaminant is in the gas phase, it is easily removed from the soil at the vapour extraction wells.

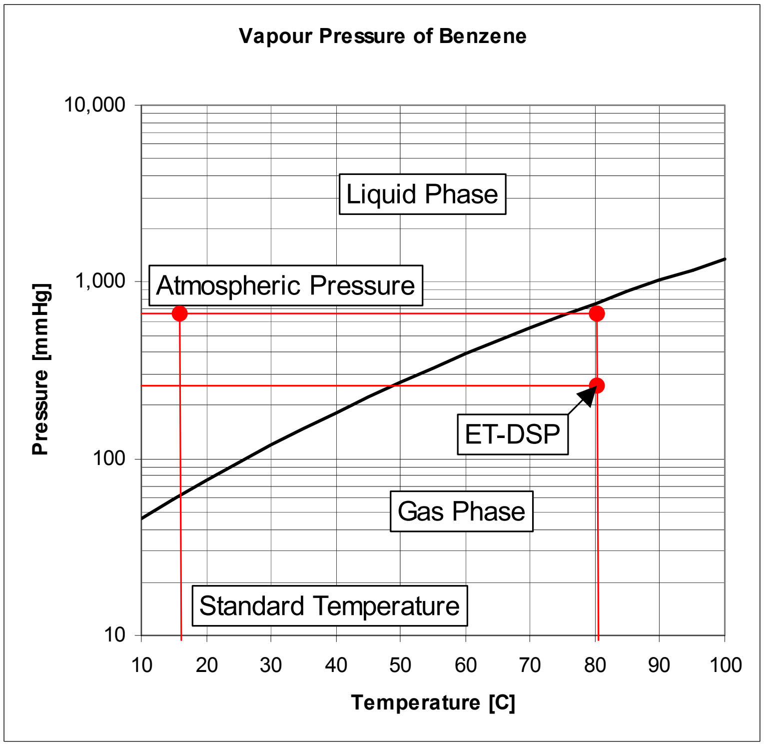

FIGURE 1. Vapour pressure plot of benzene (Hirata et. al., 1975)

The heating will 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. The increase in temperature will also expand the applicability of vapor extraction to less volatile contaminants, and allow cost-effective remediation of lower permeability and more heterogeneous soils.

DISCUSSION OF PILOT, METHODS, AND MATERIALS

CFB Pilot Site Description. The pilot test was conducted on the Canadian Forces Base located in Calgary, Alberta, Canada. It has been referred in this paper as the **CFB Pilot**. The pilot test was performed on a portion of a vacant property which was the location of a former service station. The subsurface soil and groundwater beneath the site was heavily impacted with gasoline and the primary compound of concern was benzene. The area of the pilot study encompassed approximately 165 m^2 and targeted 700 m^3 of soil of which approximately 250 m^3 were contaminated with gasoline. Benzene was highly adsorbed to an organic layer (>5% total organic carbon) approximately 1.5 meters thick, 3.5 meters below grade. The depth to groundwater was measured within the organic layer at approximately 3.5 meters below grade.

Site Specific Conditions. This site was selected to conduct the pilot test based on the following site characteristics:

1. The site was located within an open field, clear of any subsurface utilities or substructures.
2. There was no automobile or pedestrian traffic making the site easy to fence off from the public.
3. The subsurface lithology and the characteristics of the hydrocarbon-affected soils were understood, as numerous subsurface investigations had been completed at the site.
4. Other proven in-situ remediation techniques were attempted in this area of the plume and were only moderately successful.
5. The hydrocarbon contamination present beneath the site is primarily benzene. Benzene is a volatile compound whose vapor pressure increases substantially with increase temperatures.
6. The maximum benzene concentrations measured in the subsurface soil beneath the site are located within a shallow (three meters below grade) organic layer (formerly a slough bottom).
7. The relatively high total organic content (5% or greater) of the organic soil layer makes it very difficult to desorb the benzene from the subsurface soil using conventional in-situ techniques at standard temperatures.
8. Based on our evaluations and pilot testing, other in-situ remediation technologies were considered to be ineffective due to long time frames required to remediate.

CFB Pilot Electrical Characterization. In addition to characterization of the site for concentration levels of contaminant, electrical conductivity of the soil and its distribution also had to be 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 to heat the soil, determination of the power requirements, and numerical simulation of the heating process.

Based on the initial site characterization, the **ET-DSP** process was simulated for the CFB Calgary site. The simulation results are used for the design of the overall system. Based on the simulation results, the following is an optimum design for the **CFB Pilot**.

1. The distance between electrodes in a row is seven meters,
2. The distance between rows of electrodes is nine meters,
3. The minimum heating duration is 90 days,
4. Maximum operating current was estimated at 100 amps per phase, and
5. Maximum operating voltage was estimated at 280 volts phase to neutral.

ET-DSP Process. The typical pattern of electrode and vapour extraction wells and system for the **ET-DSP** is shown in Figure 2. This is the same layout that was used at the **CFB Pilot**.

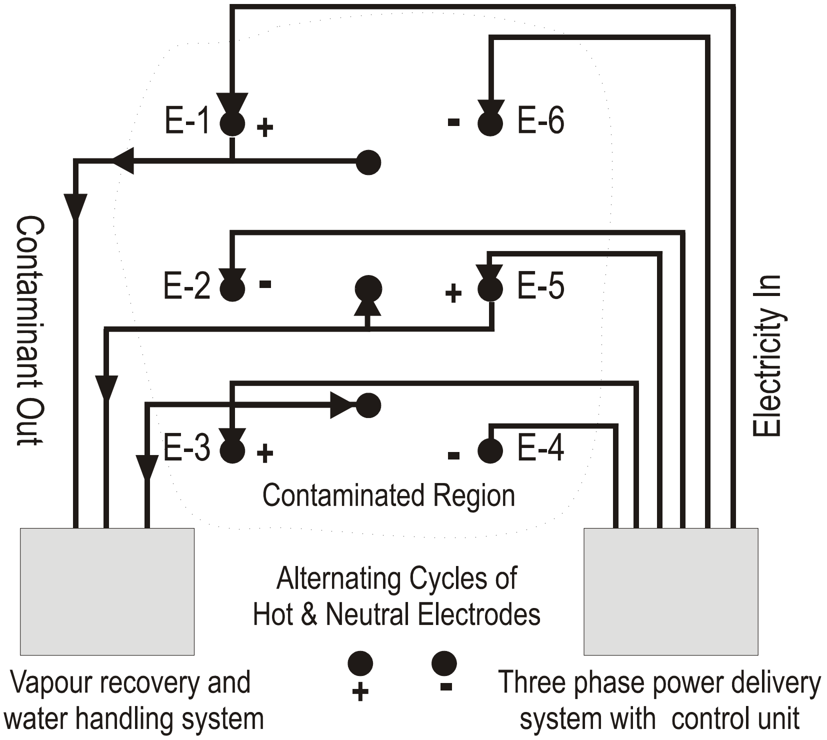

FIGURE 2. Typical layout of electrode and vapour extraction wells for the Electro-Thermal Dynamic Stripping Process.

The electrodes are arranged so that the contaminated volume of soil is contained inside the periphery of the electrodes. The vapour extraction wells are located within the contaminated soil. The position of the extraction wells relative to the electrodes is determined so that heat transfer by convection within the porous soil is maximized, thus minimizing heat losses and increasing the uniformity of the temperature distribution in the soil.

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.

The six electrodes are connected to a three phase power delivery system. The power delivery system is equipped with computer controls so that the power from the three phases can be alternated between the six electrodes. Depending on the rate of heating, the electrodes are interchanged from hot and neutral every five to ten days. Figure 3 shows the calculated temperature contours at the end of the electrical heating phase. The contours were determined using a three dimensional, multi-phase numerical simulation program. As will be discussed, these calculations are in good agreement with measured data.

Note the higher temperatures around three of the electrodes. This is consistent with these electrodes connected to the power lines of the power conditioning unit, and the other electrodes connected to the neutral.

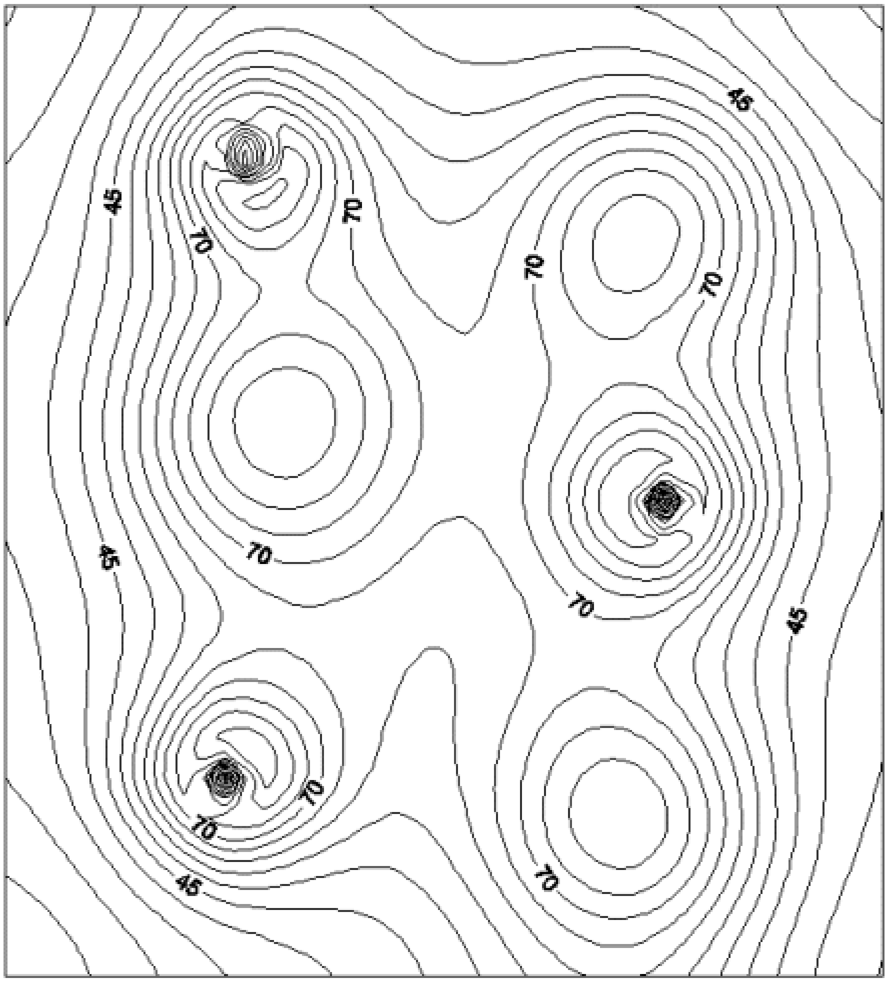

FIGURE 3. Numerical calculation of the temperature distribution in the contaminated soil after 110 days of continuous electrical heating. The contour interval is 5 ºC and the average temperature in the soil is about 60 ºC.

ET-DSP Monitoring Equipment Installation. In order to monitor the change in temperature of the subsurface soil and groundwater beneath the site, 21 multi-level thermocouples were installed within the pilot testing area. Each thermocouple was installed to approximately 3.5 meters below grade and was completed with three thermocouple wires to measure temperature changes at 1.5 meters, 2.5 meters and 3.5 meters below grade. Subsurface soil temperatures were measured daily during the full duration (116 days) of the pilot test.

DISCUSSION OF RESULTS

Electrical Heating and Temperature Results. Substantial temperature increases were measured within the electrode array during electrical heating. The average initial in-situ temperatures was 6 ºC and increased to an average of 30 ºC after 58 days, to 45 ºC after 92 days and to greater than 55 ºC after 116 days. The volume of soil within a two meter radius of the electrodes heated to an average temperature of approximately 70 ºC within 90 days of heating.

The temperatures of the soil within the electrode array after the system was deactivated decreased at a rate of approximately 0.25 ºC per day. At this rate, the in ground temperatures would not return to their original temperatures for a period of approximately 160 days (> 5 months). It is noted that the temperature patterns measured during the pilot test tracked very well with those predicted by the numerical model.

Power Consumption Results. The electrical equipment operated for a total of 108 days of the 116 days the equipment was on site. The operating uptime percentage is thus 93%. Down time was an associated cold weather factor, for example plugging of the cooling system due to freezing during cold ambient conditions. Over the period of the pilot test, the electrical equipment consumed a total of approximately 160,000 kWh of electrical energy. The monthly electrical bill was approximately $US 1,500. This includes the electrical costs for operating the soil vapour extraction equipment as well as the water pumps. The electrical heating power consumption was approximately 80% of the total.

Petroleum Hydrocarbon Removal. The subsurface soil temperatures increased to where the benzene vapour pressure was elevated by a factor of six. The multi-phase extraction equipment removed a total of 200 liters of petroleum hydrocarbon from the subsurface during 132 days of extraction, for an average extraction rate of 1.5 liter/day. It is estimated that as much as 270 liters of petroleum hydrocarbons were remaining in the subsurface prior to activating the **ET-DSP** system. Therefore, over a period of 132 days, the system successfully extracted approximately **75%** of the total mass of hydrocarbons. In regions where the temperature of the soil was greater than 70 ºC, the extracted mass of hydrocarbon removal was greater than 90%.

It should be noted that in the final 36 days, a larger extraction system was installed and removed hydrocarbons at a rate of 3.3 liters/day for a 43% (58% of the total removed) reduction in the total mass of hydrocarbons. The larger system could effectively lower the groundwater table within the electrode array to a level beneath the zone of affected soil. With the groundwater table lowered, air was able to pass through the previously saturated zone removing the hydrocarbons more rapidly from the soil. The soil remained saturated during the operation of the smaller system, thereby relying on the removal of dissolved-phase hydrocarbons in the groundwater and diffusion for removal which is a slower process.

Based on this data, if the extraction system had remained operating for a longer period of time (estimated to be approximately 30 to 50 days), a reduction of hydrocarbon mass of greater than 95 % may have been achieved. It should be noted that the extraction system was removed from the site due to time constraints established by the property owner and not by the client.

After electrical heating the soil remained hot for a long period of time. The rate of temperature decrease at the CFB Pilot was 0.25 ºC/day. During this time bio-remediation activity increases (Newmark, et. al.) and natural attenuation of the soil is accelerated.

Economics. The monthly electrical bill was approximately $US 1,500, and was a minor factor in the overall costs. If the data acquisition costs are removed from the capital costs of the project, the capital and operating costs combine to give an overall cost of remediation of approximately $US 50 per m^3.

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