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ABSTRACT

INTRODUCTION

The objective of PNL's efforts in electrically based methods for environmental restoration is to provide new and cost-effective means for removing hazardous organic contaminants from soils, and to detoxify those contaminants after they are removed. Recent work has concentrated on two areas: electrical soil heating to remove volatile and semivolatile compounds from soils, and in situ oxidation via a form of low-temperature plasma to decompose nonvolatile and bound contaminants.[1] Although both techniques are expected to require similar equipment and operating procedures, this paper covers only the electrical soil heating component, and describes recent efforts to model the heating process to enable equipment and energy requirements to be specified. An initial field test of the heating process suggests that the model presented in this paper is correct, within the range of uncertainty in the spatial variations of soil properties. Because of page limitations, a description of this test and discussion of the test results will be relegated to a subsequent publication.

The purpose of soil heating is to raise the bulk temperature of a soil to assist in the removal of organic contaminants by conventional soil-vapor extraction (SVE). Heating a soil can be beneficial when the contaminant of interest is not volatile enough to enable its timely removal by venting with air. Heating effectively increases the vapor pressure of the contaminant, which increases its rate of removal. Soil heating adds additional benefits when soil temperatures are raised to the boiling point of the indigenous soil moisture. Boiling moisture creates an in situ source of steam that can strip less volatile organics from soils--organic compounds that otherwise would not be removed by venting alone. Removal of soil moisture (as steam) also tends to increase the flow permeability of soils, which can further increase the rate of contaminant removal by simultaneous SVE. Compared to other methods such as steam or hot-air injection, applied electrical fields have the advantage of heating soils internally, where the soil itself acts as the heat source. Consequently, electrical field heating is not adversely affected by low flow permeability. This characteristic suggests that electrical heating, combined with SVE, may provide a way to decontaminate low-permeability soils like silts and clays.

SIX-PHASE ELECTRICAL SOIL HEATING

The soil heating method being developed at PNL relies mainly on electrical conduction through indigenous soil moisture to heat soils in the vadose zone. (It was also discovered that as the soil dries, an ionized plasma could be produced in the soil near the electrodes at relatively low voltages, and that the plasma is sufficiently conductive to enable electrical currents to pass through soil that is otherwise dry and nonconductive.) After considering a variety of possible electrical techniques, it was decided that a six-phase electrical system would be the most likely to provide uniform soil decontamination with a minimum number of installed electrodes. This technique uses six single-phase power transformers to divide conventional three-phase electricity into six separate electrical phases. Single-phase transformers can be used for the total voltage and power required. Each of the six electrical phases is delivered to one of six metal electrodes installed in a hexagonal pattern. Figure 1 illustrates the shape of the electrode array. Because each electrode is at a separate ac phase, each electrode conducts to every other electrode simultaneously. The phases are

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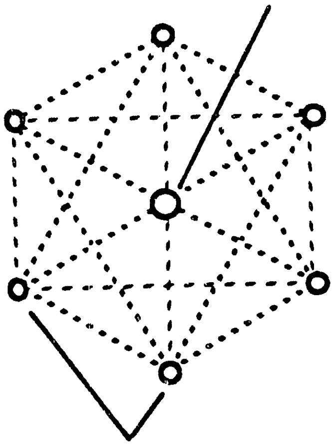

Figure 1 - Shape of Electrode Array With Primary Current Paths Indicated by Dashed Lines.

connected so that adjacent electrodes, which are spaced 60° apart in the hexagonal pattern, are also 60° out of phase. This equal physical rotation and electrical phase angle separation results in a constant ratio of voltage difference to spacing distance between all electrodes. Also, the interaction between the electrical phases produces relatively uniform heating throughout the bulk of the soil within the array.

To accomplish soil vapor extraction, a seventh, electrically neutral electrode would be place at the center of the hexagonal array and connected directly to an SVE blower. The peripheral electrodes would then serve as passive air inlets. All of the seven required electrodes could be made of conventional metal well casing, installed to the depth of the contaminant using conventional well-drilling techniques. Nonconductive PVC well sections could be used to extend the electrodes through any uncontaminated portions of the vadose zone to allow only the depths requiring decontamination to be heated.

An indoor test facility was developed and used to investigate the feasibility of the six-phase soil-heating (SPSH) technique combined with soil venting.[1] Tests in a plastic vessel containing 1.5 yd^3 of sandy soil demonstrated the feasibility of uniform heating (to 100 °C ± 2 °C, except near the floor of the test vessel), and drying from an initial 21-wt% moisture to a bulk soil moisture content of 1.2 wt%. Although these tests were performed without contaminants, previous data demonstrated the feasibility of heating and in situ steam production for removing volatile and semivolatile compounds from three types of soil (a sand, a silt, and a clay) as well as 25 wt% or more of a nonvolatile tracer compound.[2]

POWER SYSTEM REQUIREMENTS FOR FIELD APPLICATIONS

To remove organic contaminants from soils by electrical heating would require the installation of one or more electrode arrays wide enough and deep enough to encompass the contaminated volume. A power system would then need to be designed to provide sufficient voltage to each electrode array to enable a predetermined amount of power to be delivered to the soil. The amount of power required depends on many factors, but will generally be in the range of 300 to 1000 W/m^3 of soil heated, enabling decontamination to occur within a two-week to two-month period. To calculate the voltage needed to achieve the required total power requires a knowledge of the resistance of the soil load. For a six-phase system,

$$P = \frac{12V^2}{R_\varnothing}$$

where

P = power, watts
V = line-to-neutral voltage, volts rms
$R_\varnothing$ = phase resistance, ohms

The phase resistance is defined as:

$$R_\varnothing = \frac{2V}{i}$$

where i is the rms current flowing through each electrode in amperes.

ANALYTICAL EXPRESSION FOR PHASE RESISTANCE

An analytical model was developed to calculate $R_\varnothing$ for any electrode-array geometry, and for any heated medium of known electrical resistivity. This was based on a current-source superposition principle valid at low frequencies.

In this model, the phase resistance can be represented by the resistance across the diagonal of the array (with a minor refinement discussed below). This resistance is modelled as that of two parallel current paths, one representing the horizontal path between electrodes, the other representing the fringing path below the tips of the electrodes. The follo^^ng analytical expressions are used to describe these resistances:

$$R_{cylinder} = \left(\frac{\rho}{\pi L}\right) \ln \left\{ \frac{D}{d} + \sqrt{\left(\frac{D}{d}\right)^2 - 1} \right\}$$

$$R_{fringe} = \left(\frac{2\rho}{\pi d}\right) \left\{ 1 - \left[\frac{2D}{d} - 1\right]^{-1} \right\}$$

where:

ρ = resistivity. Ω-m
L = electrode submergence, m
D = electrode array diameter, m
d = electrode diameter, m

The first expression the Stanek expression for the path between two electrodes in a homogenous slab. The second expression accounts for the fringing effects at the bottom of the electrode array (as illustrated in Figure 2). Since these cylindrical and

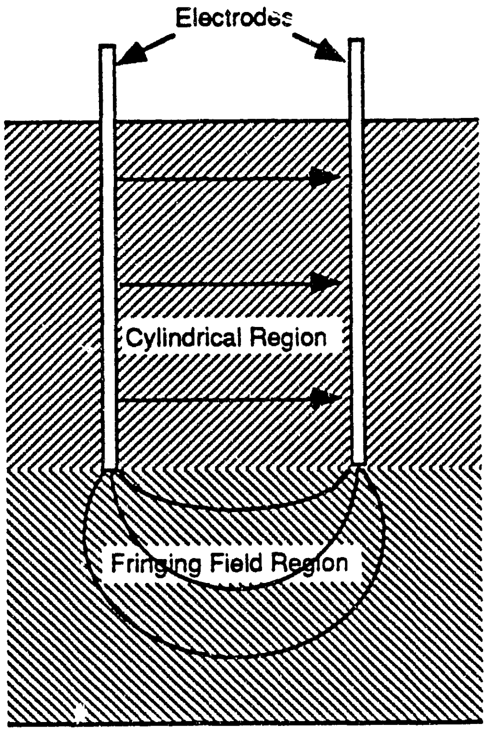

Figure 2 - Electric Field Regions Produced by Electrodes.

fringing fields occur in parallel, the final design equation for predicting phase resistance is:

$$R_{\varnothing} = \left[\frac{R_{cylinder} \, R_{fringe}}{R_{cylinder} + R_{fringe}}\right] (\Delta + 1)$$

where Δ represents the coupling effects between the six electrodes and is influenced by the presence of any finite walls surrounding the heated domain (as in the experiments described next.)

ELECTRIC FIELD EXPERIMENTS

Experiments were conducted to measure actual values of phase resistance for electrode arrays placed in a resistive medium of known conductivity. Figure 3 is a photograph of the test apparatus, which consisted of a six-electrode array lowered into a plastic tank containing 300 gal of water, with common table salt used to adjust the resistivity of the water.

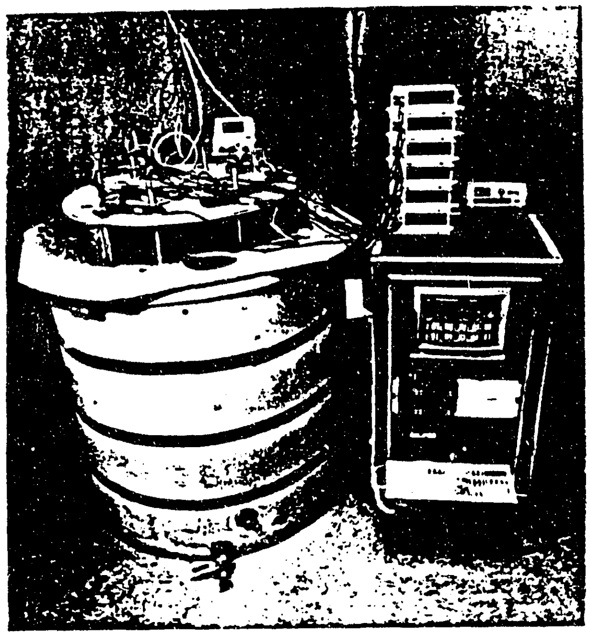

Figure 3 - Test Apparatus.

The test electrodes were constructed of stainless steel tube, although copper tube was used for one set of experiments. The electrodes were held in place by plywood sheets (placed on top of the water tank) with predrilled holes to allow the electrodes to be inserted at three different array diameters. The parameters tested included: array diameter (1, 2 and 3 ft.); electrode diameter (0.25 and 1.0 in.); electrode submergence (0 to 36 in.); electrode current (0.1 to 10 A); electrode current flux (0.001 to 1.4 A/in^2); and water resistivity (6.3 Ω-m through 1800 Ω-m.) The electrodes were connected to a six-phase power system. Applied voltage was variable between 0 and 120 Vrms using a bank of six variacs on the secondary sides of six single-phase transformers. During the experiments, the resistivity and temperature of the water were monitored, and after each test the water was stirred thoroughly to minimize temperature gradients. For each set of parameters, voltage was applied to the array, and the voltage and current associated with each electrode was measured using true-rms multimeters. These measurements were used to calculate the average phase resistance.

ANALYSIS OF EXPERIMENTAL DATA

An analysis of the experimental data was performed using the analytic expression. TEMPEST (a code developed at PNL which uses a rigorous current source superposition principle to model polyphase ac systems) was used to calculate values of Δ, which were found to range from 0.09 to 0.19 for the experimental values of L, d and D. The values of phase resistance were then predicted and compared with the measured values. Figure 4 shows an excellent agreement between predicted and observed values of phase resistance. (In this figure a linear relationship with slope 1 between the experimental and predicted resistance would indicate a perfect fit.)

An average value of Δ on the order of 0.15 was found to adequate for most applications. It was also found that under many typical field scenarios, the effect of the fringing field becomes relatively small, and may be neglected.

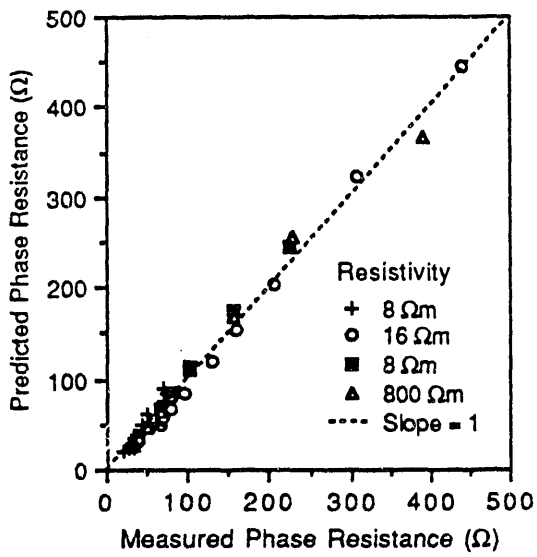

Figure 4 - Comparison of Measured and Predicted Phase Resistance.

A graphical representation of the final analytical model is shown in Figure 5, which illustrates the scaling relationships between the electrode-array geometry, the electrical conductivity of the soil and phase resistance. These relationships enable power equipment to be specified for a given array geometry and soil conductivity. Conversely, given existing equipment specifications and soil properties, a range of suitable electrode lengths, diameters and spacings can be determined.

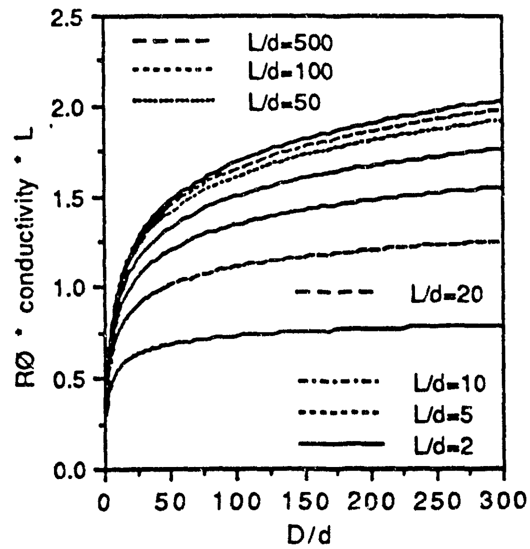

Figure 5 - Scaling Relationships for SPSH.

The next challenge was to determine how soil resistivity changed during the heating and drying process and to develop an integrated method to predict the overall change in phase resistance and heating patterns.

NUMERICAL MODEL OF DYNAMIC SOIL-HEATING PROCESS

To specify an SPSH system, changes in soil resistivity due to heating and drying must be predicted to determine resulting effects on voltage and amperage requirements. To do this, the analytical expressions describing soil heating were mapped into TOUGH2. TOUGH2 is a three-dimensional, finite-difference code that simulates the coupled transport of water, vapor, air and heat in porous media, including soil systems with complex stratigraphy, and at all locations above and below the vadose zone and water table. This code is also able to model vapor and liquid injection or extraction, enabling SVE systems to be evaluated.

More rapid heating and changes in soil resistivity occur in the regions near the electrodes. This is due to greater current densities in these regions versus the bulk soil. Therefore this region must be modelled fairly accurately to properly predict the overall phase resistance.

To do this, the heated domain is divided into two regions, one representing heating near a single electrode and a second representing heating throughout the rest of the domain, as shown in Figure 6. For the electrode-centered region, analytical expressions were developed to calculate saturation- and temperature-dependent variations in electrical conductivity as a function of radius and soil moisture content. (A discussion of these expressions is beyond the scope of this paper.) The resulting model allows relatively fine numerical noding of the soil region within inches of the electrode, allowing a more accurate depiction of the heating and drying phenomena in that region. For the rest of the heated domain, including the soil outside of the electrical array, a separate array-centered model was used based on the analytical expression for $R_{cylinder}$ using the diameter of the electrode-centered region as the electrode diameter.

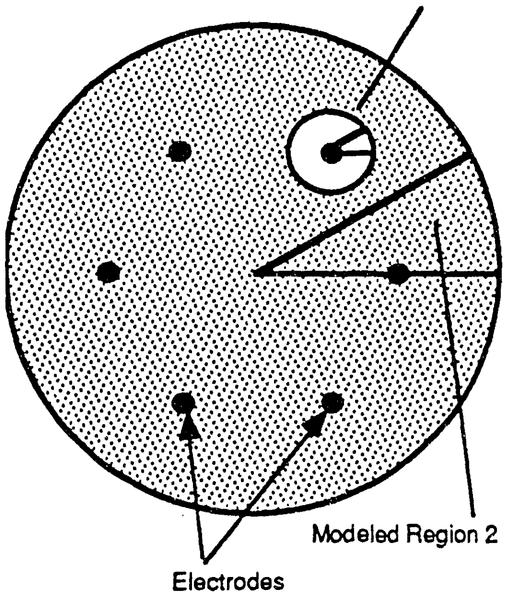

Figure 6 - Modelling Regions in Heated Domain.

To compute the overall heating patterns, models for the two regions were mapped to a single coordinate system. In this coordinate system, the total resistance between opposing electrodes is modelled as three resistances in series: a resistance associated with one electrode-centered region, the semi-infinite domain resistance ($R_{cylinder}$), and another resistance for an opposing electrode-centered region. The two domain model is duplicated on multiple layers of the modeled region. The layers enable heat and mass transfer to the soil below and to the air above the heated region, and allows vertical variations in soil moisture content and soil type. The resulting model enables heating, temperature, soil moisture, resistivity, and pressure distributions to be calculated as a function of time for any applied voltage or total power, and any array geometry provided soil properties are known.

PREDICTED PERFORMANCE OF SIX-PHASE SOIL HEATING

Example calculations using the TOUGH2 model are shown in Figures 7 and 8, for six-phase heating in a dry, Hanford sandy soil with an initial 10-wt% moisture content. These calculations assume a 20-ft-dia. array with 8-in. pipe electrodes installed to a depth of 10 ft. (This configuration was used for field tests which will be described in a subsequent publication.)

Figures 7 and 8 show histories of power and soil temperature at the center of the array for different operating conditions, all using an applied line-to-neutral voltage of 800 Vrms. In one case, soil around the electrodes is allowed to dry out due to high current fluxes at the electrode surfaces. This dry-out causes a premature increase in the overall resistance of the soil load, causing a reduction in power at a constant applied voltage. From plot (a) in Figure 7, the power decrease is predicted to occur rapidly during the ninth day of operation. Plot (a) in Figure 8 shows that this loss of power would occur well before the center of the electrode array reaches 60°C.

Plots (b) and (c) depict two other cases; one in which 2.5 gal/hr of water is added to the soil near each electrode to prevent premature dry-out, and one where the electrode diameter is increased to about 20 inches. (Such an increase in diameter could be accomplished by either adding an electrically conductive backfill around the electrode or by using a large diameter pipe.) Both techniques appear to be effective in delaying or preventing the premature dry-out phenomenon in that the center of the array approaches 100°C before the power decreases. These calculations suggest that even with a conductive backfill, the addition of water may still be required, although possibly at a greatly reduced rate. In practice, it would be expected that, by monitoring soil temperatures near the electrodes, the addition of water could be controlled so that all or most of the water added would be converted to steam and collected by SVE. Calculations using the model presented in this paper could also be used to estimate the water

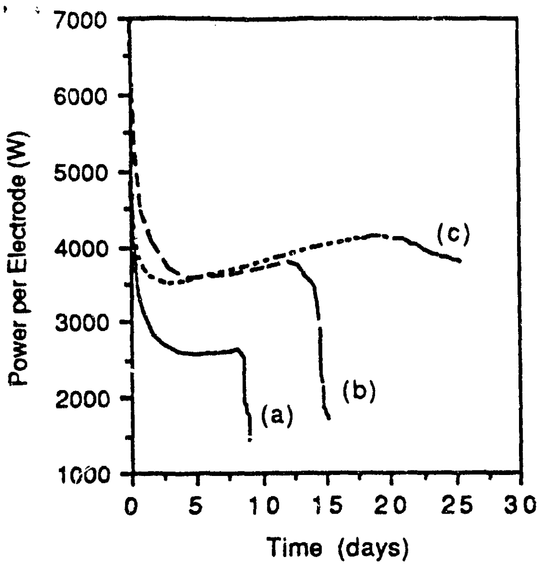

Figure 7 - Predicted Power Histories for SPSH.

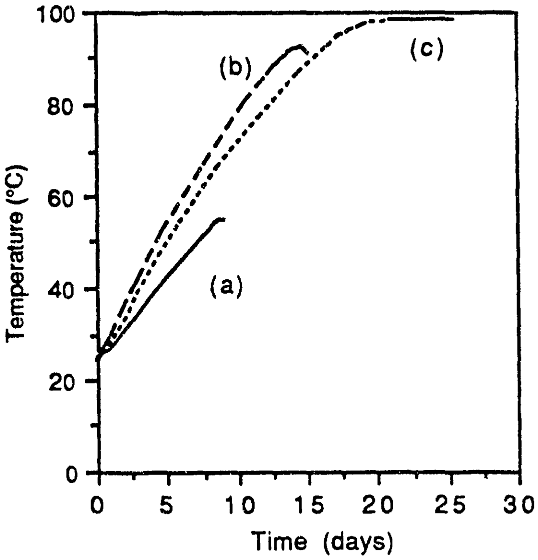

Figure 8 - Predicted Temperature Histories.

flow rate required to just prevent the dry-out phenomenon.

ENGINEERING SCALEUP RELATIONSHIPS

The ability of the models presented in this paper to accurately describe soil heating and venting processes will depend on the ability to characterize contaminated sites. Even with recent advances in characterization technology, the spatially variable properties of soil and contamination will remain difficult to determine:

- Areas needing treatment will rarely have homogeneous or even well-characterized soil.
- The hydraulic conductivity of even a narrowly classified soil type can vary by several orders of magnitude.
- The electrical conductivity of soils is dependant on moisture content and chemical composition as well as soil structure.

However, the complete model runs on a workstation and takes approximately 30 min. to model six days of actual field time. Therefore, several parametric studies can be performed rapidly, covering the range of uncertainty. During application design, this can be used to determine what flexibility is required in the power system, or if additional characterization is needed. During operation, data can be quickly analyzed in the field to provide feedback during soil cleanup operations for process control.

REFERENCES

1. W. O. Heath, S. C. Goheen, M. C. Miller, and R. L. Richardson, Investigation of Electric Fields For Low-Temperature Treatment of Soils and Liquids, PNL-, Pacific Northwest Laboratory, Richland, Washington (1992).

2. W. O. Heath, T. B. Correy, D. E. Durham, S. C. Goheen, J. D. McCall, M. McCulloh, and B. G. Place, "In Situ Soil Heating to Destroy and Remove Organics from Soils," in Hazardous Waste Remedial Actions Program Annual Progress Report, DE90 016542, HAZWRAP Support Contractor Office, Oak Ridge (1990).

3. R. L. Richardson, Application of a Six-Phase Alternating Current Power Supply for In Situ Vitrification, PNL-7696, Pacific Northwest Laboratory, Richland, Washington (1991).

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