FIELD TEST OF SIX-PHASE SOIL HEATING AND EVALUATION OF ENGINEERING DESIGN CODE

T.M. Bergsman, J.S. Roberts, D.L. Lessor, and W.O. Heath
Pacific Northwest Laboratory*

ABSTRACT

A field test was conducted to evaluate the performance of Six-Phase Soil Heating to enhance the removal of contaminants**. The test was performed for the Department of Energy (DOE) by Pacific Northwest Laboratory (PNL) as part of the VOC Arid Integrated Demonstration, which is focused on developing technologies to enhance the remediation of volatile organic contaminants in arid soils. The purpose of the test was to determine the scale-up characteristics of the Six-Phase Soil Heating technology and to evaluate a computer process simulator developed for the technology.

The test heated a 20-ft diameter cylinder of uncontaminated soil to a 10-ft depth. Six-phase ac power was applied at a rate of 30-35 kW using a power system built from surplus electrical components. The test ran unattended, using a computer-based system to record data, alert staff of any excursions in operating conditions via telephone, and provide automatic shut-off of power depending on the type of excursion. The test data included in situ soil temperatures, voltage profiles, and moisture profiles (using a neutron-probe technique). After 50 days of heating, soil in the center of the array at the 6-ft depth reached 80°C. Soil temperatures between the two electrodes at this depth reached approximately 75°C.

Data from this test were compared with those predicted by a computer process simulator. The computer process simulator is a modified version of the TOUGH2 code, a thermal, porous media code that can be used to determine the movement of air and moisture in soils. The code was modified to include electrical resistive heating and configured such that an application could be run quickly on a workstation (approximately 5 min for 1 day of field operation). Temperature and soil resistance data predicted from the process simulations matched actual data fairly closely. A series of parametric studies was performed to assess the affect of simulation assumptions on predicted parameters.

INTRODUCTION

As part of an effort to develop an in situ oxidation method to decompose organic contaminants in soils, PNL has been investigating the use of six-phase electricity to heat and dry soils. (1) Soil heating can be used to enhance the removal of volatile and semi-volatile organic contaminants by conventional soil-vapor extraction (SVE). SVE is a process that has been used successfully to remove volatile organic compounds like gasoline from sandy soils. Air is forced through the soil, the volatile contaminant diffuses into the air, and the contaminated air is removed and collected to recover or dispose of the contaminant. Successful venting requires that the contaminant be relatively volatile, that the soil be permeable to the flow of air, and that the contaminant are above the water table. In some cases the water table can be adjusted by local pumping. The main advantages of soil-venting are that it is inexpensive and fairly rapid, and avoids exhumation.

A promising way to extend the effectiveness of soil venting methods to less volatile compounds, to less permeable soils and, potentially, to lower contaminant depths near or at the water table, is to heat the soil while venting. Heating effectively increases the vapor pressure of the contaminant, which increases its rate of removal. This decreases the time required to remediate a site and enables the treatment of a site not normally treatable by conventional SVE (such as one containing semi-volatiles). Compared to other heating 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 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.

Thus far, a technique has been developed for accomplishing relatively uniform soil heating. (2) This technique uses a bank of conventional transformers to convert standard three-phase electricity into six-phase electricity. Six metal pipes are inserted as a hexagonal array into the soil and supplied each with a separate electrical phase. Thus every electrode fires to every other electrode as well as to the neutral. A seventh pipe can be inserted in the center of the hexagon, connected to a vacuum blower, and used to vent the soil. Contaminated gases are removed through this central pipe and collected for recovery or treatment of the contaminant by other means.

To date, efforts have focused on understanding the electric fields associated with six-phase heating and determining its scale-up characteristics. To understand the electric fields, a series of six-phase tests were performed in which currents were passed through aqueous salt solutions. Analysis of the test data and use of the TEMPEST code led to development of simple analytical equations that describe the electrical requirements and can be used as a basis for equipment scale-up.

A series of indoor laboratory tests were performed on uncontaminated sand to test technology feasibility. Heating of the soil in these tests was very uniform and the soil was dried to a bulk moisture content of 1.2 wt% (less than typical desert sand). However, these tests were performed indoors in a

---

* Research supported by the U.S. Department of Energy. Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under contract DE-AC06-76RLO 1830.

** This work is funded by the Ofice ofTechnology Development under VOC Arid Integrated Demonstration.

confining vessel. An outdoor field test was necessary to obtain performance data in an unconfined media and to develop definitive scale-up relationships.

This report will describe the results of the field test and compare these results with those predicted by a computer process simulator. The computer process simulator is being developed to assist with experimental design, guide hardware development, and perform application design.

FIELD TEST DESCRIPTION

The field test was conducted in uncontaminated, undisturbed soil at DOE's Hanford Reservation in southeastern Washington State. Six electrodes (6 in. diameter) were placed in a hexagonal array 20-ft in diameter and 10-ft deep. The test data included in situ soil temperatures, voltage profiles, and moisture profiles (using a neutron-probe technique).

Fifteen temperature sensors were placed at several locations in the heated soil volume. These are shown in Fig. 1. Thermocouples for measuring the bulk soil temperature were located at 2-ft, 6-ft, and 10-ft depths in the center of the array, between the B + and B- electrodes, and outside the array. At these locations, the thermocouples were attached to a 3 in ABS plastic pipe that was used for taking soil moisture readings. At the tube location outside the array, a thermocouple was also located at a depth of 12-ft.

Additional temperature sensors were used to assess temperature distribution around the electrodes. To place these temperature sensors, a rod was driven into the soil (3 to 4-ft), a thermocouple placed in the resulting hole, and the hole backfilled with sand. Thermocouple leads were isolated from the surface of the soil using plastic pipe.

Sensors were also located in the soil to measure voltages at different regions within the test area. The voltage probes consisted of steel rods driven 3-ft into the soil and connected to a voltage-divider. This allowed the voltages to be read directly on the data logger.

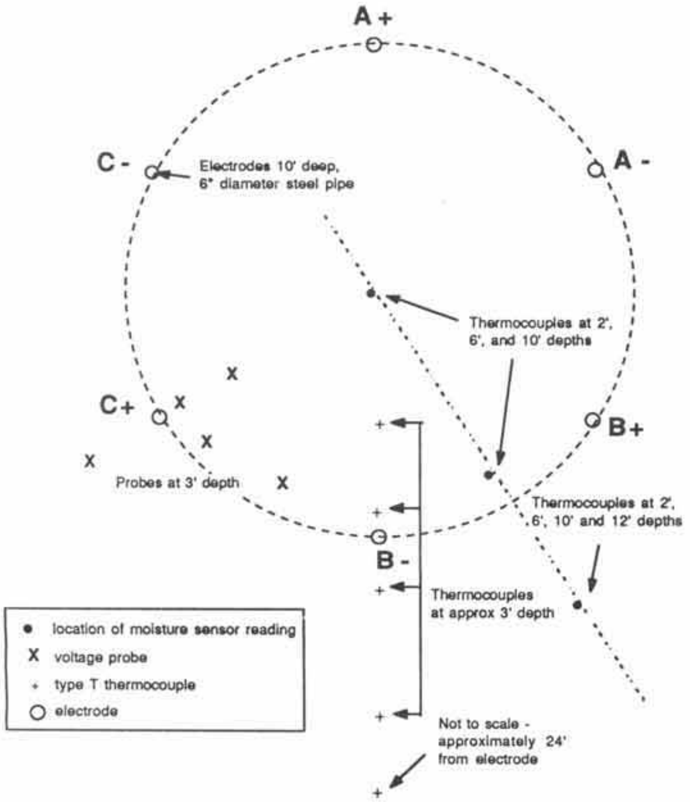

Fig. 1. Six-phase heating field test layout.

A neutron moisture sensor was used to detect changes in soil moisture during the test. Three sets of readings were taken during the test; one at the start of the test, one approximately half-way through the test, and one at the end of the test.

The power system consisted of six stacks of three variacs wired to a 480-V three-phase source. The variac wipers were connected to high voltage transformers (480/2400-V, 25 kVA) to produce six-phase power at the high-voltage terminals. The high-voltage transformers were excessed, standard utility transformers readily available at the sight. Voltages and amperages for each variac were monitored via the Fluke 45 dual-input meters.

TEST OPERATION

Before the test began, about 1000 gals of water was added to the test area between the electrodes. The water was added because of the fairly dry conditions of the soil at the time and the resulting high resistance of the soil.

Power was turned on and initially controlled to 25 kW. At the end of first week of operation, soil resistances began to increase fairly rapidly. This change is likely due to localized dryout of the soil at the electrodes. To compensate for this, a water addition system was installed. This system consisted of "drip mist" drippers (2.5 gph at each electrode), a water supply pool, and an air-operated diaphragm pump.

The system power was then increased to between 30 and 35 kW. Power levels were maintained at approximately this level for the remainder of the test. The power level was limited by the maximum operating amperage on the transformers (surplus standard utility transformers). As water was added and the array temperature increased, the system resistance decreased, increasing the system amperage requirements (see Fig. 2). Voltages were adjusted to maintain amperages below system limits. Because of the high amperages, the copper losses in the wires from the primaries to the secondaries were relatively high. To alleviate this problem, a second set of wires was installed 21 days into the test. This change is responsible for the "step change" that can be seen on the resistance curve (Fig. 2) of the system.

Soil temperatures at a 2-ft depth and a 6-ft depth in the center of the array are shown in Fig. 3. Soil temperature at the 2-ft depth initially heated relatively quickly, but the heating rate decreased later in the test. The temperature increase at

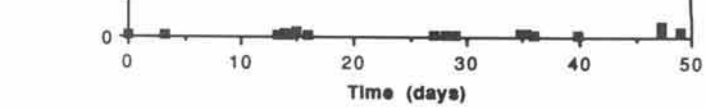

Fig. 2. Resistance for field test.

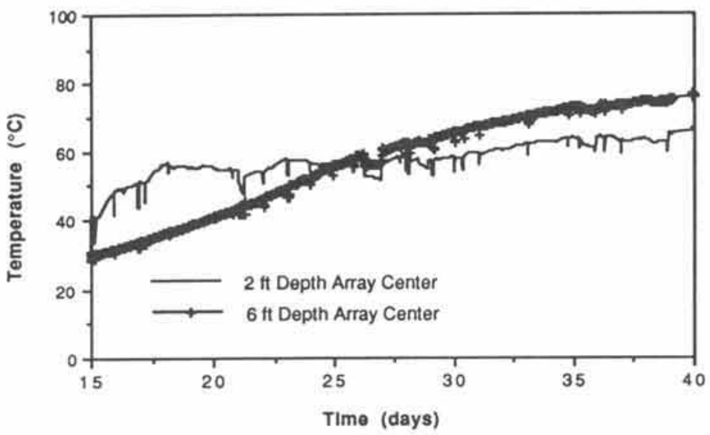

Fig. 3. Temperatures at 2 ft and 6 ft depth in center of array.

the 6-ft depth was more uniform until it leveled off at approximately 80°C late in the test. This leveling off of the temperature increase is likely due to heat losses, primarily to the surface in the case of the temperature at the 2-ft depth and to the surface and sides at the greater depth.

A plastic tarp was placed over the heated region 28 days into the test to see if heating rate could be increased. No significant change was observed. It is likely that at that point in the test heat losses from the surface were relatively small compared to heat losses from the sides and bottom of the heated area. Heat losses from the surface would tend to decrease as the surface soil dries, since evaporating soil moisture is responsible for a significant amount of this heat loss. The soil surface appeared very dry at the time the plastic tarp was added. An additional source of heat loss was steaming at the electrodes. Visible steam was quite evident at many of the electrodes approximately 15 days into the test. A proper cover design could mitigate this loss.

The total energy delivered to the system during the entire test was 34,000 kWh or 244 kWh per cu. yd heated volume. (The heated volume is assumed to be 20% greater than the array region.) This represents approximately $17 per cu. yd energy cost at a rate of $0.07 per kWh.

COMPUTER PROCESS SIMULATOR

A computer process simulator was designed to assist in technology development and application design. (2) The simulator is a modified version of the TOUGH2 code (3) (Transport Of Unsaturated Groundwater and Heat), a thermal, porous media code capable of predicting the movement of air and water in soils. A semi-analytical expression for the electric field was incorporated into this model to calculate the joule heat distribution as a function of soil water content and location. The simulator was configured to run quickly on a workstation; one day of field operations required approximately 5 min of computation time.

The model for the joule heating was developed by dividing the domain affected by joule heating into several subregions, each tailored so a local semi-analytical model would best match rigorously computed joule heating distributions. The two primary regions consist of a horizontal region along the length of the electrode and a fringing field region below the electrode. These two regions are considered to be in electrical parallel. Since moisture content and soil structure are likely to vary with depth the joule heating model for the horizontal region includes separate horizontal layers of soil. These layers are considered to be electrical parallel, each receiving the same electrical potential across it. Within each layer, the domain is divided into 3 regions; close to the electrode, inside the electrode array far from the electrode, and outside the array far from the electrode. Specific models for these subdomains are described in more detail below.

The semi-analytical joule heating model for each layer was developed by matching local analytical joule heating distributions to those calculated by a rigorous electric field solution in a computer code called TEMPEST.* TEMPEST is a computational fluid dynamics (CFD) code developed by Pacific Northwest Laboratory and is typically applied to fluid flow and heat transfer application in nonporous media. The ability to solve electric field equations for multi-phase electrical systems was recently implemented for modeling vitrification processes. This code does not have multiple fluid phase capabilities and is not specifically suited to porous media calculations.

The joule heating around the electrodes can be characterized by a simple description of joule heating occurring in soil between two concentric electrodes. The inner electrode in this concentric configuration corresponds to the actual electrode in the six-phase array. For this expression, the outer electrode of the concentric pair is assumed to extend to a radius one quarter of the distance to the next electrode.

The expression for joule heating delivered to node n, Pn, as a function of its radius and electrical conductivity is

$$P_n = \frac{P_{concentric}\left(\frac{1}{\sigma}\right)_n \ \ln\left(\frac{r_n}{r_{n-1}}\right)}{\Re} \qquad \text{(Eq. 1)}$$

where

$P_{concentric}$ = total power for the concentric electrode region

σ = electrical conductivity of node *n*

r_n = radius of outer edge of node *n*

r_{n-1} = radius of inner edge of node *n*

$$\Re = \sum_{n_{min}}^{n_{max}} \left(\frac{1}{\sigma}\right)_n \ln\frac{r_n}{r_{n-1}}$$

where

n_{max} = node closest to outer electrode

n_{min} = node closest to inner electrode.

---

* D.S. Trent and L.L. Eyler. 1993. TEMPEST - A Computer Program for Three-Dimensional. Time-Dependent Computational Fluid Dynamics: Theory Manual. Version T, Mod 3. Draft Report, Pacific Northwest Laboratory, Richland, Washington.

If the soil of a layer is homogeneous, the power delivered to the region inside the electrode array would equal that delivered outside the array. However, this is rarely the situation. The area inside the array is of much smaller area and is therefore assigned higher power per unit volume. This area heats up and dries out sooner, changing the region's electrical resistivity (resistivity is decreased during heating and increased during drying).

The power delivered to the areas inside and outside the electrode array is dependent on the electrical conductivity of these regions. A series of TEMPEST simulations were performed, varying the ratio of electrical resistivity inside and outside the electrode array. These results showed a linear relationship of slope = 1 between the ratio of conductivities (inside/outside) and the ratio of the delivered power (inside/outside).

In order to calculate the power delivered to the regions near the electrode, inside and outside the electrode array, the regions are considered as series resistances between opposite electrodes in the six-phase array. Current flows through the region surrounding one electrode, across the uniformly heated regions distant from the electrode and through the region surrounding the opposite electrode in the array. These regions have resistances which can be approximated by

$$R_{\mathrm{electrode}} = \frac{R}{2\pi L} \qquad \text{(Eq. 2)}$$

$$R_{array} = \left(\frac{1}{2L\pi\sigma_{avg}}\right) \ln\left[\frac{r_{max}}{r_{min}} + \sqrt{\frac{r_{max}}{r_{min}})^{2} -1}\right] \qquad \text{(Eq. 3)}$$

where

$R_{\mathrm{electrode}}$ = resistance across concentric electrode model

R_{array} = resistance between concentric electrode models

σ_{avg} = average electrical conductivity far from electrodes (average ofinside and outside)

r_{max} = outer radius of concentric model

r_{min} = inner radius of concentric model

L = thickness of modeled soil layer.

The resistance between electrodes of a single layer can be expressed as

$$R_{\mathrm{layer}} = 2R_{\mathrm{electrode}}\,R_{\mathrm{array}} \qquad \text{(Eq. 4)}$$

There are three electrode pairs in the typical six-phase configuration that do not act independently. Each pair induces a small current between the other two. This correction is given as

$$R_{\mathrm{actual\ layer}} = R_{\mathrm{layer}}\left(1 + \frac{R_a}{R_d}\right) \qquad \text{(Eq. 5)}$$

where

$$\frac{R_a}{R_d} = \frac{\ln 3}{2\ln\left(\frac{2r_{array}}{r_{electrode}-1}\right)}$$

r_{array} = radius of electrode array

$r_{\mathrm{electrode}}$ = radius of electrode

This actual resistance is calculated in each layer of soil along the length of the electrode. All of these layers are considered parallel paths between electrodes. Layers with higher total resistances receive less power than others.

The region below the electrodes has a resistance modeled by an analytical expression for resistance two half spheres at the edge of an infinite domain

$$R_{fringe} = \left(\frac{1}{\pi\ \sigma_{avg} r_{electrode}}\right) 1 - \frac{1}{2\left(\frac{r_{array}}{r_{electrode}} - 1\right)} \qquad \text{(Eq. 6)}$$

For the total resistance between electrodes, the resistances for the layers and fringing field are considered in parallel

$$\frac{1}{R_{\mathrm{total}}} = \frac{1}{R_{\mathrm{fringe}}} + \sum_{i+1}^{\text{number of layers}} \frac{1}{R_{\mathrm{layer\ i}}} \qquad \text{(Eq. 7)}$$

The power delivered to the entire domain can be expressed as

$$P_{\mathrm{total}} = \frac{3V^{2}}{R_{\mathrm{total}}} \qquad \text{(Eq. 8)}$$

where

V = RMS voltage between opposite electrodes.

The expression contains a factor of 3 because three-sets of electrodes are supplying power to the domain.

PREDICTIONS VERSUS ACTUAL FIELD DATA

Figures 4, 5 and 6 show actual and predicted data for the field test. Actual experimentally measured power was used as an input parameter to the simulator, since this parameter was frequently changed in the field operation. The simulator was then used to predict resulting temperatures and resistance. The simulator was run for only a segment of the test (14 to 28 days) because operations during this time period were relatively constant.

Predicted temperatures matched actual temperatures fairly closely. These predictions were found to be fairly sensitive to soil moisture content. The assumed saturations used

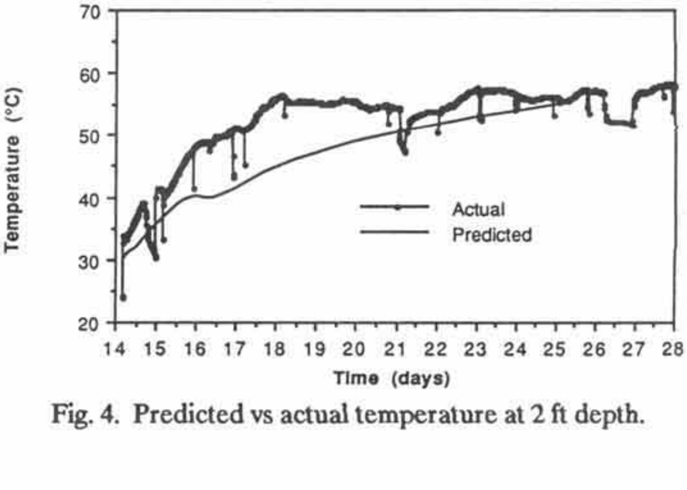

Fig. 4. Predicted vs actual temperature at 2 ft depth.

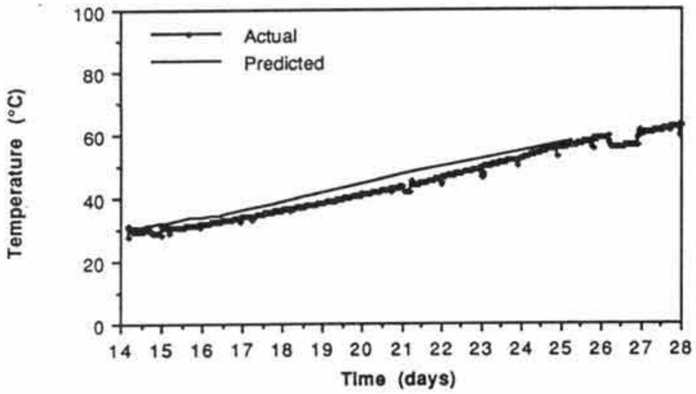

Fig. 5. Predicted vs actual temperature at 6 ft depth.

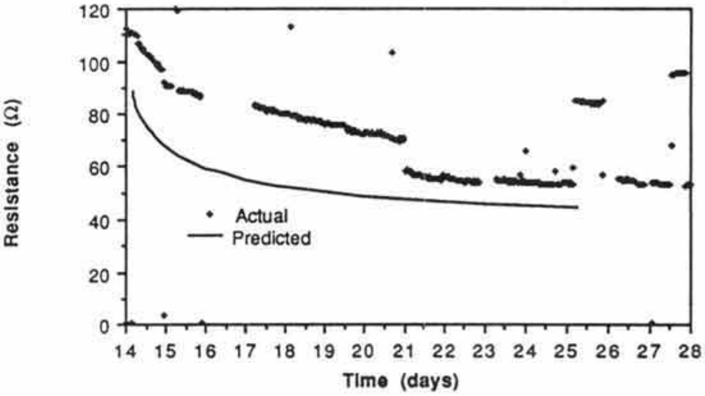

Fig. 6. Predicted vs actual resistance.

for the simulator were 0.81 saturation for the 2-ft surface layer, 0.88 saturation inside the array, and 0.74 saturation outside the array. Initially, the simulator underpredicts system resistances by a fairly significant degree. The primary reason for this is that the simulator does not include above surface resistances such as copper loss in the wiring and transformers. As an example, when the power system was rewired, the overall system resistance dropped, and the predicted and experimental data matched more closely.

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". Presented at A&WMA and EPA's International Conference "*In Situ* Treatment of Contaminated Soil and Water". Cincinnati, Ohio. February 3-6, 1992.
2. W. O. HEATH, J. S. ROBERTS, D. L. LESSOR, and T. M. BERGSMAN, "Engineering Scaleup of Electrical Soil Heating for Soil Decontamination". Presented at SPECTRUM '92. Boise, Idaho. August 23-27, 1992.
3. PRUESS, K. 1987 TOUGH User's Guide. LBL-20700, Lawrence Berkeley Laboratory, University of California, Berkeley, California.