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A. L. Ramirez
W. D. Daily

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Monitoring Radio-Frequency Heating Of Contaminated Soils Using Electrical Resistance Tomography

A. L. Ramirez, W. D. Daily
Lawrence Livermore National Laboratory
Livermore, CA

ABSTRACT

Electrical resistance tomography (ERT) was used to monitor a radio-frequency heating process used for the insitu remediation of volatile organic compounds from subsurface water and soil at the Savannah River Site, near Aiken, South Carolina. A dipole antenna located in a horizontal well in the unsaturated zone was used to heat a contaminated clay layer. The heat-induced changes were tomographically imaged by their effects on the formation electrical resistivity. The resistivity changes observed appear to be related to heating and vaporization of the pore water, formation of steam condensate, and infiltration of rainwater through the heated zones and adjacent areas. There is a clear asymmetry downward in the resistivity decreases associated with the heating process. The resistivity decreases observed in the vicinity of the heating well are believed to be caused by the heating and downward migration of warm water originally located within a radius of a few feet around the heating well; the magnitude of the change is between 10-20 %. The decreasing resistivity implies an increasing rate of radio wave attenuation as heating progressed; therefore, the rate of energy deposition around the heating well increased while the penetration distance of the radio waves decreased. Saturation changes in the clay near the antenna during heating were estimated to be 50-55% based on the observed resistivity decreases. Resistivity changes observed at distances greater than 3 meters to one side of the antenna appear to be related to rainwater infiltration. We propose that gaps in near surface clay layers allow rainwater to migrate downward and reach the top of clay rich zone penetrated by the antenna borehole. The water may then accumulate along the top of the clay.

Introduction

The remediation of soils and groundwater contaminated with organic and inorganic compounds is an important objective of many environmental restoration efforts. A wide range of technologies is available and new technologies are being developed to remedy and assess contaminated sites. Many of these remediation processes can interact with the contaminated volume in ways that are difficult to predict; therefore, it is advantageous to monitor this interaction so that the effectiveness of the remediation process can be assessed. We report herein on the use of electrical resistance tomography (ERT) to image underground processes important in many remediation efforts. This imaging technology, when used either separately or in combination with other geophysical, hydrological or geochemical techniques can be a

powerful tool in monitoring the interaction between the remediation process and the contaminated environment.

The Integrated Demonstration for VOC's in Soils and Groundwater at Non Arid Sites (VOCNAS) was undertaken by the Department of Energy (DOE) to demonstrate novel technologies for the *in situ* remedial cleanup of volatile organic compounds from saturated and unsaturated soil horizons at the Savannah River Site, South Carolina. The project used one directionally drilled horizontal well to heat the contaminated soil and extract contaminants from the subsurface. The technique used during VOCNAS to thermally enhance the removal of TCE and PCE is referred to as radio-frequency heating (RFH) or dielectric heating.

Electrical resistivity of soils is a function of moisture content, temperature, mineralogy (e.g. clay content) and water salinity (Hearst and Nelson, 1985). Heating causes moisture content, temperature, and fluid conductivity changes which all affect electrical resistivity. The successful application of ERT provides a two-dimensional view of the subsurface resistivity distribution. This information helps us to understand the interaction between the heating process and the heterogeneous subsurface, the effects of heating on fluid flow, and the interaction between heating and other processes such as rainwater infiltration. Such insight is useful to understand remedial processes as well as the contaminant movement. Groundwater flow is likely to influence contaminant mobilization and transport as well as heat transport; and geologic structure affects the flow of groundwater and vapor. Underground imaging techniques reduce the need for the many boreholes that would otherwise be required to densely monitor such underground flow.

The demonstration of RFH was performed by KAI Technologies, Inc. of Woburn, Massachusetts. The Westinghouse Savannah River Technology Center (WSRTC) in cooperation with the Westinghouse Science and Technology Center directed the heating demonstration and the related surface and subsurface monitoring. As part of the monitoring team, Lawrence Livermore National Laboratory (LLNL) was responsible for conducting ERT surveys between pairs of vertical boreholes to map the changes in electrical resistivity distribution and from these data infer changes, both spatial and temporal, in moisture content and in temperature. Based on these changes, inferences can be made regarding the influence of heating and geologic heterogeneities on fluid movement and the interaction between the heating process and natural processes such as rain water infiltration.

THE RFH used a dipole antenna 5.1 m (16.7 ft long) emplaced in a horizontal well located in the vadose zone at 12.2 (40 ft.) depth (Beleski et al, 1993). This well intersects a clay rich horizon contaminated with TCE and PCE. A portion of this well was screened within the clay rich zone to allow the removal of vaporized contamination using a vacuum extraction system. The maximum power output of the resonant dipole antenna was approximately 25 kW and the operating frequency was approximately 13.56 MHz. The heating demonstration was conducted over a period of approximately 5 weeks. A detailed description of the RFH demonstration is provided by Beleski et al, (1993).

Borehole Configuration and Data Collection:

The site is located near Aiken, South Carolina within the Department of Energy's Savannah River Site. The experimental site consisted of alternating units of sand, clay and gravel

deposited in shallow marine, lagoonal or fluvial environments. The vadose zone is approximately 41 m (135 feet) thick. Clay layers are usually thin or discontinuous. The sand units ranged from fine to coarse grained and were, in general, moderately sorted with relatively little silt and clay. The silty clay units or clayey sand units exhibited relatively low permeability. Additional site details are provided by Eddy et al., (1991).

Figure 1 shows a plan view of the site. The ERT image planes and their proximity to the horizontal heating well are also shown. Measurements were made between a series of three vertical boreholes drilled in the vicinity of the horizontal well used for heating and vacuum extraction. The ERT boreholes (P1, P2 and MHV-25T) were constructed by fixing stainless steel electrodes externally to the PVC casing; the borehole annulus was backfilled with the drill cuttings. A separate wire connected each electrode with the surface measurement system. Borehole P1 has 10 electrodes, evenly spaced between 3.1 and 16.8 m (10 and 55 ft) depth. Borehole P2 also has 10 electrodes, evenly spaced between 3.8 and 17.5 m (12.5 and 57.5 ft.) depth. Borehole MHV-25T also has 10 electrodes, evenly spaced between 4.6 and 18.3 m (15 and 60 ft) depth. Crosshole resistivity surveys were performed between P and P2, and between P2 and MHV25T.

An additional 20 electrodes were located at the ground surface. The surface electrodes were used together with electrodes within P1 to survey a vertical plane approximately parallel to the horizontal well where the antenna was located. Data from these twenty surface electrodes enhanced the image resolution near the ground surface.

During the period between March and April of 1993 we imaged the effects of the RFH and vacuum extraction from the horizontal well (AMH-5), located in the vadose zone at a depth of approximately 12.2 m (40 ft.). ERT data were collected before and during the process with the goal of producing resistivity difference images of the process. The resistivity differences were obtained by subtracting the tomographs representing the baseline case from tomographs representing the resistivities during RFH to show only the changes. The antenna's power history, rainfall data, and the dates when ERT surveys were performed are shown in Figure 2. The effects of RFH and rainwater infiltration on the formation's electrical resistivity will be the focus of our discussion.

Electrical Resistance Tomography

Electrical resistance tomography (ERT) is a technique for determining the subsurface electrical resistivity distribution through measurement of injected currents and resulting electrical potential distributions in boreholes and at the surface. The bulk resistivity is a function of moisture content and temperature. Resistivity typically decreases with increasing moisture content and increasing pore water temperature. Resistivity is also dependent on soil and water chemistry and other factors. For example, we shall see that clay rich zones are strongly conductive, and the dominant mechanism for electrical conduction is surface conduction along the double layer present on clay particles.

Cross borehole ERT is accomplished with a number of electrodes in electrical contact with the soil mass in each borehole. We apply a known D.C. (direct current, polarity switched) current to two electrodes and measure the resulting voltage differences between other pairs of electrodes. Next, we apply the current between two other electrodes and again measure the

voltage differences using electrode pairs not being used for the source current. Each ratio of measured voltage and current is a transfer resistance. We repeat this process until all the linearly independent combinations are measured. For n electrodes there are $n(n - 3)/2$ independent transfer resistances. These measurements for a cross-borehole survey are similar to those used in a conventional surface dipole-dipole resistivity survey.

Calculating the distribution of resistivity in the vicinity of the boreholes, given the measured transfer resistances, is a highly nonlinear problem because the current paths are dependent on the resistivity distribution. However, this type of inversion has been widely studied [e.g., Henderson and Webster (1978), Pelton *et al.*, (1978), Nariida and Vozzof (1984), Wexler *et al.* (1985), Brown *et al.* (1985), Isaacson (1986), Berryman and Kohn (1990)]. We will use the approach described in detail by Ramirez *et al.*, (1993).

The reconstruction plane for the P1-P2-MHV-25T tomography plane was modeled by a finite element mesh 19 elements wide (between the boreholes) and 20 elements long (along the boreholes). The mesh and the relative locations of boreholes and electrodes are shown in Figure 3. A similar mesh is used for the plane defined by P1 and the surface electrodes but having more elements horizontally and vertically to accommodate a wider, taller area. The P1-P2-MHV-25T reconstruction plane was modeled by a finite element mesh 38 elements wide (between the two surface electrodes at the ends of the surface array) and 22 elements long (along the borehole). Other elements (not shown in the figure) were used to model the resistivity external to the region between the boreholes although their values are poorly constrained by the data and therefore are not included in the image. In all reconstructions we will show in the results section, only the elements modeled between the boreholes will be displayed. After reconstruction, the tomographs are spatially smoothed to give the appearance of a continuous resistivity distribution. This, of course, doesn't improve resolution, which can be no better than one square element, 0.75 m on a side.

Discussion of Results:

Figure 4 shows the results obtained along plane P1-P2-MHV25T. The top and bottom sides of the images were skewed to account for differences in electrode elevations (electrodes in P1 were 2.5 ft. higher than those in P2 and 5 ft. higher than those in MHV-25T). This happened because P1 and P2 had some sloughing before the electrodes were lowered into position. The top color bar (lower right hand corner of the Figure) is for the background image (top left) and represents 10^2 to 10^4 ohm m on a logarithmic scale. The bottom color bar is for all the rest of the images which are the sequence showing changes in resistivity from the background and represents -800 to +800 ohm m. If an image had no change in resistivity it would be uniformly light blue (at the center of the color bar).

Notice first the background image (upper left) of Figure 4. This was actually taken on March 27th, and not the 25th, because it was the first time we had a full data set for both planes (P1 P2, and MHV-25T). Figure 5 compares a geologic cross section of the experimental site (from Eddy-Dilek *et al.*) and the background image. In the background image, a region of lower resistivity is delineated as a layer at 35 ft depth at P1, inclined down toward P2, but expanding toward the surface from P2 toward MHV-25T. This is the clay layer where the heating antenna was located. However, the deformed clay layer between P2 and MHV-25T is perplexing and probably does not represent the true shape of the clay unit. We speculate that some other

phenomenon such as changing mineralogy or increasing moisture content causes a decrease in the electrical resistivity of the clay between boreholes P2 and MHV-25T. Beleski et al. (1993) show data that indicates that about 19 inches of rain fell at the site during the three month period preceding the test. We speculate that rainwater seeping into the formation may have collected preferentially on top of the clay between boreholes P-2 and MHV-25T because (as shown by the cross-section in Figure 5) the top of the clay forms a low point in this area.

A layer of "clay balls" shown in the cross section does not correlate with features in the background image shown in Figures 4 and 5. This lack of correlation may be caused by the resolution limits of this technique. Eddy-Dilek et al. describe the clay balls as gravel-sized and embedded in a highly variable lithological unit. The thinness of the clay ball layer and the small size of the individual clay balls probably preclude the detection of this layer.

The difference images in Figure 4 are arranged in sequence from left to right along the top row and then continuing along the middle and bottom row with the number of days noted between successive images. The last image on the second row (labeled "same day") of Figure 4 shows resistivity differences between two data sets taken on April 1st close enough in time that we assume nothing is changing underground during that short period. Various types of experimental errors combine to insure that the two data sets are not identical. The reconstructions and their subsequent difference shows how these errors propagate through the entire data acquisition and analysis system to yield an estimate of image reliability. Only changes larger than seen in this image are assumed to be real.

We will first look at the changes occurring adjacent to the heating well (located between P1 and P2). All are comparisons relative to the background data (March 27th except for the P1-P2 images which are relative to March 25th). By and large there is a monotonic progression of resistivity decrease with time around the heating well between P1 and P2. We believe that several concurrent processes are responsible for the results observed between P1 and P2. First, the sediments and associated vadose water are being heated. Second, vadose water is being evaporated and third, steam is condensing. Typically resistivity increases with decreasing saturation. These results suggest that any drying which may have occurred was insufficient to increase the resistivity of the formation. The resistivity decreases observed are probably associated with increases in the surface conductance of the clay particles. The exchange cations in the double layer around each particle provide a surface conductor for electrical current separate from, but parallel to, the conduction path through the pore space. The surface conductor pathway tends to dominate in clays with significant cation exchange capacity because of the higher concentration of cations in the double layer. As temperature increases, surface conduction within the double layer increases because the mobility of the exchangeable cations increases. This increase in surface conductance more than balances the decrease in conductance along the pore volume due to drying effects. Additional discussion of this effect is presented in the section "Resistivity Changes and Saturation Changes".

The first difference (middle of top row, labeled 3/27/93-3/25/293) image shows changes between P1 and P2 (the only data available). Not much has happened after 2 days except perhaps a drop in resistivity at the lower left corner of the image. The changes are small--barely above statistical significance. After 4 days of heating (image labeled 4/01/93-3/27/93) we see a progressive drop in resistivity around the heater hole which continues throughout the sequence.

There is an asymmetry downward in the conductive anomaly associated with the heating well, particularly in resistivity differences obtained during the first 12 days of heating. The asymmetry becomes more pronounced with time and by day twelve is stable throughout the sequence. At the antenna well elevation the resistivity anomaly is widest and extends to boreholes P1 and P2. The anomaly extends downward below the antenna well and its width is significantly reduced such that it does not reach the P1 and P2 locations.

Temperature data obtained along boreholes MHV21T and MHV24T is shown in Figure 6. The "a" thermocouple in each borehole is located at a depth of 14.6 m (48 ft.), "b" is located at 11.6 m (38 ft.) (two ft. higher in elevation than the heating antenna), and "c" is located at 8.5 m (28 ft.). This data shows that the temperatures above the horizontal well ("c" thermocouples) are somewhat lower than those below the well. This temperature distribution may be caused by one or more of the following conditions. 1- The downward asymmetry in temperature may be related to the resistivity anomaly asymmetry. Downward drainage of warm condensate below the antenna would deliver additional heat to those portions of the clay where the condensate forms. 2- The preferential removal of steam from above the horizontal well removes heat from this region. 3- The "a" thermocouples are slightly closer than the "c" thermocouples to the antenna in the horizontal well. We cannot establish which of these three conditions is the most likely cause of the temperature asymmetry observed.

There are at least four mechanisms which might account for the asymmetry in the resistivity differences. 1-Radio-frequency energy is preferentially deposited below the antenna. This is unlikely since the antenna is located near the center of the clay layer. The radiation pattern of the antenna is probably omnidirectional; we disregard this mechanism because there is no reason why more energy would be directed downward. 2-Large portions of the steam generated around the antenna is not removed by the extraction system and remains within the clay, condenses and the condensate moves downward under gravity. 3-Infiltrated rain water is warmed as it moves through the heated zone and continues to move downward after being warmed. 4-The steam removed from the clay layer by the extraction system mostly came from above the horizontal well while little steam was removed from below. This condition would allow removal of steam (and therefore heat) generated above the horizontal well while allowing steam generated below the horizontal well to remain in the clay and condense. Mechanisms 2 and 4 are consistent with piezometer and flowmeter data presented by Beleski et al (1993). These data show that very low vapor extraction rates were achieved and that the bulk of the flow into the well came from elevations above the horizontal (antenna) well. Beleski et al also indicate that significant amounts of liquid water moved in to the antenna well during the test. This is strong evidence that liquid water could move (probably downward) within the clay and is consistent with mechanisms 2 and 3.

A resistivity depression develops upward from the antenna later in the sequence (after 12 days, 4/8/93) but is limited in vertical extent to about 10 feet above the antenna and has a smaller magnitude than the resistivity depression below the antenna (refer to Figure 4). We can only speculate why the resistivity decreases above the antenna develop after 12 days of heating. Beleski et al (1993) point out that the piezometer data shows that between day 16 (4/10/93) and day 22 (4/22/93) a "vapor lock" condition developed in the antenna well which reduced the extraction flow rates significantly. The preferential removal of gases from sediments above the antenna may explain why the resistivity anomaly did not grow upwards during the first twelve days of heating; the extraction system would remove more steam from

above, thereby restricting the upward progress of warmer temperatures and higher moisture content caused by steam condensate. When the vapor lock condition reduced the vapor extraction rates after day 16, much more steam remained in the sediments above the antenna. This additional steam may have allowed faster upward progress of warm, moist conditions which caused the resistivity differences observed.

The rainfall data shown in Figure 2 may provide a second clue regarding the development of the resistivity anomaly above the antenna elevation. Note that the period between March 22 (background data was collected on March 25 and 27) and April 8th was relatively wet (5.5 inches of rain) in comparison to the time period after April 8th (0.6 inches of rain). It is probable that during the wet period larger volumes of rainwater infiltrated the vadose zone and reached the top of the clay unit being heated. This larger water volume of water could be moving laterally along the upper contact of the clay unit. As the water moved laterally, it carried away some of the heat and quenched the upward progress of the heating front. Infiltration could also replenish any water loss caused by the heating. Later on, as rainfall diminished, less water reached the upper clay contact. This would allow the heat front above the antenna to retain enough heat to penetrate upwards.

There is no evidence, even late in the sequence, of an increase in resistivity near the heater as might be expected from dehydration. We interpret this to mean that the clays and surrounding soil are progressively heated such as to increase ion mobility in the pore water. Any drying taking place is insufficient to overcome the increased ion mobility effects and elevate the resistivity. Similar behavior has been observed in clay rich soils where a steam flood reduced the moisture content of the soil while increasing its temperature (Ramirez et al. 1993). The resistivity of the soil decreased as the steam flood penetrated a gravel layer in the saturated zone and reduced its moisture content.

The decreasing resistivity (increasing conductivity) implies increasing attenuation rate of the radio-frequency waves used for heating because the attenuation rate is proportional to electrical conductivity. The equation for the attenuation rate is shown in (1) for the case where displacement currents are much larger than conduction currents (Von Hippel, 1954).

$$\alpha \cong \frac{\sigma}{2} \sqrt{\frac{\mu}{\epsilon_r}}$$

where:

α = attenuation rate (1/m)

σ = conductivity (S/m) (1)

μ = magnetic permeability (henry / m)

ϵ_r = electromagnetic permittivity (farad / m)

This equation shows that attenuation rate increases as conductivity increases (resistivity decreases) and as permittivity decreases. The change in resistivity around the heating well is approximately 10% of the baseline resistivity value. This change implies a proportional 10 % attenuation rate change if the magnetic permeability and electromagnetic permittivity did not change. Its well known that the permittivity of water decreases with increasing temperature

and that the permittivity of soils decreases with decreasing moisture content (Hearst and Nelson, 1985). Thus, we can safely assume that the permittivity of the soil around the antenna decreased during heating because the soil probably became drier and hotter around the antenna. The magnetic permeability probably remained constant because it is primarily a function of the volume fraction of iron bearing minerals in the soil and this fraction probably remained constant. The combined effects of the measured resistivity decreases and postulated permittivity decreases must have resulted in increases in the electromagnetic attenuation rate of at least 10%. Increasing the rate of radio wave attenuation as heating progresses will increase the rate of energy deposition around the heating well while the penetration distance of the radio waves decreases. Beleski et al. (1993) indicate that as time progressed, the rate of temperature increase inferred from thermocouple readings became smaller with time. This observation is consistent with the inference of increasing attenuation rate with time, i.e., as the attenuation rate increased, less heat was deposited near the thermocouple boreholes because a bigger fraction of the heat was being deposited closer to the RF antenna well.

We now look further at the resistivity changes between boreholes P2 and MHV-25T. The layered structure of the clay rich zone in this region is more evident in the difference images than in the background image. This region appears to become progressively less resistive as it either takes up more water or becomes warmer. It may be directly heated by the radio-frequency energy (very unlikely because it would require radio-wave transmission through 12.2 m (40 ft.) of the clay rich zone). The resistivity decreases until day 12 (4/08/93) and then it remained relatively stable. At the time the resistivity changes reached a maximum, the power applied was only 30 % of the total shown in Figure 2. Continuing RF heating should lead to lower resistivities, not stable resistivities.

A second possibility is that rainwater that infiltrates the vadose zone drains downward and sideways. Eventually, the water reaches the top of the clay layer located at about 10.7 m (35 ft.). The water may then move laterally because of the differences in elevation along the top of the clay layer. Water moving along the upper contact of the clay layer will remove heat as it traverses the hot region and continues to move sideways toward MHV-25T. In doing so, this warm water depresses the resistivity along the path. Note that there are intermittent sandier layers within this clay zone; slow lateral and vertical movement of water over short distances may be possible. This conclusion is supported by the fact that the resistivity depression appears near the top of the clay layer.

A third possibility is that the relatively large decreases in resistivity between boreholes P2 and MHV-25 are related to vertical migration of rainwater and the formation of an ephemeral perched water table above the clay rich zone at 10.7 m (35 ft depth). This hypothesis is supported by the fact that the maximum resistivity decrease observed develops between day 4 and day 12 (between March 22 and April 8) where a total of 5.5 inches of rain fell. The data collected on days 20 and 22 (April 16 and 18) shows that the resistivity changes between P2 and MHV-25T remain at approximately the same magnitude as observed on day 12 (April 8). Between the 8 and the 18 of April only 0.6 inches of rain fell in the area and the last two data sets on April 16th and 18th were taken after a dry spell of at least six days while the band of resistivity decrease remains unchanged. In contrast, the resistivity changes between boreholes P1 and P2 (where the heating antenna was located) increased in magnitude and vertical extent between April 8 and 18 as heating progressed.

The last hypothesis, the vertical infiltration of rainwater and accumulation on top of the clay layer being heated, is also consistent with the known geology of the site. The geologic cross-section of this region shows a gap in a near-surface clay layer located directly above this area of resistivity decreases. Figure 5 compares this cross-section with one of the resistivity difference images extracted from Figure 4. The near-surface clay layer (located depths between 1.2 and 3.7 m (4 and 12 ft.)) locally prevents the vertical migration of rain water during periods of heavy rainfall. When enough water accumulates along the top boundary of this clay layer, the water spills through gaps in the clay. The water migrates downward until it accumulates on top of the clay rich zone located between 10.7 and 13.7 m (35 and 45 ft.) depth. This perched water may also move laterally where there are elevation differences along the upper contact of the clay; the geologic cross-section in Figure 5 shows elevation differences along the top contact of the clay. Water may also slowly penetrate the sandy lenses within the upper section of the clay rich zone. There are some resistive increases shallower than about 7.6 m (25 ft.), especially between P1 and P2, which are probably due to drainage of the vadose zone after the large rainfall events during the test. We don't know the origin of the general resistivity increase in the lower part of the plane between P2 and MHV-25T. However, it appears to be real and is in the data as early as April 1st.

Figure 7 shows a combination the geologic cross section and a cartoon which illustrates a proposed model of subsurface processes which explain the ERT results observed in Figure 4. This model summarizes our conclusions based on comparisons of the ERT results and other site data. The proposed mechanisms include heating of the clay, condensate drainage and rainwater infiltration.

Figures 8 and 9 show tomographs of resistivity differences for the plane defined by the electrodes in P1 and along the surface. Remember that these electrodes defined a plane which roughly paralleled the trend of the antenna well. Tomographs in these figures show that: 1) there is reasonable agreement between the P1-P2-MHV-25T tomograph and the P1 surface tomograph, 2) the resistivity is observed to decrease and 3) the largest resistivity decreases observed along the P1-surface tomograph occur below the antenna elevation. Figure 9 also compares a resistivity difference image with a geologic cross section parallel to the image plane. There is no reason to expect a direct correlation between resistivity differences and lithology; however, we show the cross section because it helps the reader better understand the relationship between resistivity differences, fluid movement and heterogeneities in permeability.

Figures 8 and 9 both show that the shape of the conductive anomaly near the edges of the antenna curves downward to form an inverted "u". The anomaly extends downward more along the edges of the antenna than near the antenna's center. This anomaly shape may be caused by one or more of the following conditions: 1) The curved shape is an artifact of the variations in resolution across the image plane. Figure 9 compares a true resistivity difference image (middle of the figure) and a simulated resistivity difference image (bottom image). The simulated difference image shows how resistivity decreases would appear if the resistivity decreases occurred within a long horizontal rectangle located at approximately the same elevation as the real anomaly. This comparison shows that the inverted "u" shape of the real anomaly is probably not caused by variations in resolution across the image plane; however, the simulation shows that significant shape distortions can be expected. 2) The soil temperatures near the edges of the antenna are likely to be smaller than temperatures near the antenna's center. This condition could result in more condensate forming near the edges

than near the center. This condensate would then drain downward over time thereby increasing the moisture content and temperatures of the soil along its path. Interpretations based on arguments of condensate drainage are consistent with interpretations of the results for plane P1-P2-MHV-25T. 3) The anomaly is distorted by the tomography algorithm because it makes the assumption that the resistivity structure is two-dimensional, i.e., the resistivity is constant along the axis orthogonal to the tomography plane. If we assume an approximately cylindrical heated zone with its axis collinear with the antenna axis, we can see that such a cylinder would be to one side of the plane defined by borehole P1 and the surface electrode array (Fig. 1). This geometrical arrangement is inconsistent with 2-D assumption. Violations of the 2-D assumption can cause significant distortions in the inverted resistivity structure.

Resistivity Changes and Saturation Changes:

We now use the resistivity differences shown in Figure 4 to estimate the saturation changes caused by the heating process. The work of Waxman and Thomas (1974) shows that clay conductance contributes a significant fraction of total conductance under some conditions and modifies the saturation - porosity - resistivity relationship. The conductance effects become more significant with increasing clay content, decreasing S_w (saturation), and increasing R_w (water resistivity). The model proposed by Waxman and Thomas assumes: 1) a parallel conductance mechanism with free electrolyte and clay-exchange cation components, and 2) an exchange cation conductance, B that depends on the equilibrating electrolyte concentration and temperature. At a fixed temperature, B , approaches a maximum value for low R_w and a minimum value for high R_w . The exchange cations provide a conductor for electrical current separate from, but parallel to, the conduction path through the pore space. We use this model to show that the observed decreases in bulk resistivity can be attributed to the effect of exchange cations on electrical conductivity as temperatures increased, even though saturation decreased in the sediments affected by the heating process.

Chesnut and Cox (1978) derived the following formula from the Waxman and Smits model:

$$R_t = \frac{(\phi S_w)^{-\nu} R_w}{1 + R_w B Q_{vb} (\phi S_w)^{-1}} \quad (2)$$

where:

R_w = water resistivity, ohm-cm

R_t = resistivity of water bearing sediment (or rock), ohm-cm

ϕ = fractional porosity

S_w = water saturation as fraction of pore volume

B = equivalent conductance of exchangeable cations,
(cm³/meq)/(ohm-cm)

Q_{vb} = cation exchange capacity of sediment, meq per cm³ of bulk volume

ν = combined saturation and porosity exponent, typically about 2

For the case of the clay layer at the experimental site, we have a fairly high R_w and "dirty" (i.e. high clay content and a fairly large cation exchange capacity) sediments, for which the second

term in the denominator of the modified Waxman-Smiths equation is large compared to unity. For large R_w , the exchange-ion conductance term, B , approaches $0.17B_{max}$, which is a function of temperature only. Then, using equation 2, the ratio of resistivity at temperature t_1 and a water saturation of S_{w1} (before heating) to the resistivity at t_2 and a water saturation of S_{w2} (after heating) is:

$$\frac{R_{t1}}{R_{t2}} \approx \frac{(S_{w1})^{-1}}{(S_{w2})^{-1}} \times \frac{B_{max2}}{B_{max1}} \quad (3)$$

R_{t1} is the resistivity before heating and R_{t2} is the resistivity after heating.

We can use equation 3 to make estimates of saturation change caused by heating if we assume some sediment properties. We will assume that initial saturation (S_{w1}) of the clay unit was 0.82; this is the average saturation for the clay unit along borehole MHV-24 based on saturation values of core samples reported by Eddy-Dilek et al, 1993. We also assume that the initial temperature is 20 °C. B_{max} data is obtained from Waxman and Thomas (1974) as function of temperature. Figure 10 shows plots of saturation versus resistivity ratios (before heating / after heating) as a function of saturation (S_{w2}) and temperature. The figure shows, for example, that for a temperature of 60 C, the resistivity ratio becomes one for a saturation of about 0.36. This means that, given a temperature of 60 C close to the heating well, the resistivity would decrease due to heating as long as the saturation (S_{w2}) was greater than 0.36 (36%). Given that we only observed resistivity decreases, we conclude that the saturation during the test had to be greater than 36%.

Beleski et al. (1993) show that the temperature of the closest thermocouple (at a radius of 1.9 m) to the antenna was about 54 °C for data from 4/16/93. Resistivity ratios calculated using tomographs from 4/16/93 and 3/27/93 show a ratio of about 1.3-1.4 at distances of about 1.9 m from the antenna. Using the results in Figure 10 for a temperature of 55 °C, we estimate that the saturation corresponding to a resistivity ratio of 1.3 to 1.4 is about 0.50 to 0.55 (50 to 55%). This estimate compares reasonably with moisture content analysis of post-test samples within the clay which average 65 % (based on saturation values of core samples reported by Eddy-Dilek et al, 1993) and given that the core samples were collected as far as 10 ft away from the ERT plane.

Summary and Conclusions:

We have described work where we use electrical resistance tomography to image underground processes in in-situ soil remediation efforts at the Integrated Demonstration for VOC's in Soils and Groundwater at Non Arid Sites. The effects of radio-frequency heating in the vadose zone around a horizontal well were monitored during a period of approximately 4 weeks. From an array of electrodes located in 3 boreholes and along the ground surface, we imaged vertical planes between two hole pairs and fit these planes together for an overall picture of the effects of heating.

The ERT results obtained during this study were somewhat surprising. We expected to see a more or less symmetrical zone of reduced resistivity grow around the heating well as the clay temperatures rose and the mobility of ions within the clay increased. At some point a zone of

increased resistivity was then expected as the material nearest the antenna became almost completely dry and the film of water within the pore structure became discontinuous.

The images suggest a somewhat more complex process or, what is more likely, several processes contributing to the results. These include heating and vaporization of the pore water, formation of steam condensate, and infiltration of rainwater through the heated zones and adjacent areas. There is a clear asymmetry downward in the conductive anomaly associated with the heating well. This asymmetry was observed on ERT planes approximately parallel and orthogonal to the heating antenna. The asymmetry becomes more pronounced with time. The resistivity decreases observed in the near vicinity of the heating well are believed to be caused by the heating and downward migration of pore water originally located within a radius of a few feet of the heating well. The decreasing resistivity implies an increasing rate of radio wave attenuation as heating progressed; therefore, the rate of energy deposition around the heating well increased while the penetration distance of the radio waves decreased. The resistivity decreases observed suggest that the saturation of the clay near the heater was approximately 50-55%.

Relatively large decreases in resistivity occurred between boreholes P2 and MHV-25T. These changes may be largely unrelated to the effects of heating and instead may be primarily related to rainwater moving through the vadose zone. A comparison of the time history of these changes and rainfall data suggests that the observed resistivity decreases may be related to rainwater infiltration. The geologic cross section for this area shows a gap in a near-surface clay layer that overlies this region. We propose that rainwater spilling through this gap (and others which may be present) migrates downward and collects above the clay rich zone penetrated by the horizontal well.

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Figure 1. Plan view of the experimental site showing the location of the boreholes used for ERT (P1, P2, and MHV-25T), surface ERT electrodes and heating antenna location. The antenna was located in a horizontal well (AMH-5) that intersected the clay rich zone at a depth of approximately 12.2 m (40 ft). Other MHV wells (all vertical) shown were used by WSTRC for site characterization and process monitoring. Also shown is the alignment of a geologic cross-section presented in a subsequent figure. Well location data for the wells from Beleski et al., 1993.

Figure 2. The upper bar graph shows the rainfall measured before and during the heating test. The lower line graph shows the average power and total energy applied to the formation as a function of time. Rainfall data was provided by the Westinghouse Savannah River Technology Center. Antenna power data from Jarosch et al, 1993. The heating process started on the March 25, 1993 at 12:06 PM.

Figure 3. Finite element mesh used to calculate the tomographs for plane P1-P2-MHV-25T. A similar mesh was used for the plane defined by borehole P-1 and the surface electrodes.

Figure 4. ERT images for plane P1-P2-MHV25T. The background (before heating) image (upper left corner) and the resistivity difference images are shown. The resistivity difference images show changes occurring while the heating demonstration progressed. The image labeled "same day" shows changes which occurred over a period of a few hours when the formation properties should have remained relatively constant; this image provides an estimate of the reliability (precision) of the other difference images. The labels below each image indicate the dates of the ERT surveys used to calculate the background and resistivity difference tomographs.

Figure 5. Comparison of geologic cross-section, background ERT image and a resistivity change image along the ERT planes defined by boreholes P1, P2, and MHV25T. The location of the geologic cross-section relative to the ERT planes is shown in Figure 1. The geologic cross-section was adapted from a cross-section by Eddy et al., 1993.

Figure 6. Plot of temperature versus time for thermocouples located on boreholes MHV-21T and MHV-24T. The "a" thermocouple in each borehole is located at a depth of 14.6 m (48 ft.), "b" is located at 11.6 m (38 ft). (2 ft. higher than the heating antenna), and "c" is located at 8.5 m (28 ft.). Temperature from Jarosch et al., 1993. Note that within each well the deepest thermocouple ("a") shows higher temperatures than the shallowest thermocouple ("c").

Figure 7. Schematic diagram showing possible mechanisms which may have caused the ERT results observed.

Figure 8. Isometric view of planes approximately parallel and perpendicular to the antenna well. Image shows differences in resistivity between 4/18/93 and 3/27/93 surveys. Plane to the left is defined by borehole P1 and electrodes located at the ground surface. Plane to the right is defined by boreholes P 1, P 2 and MHV-25. Color scale for resistivity differences shown in Figure 4.

Figure 9. Comparison of geologic cross section, resistivity difference image and simulated resistivity difference image for plane P1-surface. The geologic cross section has been adapted from cross sections by Eddy, 1993. The resistivity difference image is the same as that shown in Figure 8.

Figure 10 shows plots of saturation versus resistivity ratios (resistivity before heating (R_{t1}) / resistivity after heating (R_{t2})) as a function of saturation (S_{w2}) and temperature (T_2).

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