INNOVATIVE
TECHNOLOGY
Summary Report

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Electrical Resistance Tomography for Subsurface Imaging

Characterization, Monitoring, and
Sensor Technology
Crosscutting Program and
Subsurface Contaminants Focus Area

Prepared for
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Office of Environmental Management
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Summary Report

Electrical Resistance Tomography for Subsurface Imaging

OST/TMS ID 17

Characterization, Monitoring, and
Sensor Technology
Crosscutting Program and
Subsurface Contaminants
Focus Area

Demonstrated at
Lawrence Livermore National Laboratory
Livermore, California
Savannah River Site
Aiken, South Carolina

INNOVATIVE
TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE’s Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under “Publications.”

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SECTION 1

SUMMARY

Introduction

Characterizing and monitoring underground conditions and the location of subsurface contaminants is a challenging and costly endeavor. Many sensors and non-invasive geophysical measurement techniques have been developed to interpret the nature of the subsurface without disturbing it. Each of these sensors and techniques has its application and limitations. Sensors and non-invasive measurement techniques developed for other purposes have been used for site characterization, monitoring, and remediation with varying degrees of success. Applying these sensors and techniques under real world conditions, where the extent and location of contaminants are largely unknown, is often expensive because their use is usually labor intensive and requires drilling closely spaced boreholes to adequately define contaminated areas

The cost and environmental impact of drilling numerous boreholes (see Figure 1) make it desirable to develop less costly and more environmentally benign techniques for satisfying the site characterization, remediation, and monitoring needs of the U. S. Department of Energy (DOE). Electrical Resistance Tomography (ERT) For Subsurface Imaging, the technology summarized in this report, is one of the promising new technologies developed by the DOE. ERT, when used in conjunction with other technologies, can reduce adverse impacts to the environment and lower site characterization, monitoring, and remediation costs at DOE sites.

Figure 1. Conventional site surveys and site characterization are conducted using drill rigs similar to the rig pictured above. Drilling boreholes into the subsurface is expensive and adversely affects a relatively large surface area at each drill site. Contaminated material is also brought to the surface in the process, and new migration pathways may be created in the subsurface between soil and groundwater horizons.

ERT For Subsurface Imaging was developed for the DOE Office of Science and Technology (OST) by Lawrence Livermore National Laboratory (LLNL). This innovative technology allows site investigators to view two- or three-dimensional electrical resistivity images of the subsurface on an on-site computer terminal within minutes of data acquisition. ERT For Subsurface Imaging technology has been successfully demonstrated for monitoring remediation processes, detecting potential leaks under high-level waste tanks, measuring moisture movement in fractured rock, and for verifying the effectiveness of subsurface barriers. This technology has been transferred to industry. Information on the patents and patents pending resulting from development of ERT For Subsurface Imaging is provided in Section 4. Reports and articles published on this technology and its field tests and demonstrations are listed in Appendix A.

Technology Summary

ERT For Subsurface Imaging is a geophysical imaging technology that measures electrical resistivity in soil and rock. This technology can be used to obtain "snapshot" images of relatively static subsurface conditions for site screening or characterization. It can also be used to obtain a series of images showing the relatively rapid changes caused during environmental remediation. The ability to look at differences in resistivity over time eliminates many sources of resistivity that remain constant during remediation and allows selective imaging of the changes occurring during remediation. Remediation processes, such as those using subsurface heating or steam injection, can cause rapid temperature and liquid saturation changes that immediately affect electrical resistivity. Any natural or remedial process that affects electrical resistivity can readily be measured by ERT, and the results can be used to guide remediation efforts. The two- or three-dimensional images of the subsurface can have a scale of feet or many thousands of feet depending upon the configuration and spacing of electrode arrays.

An ERT For Subsurface Imaging data acquisition system acquires a series of voltage and current measurements from surface electrode arrays or electrode arrays emplaced underground. The electrode arrays consist of electrode dipoles that communicate with other dipoles. The electrode dipoles are fastened at regular intervals (typically 5 feet apart) to a supporting shaft or string. The electrode arrays can be spaced very close to each other or hundreds of feet apart, depending upon the resolution needed. ERT works well in both the vadose (unsaturated) and saturated subsurface zones. The extensive data resulting from measurements taken between the electrode arrays are processed to produce electrical resistivity tomographs using state-of-the-art inversion algorithms. These calculated tomographs show spatial variations in electrical resistivity. The tomographs show the location and shape of electrical resistivity zones on a computer monitor, and those visual images can be used as a guide for focusing more detailed characterization and monitoring evaluations.

Comparison with Baseline Technology

The baseline technology for measuring underground conditions is the systematic penetration of the subsurface with boreholes and/or hydraulic push holes in a systematic pattern to permit the use of conventional measuring instruments, such as geophysical logging tools, and the employment of underground sampling techniques. The samples collected are usually sent off-site to a laboratory for analysis. Data from the laboratory analyses generally takes one to several weeks to receive. Moreover, the time delays resulting from off-site analysis can result in significant downtime costs when the results of those analyses are essential to guiding characterization and remediation operations.

While the costs of using the baseline drilling, measurement, and analytical technologies to obtain characterization data cannot be avoided, using ERT For Subsurface Imaging can potentially reduce those costs by allowing site investigators to see images of the areas where further evaluation by other technologies is needed. The electrode arrays used for subsurface imaging can initially be set up on the surface or spaced at wide intervals underground to locate areas where more detailed data are needed. The initial screening of an area, especially a large area, can be used to aid site investigators in determining where to focus resources. Using this approach, it is apparent that the cost savings will generally increase in proportion to the size of the site. Upon completion of the initial screening, more tightly spaced ERT arrays can be positioned to obtain higher resolution for more intensive characterization or monitoring activities. Where feasible, the use of cone penetrometer or other hydraulic push technologies to create openings for emplacing electrode arrays in the subsurface can also substantially reduce the cost of deploying ERT For Subsurface Imaging.

ERT For Subsurface Imaging permeates virtually everything between electrode arrays and can, for instance, pinpoint changes that may indicate leak sources or contaminant plumes. However, the resolution of the tomographic images created from the electrical resistivity data collected is controlled by the configuration and spacing of the electrode arrays. While ERT cannot identify what has leaked or what resides in a suspected contaminant plume, it can visually show the location of a suspected leak or plume and the degree of variation in electrical resistivity of the suspected leak or plume. In contrast, data collected by conventional sampling and geophysical logging in closely spaced holes is not necessarily representative of the subsurface media between the holes. For instance, the conventional method of geophysical well logging requires that the measured values be interpolated between the boreholes. Consequently, the reliability of interpretations of what exists between the holes is generally reduced as the distance between the holes increases. Because ERT For Subsurface Imaging permeates its entire subsurface domain, it can be used to reduce the off-site laboratory sample analyses needed to identify what contaminants and contaminant concentrations may or may not be present in electrical resistivity images that exhibit areas of relatively uniform electrical properties.

Demonstration Summary

When the DOE began funding ERT research and development in FY 1991-1992, it was quickly shown that ERT had the ability to map geological features and subsurface conditions. This was possible because soil electrical properties vary with temperature, soil type, fluid saturation, and other parameters, and an electrical current could readily be conducted through the subsurface. The demonstrations described in this ITSR were conducted over a period from FY 1991 to FY 1998.

During FY 1991 to FY 1993, ERT For Subsurface Imaging was used successfully for monitoring several remediation operations involving soil heating, pump and treat, electrokinetics, steam injection, and more. ERT was used as a principal component of a Dynamic Underground Stripping^{TM} process (another DOE/OST technology {TMS 7} developed by LLNL) to remediate contaminated soil and groundwater at Lawrence Livermore National Laboratory. In FY 1993, ERT For Subsurface Imaging was used in a demonstration to monitor a radio frequency heating process used for the *in situ* remediation of volatile organic compounds in subsurface water and soil at the Savannah River Site in Aiken, South Carolina. In FY 1996-1997, ERT For Subsurface Imaging technology was used to characterize moisture movement and coupled processes at Yucca Mountain. It was also demonstrated at a commercial site in Visalia, California, which was undergoing remediation. Nine demonstrations are described in more detail in Section 3. Several vendors now offer ERT For Subsurface Imaging services for site characterization and remediation monitoring (Section 4).

Demonstration Results

- In the Dynamic Underground Stripping Project at LLNL, the comparison of ERT tomographs with induction well logs, formation temperature logs, and lithologic logs indicated that the ERT tomographs reliably mapped the subsurface regions invaded by the steam flood.
- During a radio-frequency heating process used for the in situ remediation of Volatile Organic Compounds (VOCs) at the Savannah River Site, ERT tomographs were interpreted to show changes in resistivity related to the heating and vaporization of pore water, formation of steam condensate, and infiltration of rainwater through the heated zones and adjacent areas.
- Tomographs of brine releases from a steel tank mockup at the Hanford Reservation showed that field resistivity changes could be readily detected and that the lateral and vertical extent of the plume could be approximated.

- A controlled release of Dense Non-Aqueous Phase Liquids (DNAPLs) within a steel tank at the Oregon Graduate Institute of Science and Technology showed that the ERT tomographs clearly delineated the plume as a resistive anomaly.
- The long-term monitoring capability of ERT for Subsurface Imaging was used to monitor changes in electrical resistivity during drawdown pumping of DNAPLs at Hill Air Force Base.
- During a thermal DNAPL remediation project at the Visalia Pole Yard, ERT tomographs were used to control the remediation process and optimize sample collection.
- In a single heater test conducted underground in hard rock at Yucca Mountain, changes in electrical resistivity with groundwater movement were consistent with other physical evidence of temperature changes and water movement in the rock.
- The results of ERT For Subsurface Imaging were compared with several other techniques used to reveal the movement of groundwater around a heated drift at Yucca Mountain and they agreed well with the other sources of physical evidence.
- At Dover Air Force Base, ERT For Subsurface Imaging was used to verify the performance of a full-scale emplacement of a thin-wall grout barrier.

Contacts

Technical

Principal Investigators:
William Daily
Lawrence Livermore National Laboratory
7000 East Avenue
P.O. Box 808, L-130
Livermore, CA 94550
(925) 422-8623 or -1710
fax: (925) 422-2495
daily1@llnl.gov

Abelardo Ramirez
Lawrence Livermore National Laboratory
7000 East Avenue
P.O. Box 808, L-208
Livermore, CA 94550
(925) 422-6909
fax: (925) 422-3925
ramirez3@llnl.gov

Management

DOE-OAK Technical Program Officer
Kim Abbott
U.S. Department of Energy
Oakland Operations Office
1301 Clay Street, Room 700N
Oakland, CA 94612
(510) 637-1501
fax: (510) 637-2001
kim.abbott@oak.doe.gov

SCFA Product Line Manager

Scott McMullin
Metals and Radionuclides Product Line
U.S. Department of Energy
Savannah River Operations Office
PO Box A, Bldg 703-468
Aiken, SC 29802
(803) 725-9596
scott.mcmullin@srs.gov

DOE NV Field Program Manager

Joe Ginanni
U. S. Department of Energy
Nevada Operations Office
P.O. Box 98518, MS 505-TDD
Las Vegas, NV 89193-8518
(702) 295-0209
fax: (702) 295-1810
ginanni@nv.doe.gov

DOE HQ Program Manager

Charles Nalezny, EM-53
U. S. Department of Energy
Cloverleaf Building
19901 Germantown Road
Germantown, MD 20874
(301) 903-1742
fax: (301) 903-7457/-7234
charles.nalezny@em.doe.gov

Notice:

All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference # for Electrical Resistance Tomography for Subsurface Imaging is 17.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

Electrical Resistance Tomography (ERT) For Subsurface Imaging employs surface and/or subsurface electrode arrays to measure the resistivity distribution in soil and rock between the electrode arrays. Electrode arrays are composed of electric dipoles arranged vertically on an emplacement string. The electrode array shafts or strings are emplaced in two or more boreholes (or hydraulic push holes) with some electrode dipoles acting as *current-source electric dipoles* and other dipoles acting as *potential-measuring dipoles*. The electrical resistivity data from the current-source and potential-measuring dipoles in the electrode arrays are acquired and processed by the High-Speed Data Acquisition System (see Figure 2) to produce two- or three-dimensional subsurface images on a continuous basis. An Auto Pilot System can also be selected for unattended data collection and analysis; this feature can provide cost-effective, long-term monitoring of contaminant plumes, tanks, or contaminant-migration barriers.

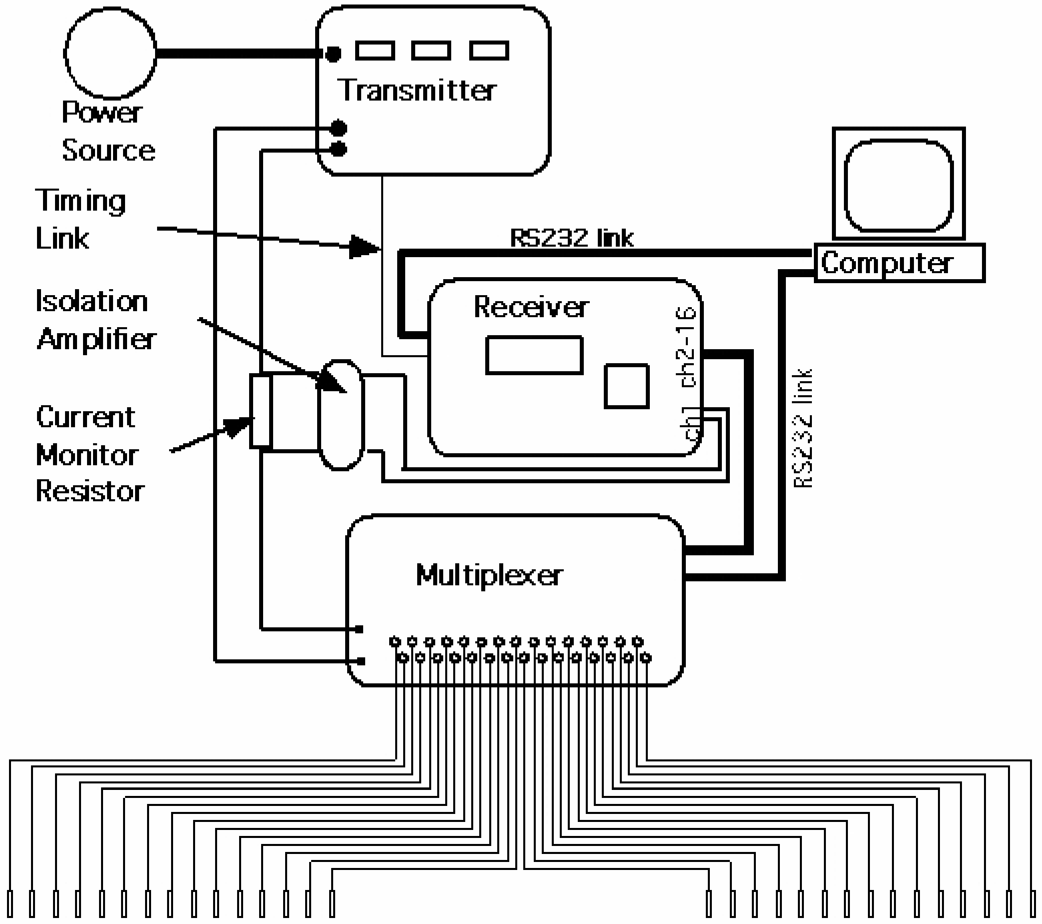

Figure 2. Diagram of High-Speed Data Acquisition System Used in Electrical Resistance Tomography For Subsurface Imaging

The electrodes in each borehole are generally grouted in place to fix their location and provide better electrical contact with the formation. Current is conducted through the formation from one electrode dipole at a time, and the potential difference is measured between it and the other electrode array dipoles in the ERT monitoring network. The procedure is repeated for many vertical and horizontal positional combinations of source and receiver electrode dipoles in rapid succession to produce the data for three-dimensional images. The data collection process is automated to quickly monitor the formation.

Calculating the distribution of resistivity in the vicinity of boreholes based on the measured transfer resistances is highly nonlinear. The non-linearity results because the current paths are dependent on the resistivity distribution. The ERT inversion process involves solving both the forward and inverse linearity problems. The solution to the forward linearity problem uses the finite-element method to compute the potential electrical response in the soil due to the current source. The reverse linearity problem is solved by an iterative inversion routine to approximate the resistivity distribution. The final product of the process is an image (tomograph) showing the distribution of resistivity between the electrode arrays. By interconnecting a network of boreholes with vertical electrode arrays, and measuring electrical resistivity between all of the vertically spaced electrodes in the network, a three-dimensional representation of the area being investigated is developed. Three-dimensional resistivity images obtained before, during, and after a remediation process can be used to determine the progress of the remediation. The pattern of resistance changes can be correlated with the properties of interest in the remediation process.

System Operation

To perform a typical ERT For Subsurface Imaging survey, electrode arrays are emplaced vertically in holes (see Figure 3) in a pattern suitable to characterize the area of interest in two or three dimensions. The number of electrode arrays required and the spacing of the arrays depend upon several parameters. Data on the electrical resistance measured between different dipoles at various elevations and angles between the electrode arrays are collected by the data acquisition system for use in imaging and mapping resistivity variations. The data collected are then processed with an inversion code to produce a cross-sectional image of spatial resistivity variations that can be monitored over time. Migrating liquids appear as regions with resistivity changes.

Figure 3. An electrical array with electrode dipoles attached to a supporting shaft or string is being lowered into a borehole. Once in place, the hole will be filled with grout to increase conductivity between the electrodes and the subsurface environment.

ERT subsurface imaging technology is ideally suited for field operations (see Figure 4) requiring minimal field personnel because, once the electrode arrays are installed, the data collection system can be set up to run automatically with minimal personnel intervention. In contrast, conventional well logging and sampling requires field personnel to be present since a physical probe or sampler must be moved vertically within a borehole.

Figure 4. The field operations center for an Electrical Resistance Tomography For Subsurface Imaging network is typically located in a van or truck. A fast laptop computer can be programmed to process the data collected into two- or three-dimensional tomographs for site investigators to use on-site. Once the subsurface electrode arrays are emplaced and the network is set up, it can be run by a technician or put in automatic mode.

SECTION 3

PERFORMANCE

Demonstration Plan

The following demonstrations describe how ERT For Subsurface Imaging performed as one of the tools used for monitoring remediation processes, fluid migration, locating a Dense Non-Aqueous Phase Liquid (DNAPL) plume, and subsurface barrier leak detection. The demonstrations described in this ITSR were conducted over a period from FY 1991 to FY 1998. The details for the technology demonstrations described below can be found in the reports cited in Appendix A. The following subsection describes the demonstrations from nine separate demonstrations and their results.

Demonstrations and Results

- During FY 1991-1993, the capability of ERT For Subsurface Imaging was demonstrated in the Dynamic Underground Stripping Project at Lawrence Livermore National Laboratory (LLNL). This environmental remediation demonstration relied upon the ability of ERT technology to rapidly map the penetration of steam. During the demonstration (See Boyd et al. 1994 and LaBrecque et al., 1996), ERT was used to monitor changes in subsurface resistivity during steam injection. The injected steam caused changes in soil resistivity because the steam displaced some of the native pore water, increased the temperature of the remaining pore water and soil, and changed the ionic content of the pore water. The effects of the steam invasion could be detected by mapping changes in soil resistivity as a function of time and space. Comparisons of ERT tomographs with induction well logs, formation temperature logs, and lithologic logs indicated that the ERT tomographs reliably mapped the subsurface regions invaded by the steam flood. The data also indicated that steam invasion was limited in vertical extent and showed that, with time, the steam invasion zone extended laterally to all areas monitored by the ERT technique.

- In FY 1993, investigators demonstrated that ERT For Subsurface Imaging was an effective monitoring tool during a radio-frequency heating process used for the *in situ* remediation of volatile organic compounds (VOCs) in subsurface water and soil at the Savannah River Site near Aiken, South Carolina (See Ramirez et al., 1991 and 1993). A dipole antenna located in a horizontal well in the unsaturated zone was used to heat a contaminated clay layer. The heat caused changes in the electrical resistivity of the formation; ERT produced tomographs of those changes. The changes in resistivity shown in the tomographs were interpreted by investigators to be related to the heating and vaporization of pore water, formation of steam condensate, and infiltration of rainwater through the heated zones and adjacent areas. A clear asymmetry downward was revealed by the resistivity decreases associated with the heating process. The investigators inferred that the gaps in the near surface clay layers allowed rainwater to migrate downward and reach the top of the clay-rich zone penetrated by the antenna borehole.

- At the Hanford Reservation near Richland, Washington, the performance of ERT For Subsurface Imaging technology was demonstrated during FY 1994-1995 under a 50-foot diameter steel tank mockup (See Ramirez et al., 1996). Two brine releases were tracked with ERT to evaluate its ability to detect leaks beneath metal underground storage tanks. The image planes were arranged to provide a series of detailed images at many levels which, when assembled, gave an overall view of the plume forming beneath the tank during the releases. First, about 3,800 liters of saline solution were released along a portion of the tank's edge and later 1,900 liters were released near the center of the tank. The average release rate at the tank edge was 26 liters per hour, and the average release rate for the tank center was 3 liters per hour. Two- and three-dimensional tomographs were calculated using data collected before, during, and after each leak. The tomographs mapped the spatial and temporal evolution of resistivity changes caused by the leak as the solution penetrated the soil. Readily detectable resistivity decreases were observed and used to map the associated plume. The results showed that the metal tank has significant effects on the results obtained, primarily in reducing sensitivity to the leak within 5 feet of the tank bottom. The changes in the tomograph images are consistent with the behavior expected for infiltration of water into a fairly homogeneous unsaturated soil. There is a clear decrease in resistivity of the volume directly below the release point from which the plume appears to drain downward by gravity and spreads laterally by capillary suction and as it encounters soil heterogeneity. According to the investigators, the approximate leak location can be estimated as the point directly above the region of maximum change in the top few planes. The lateral and vertical extent of the plume as a function of time can also be approximated from the images.

- The performance of ERT For Subsurface Imaging was demonstrated and evaluated for detecting and delineating free-product Dense Non-Aqueous Phase Liquids (DNAPLs) in the subsurface (See Daily et al., 1995). A controlled release of DNAPLs was monitored by ERT during FY 1995 at the Oregon Graduate Institute of Science and Technology in Beaverton, Oregon. In this demonstration, 190 liters of perchloroethylene (PCE) were released at a rate of 2 liters per hour from a point one-half meter below ground surface. The spill was conducted within a double-walled steel tank where saturated layers of sand, bentonite, and a sand/bentonite mixture were installed. Electrical resistance data were collected before the release, several times during the release, and several times after the release. Data from before the release were compared with data obtained during the release for the purpose of imaging the changes in conductivity resulting from the plume. Conductivity difference tomographs showed a decrease in electrical conductivity as the DNAPL penetrated the soil. A pancake-shaped resistive anomaly developed on the top of a bentonite layer at 2 meters in depth. The anomaly grew in magnitude and extent during the release; borehole television survey data confirmed the anomaly to be free-product PCE whose downward migration was stopped by the low permeability bentonite. The investigators concluded that the tomographs clearly delineated the plume as a resistive anomaly.

- The monitoring capability of ERT For Subsurface Imaging was demonstrated at a DNAPL-contaminated site in FY 1996 (See Newmark et al., 1997). The results were subjected to independent peer review and favorable comments were received by LLNL from the reviewers. This year-long demonstration took place at Hill Air Force Base in Utah where a free-product DNAPL plume that had accumulated along the base of the uppermost aquifer was being removed by pumping. The plume was predominantly trichloroethylene (TCE), but also contained trichloroethane (TCA), PCE, and methylene chloride. ERT was used to image changes in the electrical properties of the formation during drawdown pumping of free-product DNAPL.

- The applicability of ERT For Subsurface Imaging was demonstrated in 1996 at the Visalia Pole Yard, Visalia, California, during a thermal DNAPL remediation project (See U.S. Environmental Protection Agency, 1998). The site was contaminated with creosote. A suite of techniques was used to monitor the physical changes and progress of chemical destruction *in situ* using Hydrous Pyrolysis/Oxidation (HPO). ERT and temperature measurements provided the primary information regarding the temporal and spatial distribution of the heated zones. Since HPO is largely an aqueous-phase reaction, it is essential to capture the fluid chemistry for evaluation. At elevated temperatures, many of the key constituents are sufficiently volatile to make traditional sampling techniques unsuitable. Accurate fluid sampling, combined with the identification of noble gases in the native and injected fluids, permitted the quantification of the amount of *in situ* destruction occurring in the treated region. Tomographs were successfully used to control the remediation process and pinpoint the optimum sample collection sites.

- The ability of ERT For Subsurface Imaging to show the movement of water in rock was demonstrated during the Single Heater Test in volcanic tuff (See Ramirez and Daily, 1998). This was one of the *in situ* thermal tests being conducted in the Exploratory Studies Facility at Yucca Mountain, Nevada. The purpose of the test, which took place in FY 1996-FY 1997, was to monitor the movement of liquid water and condensate in welded tuff around a single heater emplaced in a horizontal borehole. Emphasis was placed on measuring the movement of condensate out of the system. Resistivity tomographs were derived from data collected before, during, and after the heating episode. The tomographs produced during heating showed a region of decreasing resistivity approximately centered around the heater. The size of this region grew with time and the resistivity decreases became stronger for the rock just below the heater. Both temperature and saturation were found to cause the changes in resistivity. As the rock mass cooled, a region of increasing resistivity developed that was centered around the heater. The size of this region grew with time, as did the resistivity. The tomographs indicated that, during the heating phase, a region of drying formed around the heater. During the cooling phase, the dry region remained relatively stable. Wetter rock regions that had developed below the heater during the heating phase became smaller in size during the cooling phase. During the heating phase, there were competing effects at work; i.e., temperature increases caused resistivity decreases while drying caused resistivity increases. The ERT results were consistent with other physical evidence of temperature changes and water movement in the rock.

- At the potential repository site at Yucca Mountain, ERT For Subsurface Imaging was one of the technologies deployed to measure the hydrological response of the host rock mass to heating and cooling (See Ramirez and Daily, 1997). ERT was used in a Drift Scale Test conducted during FY 1998 to monitor the movement of liquid water around a heated drift with an emphasis on measuring the movement of condensate out of the system as a result of the heating and subsequent cooling. In the Drift Scale Test, eight boreholes were drilled above and below the drift to form vertical planes parallel to the observation drift. The boreholes were equipped with 140 electrodes to image changes in moisture content caused by temperature changes. ERT tomographs from before and during the heater test were compared. As expected, the largest changes in resistivity occurred closest to the heater. A region of drying developed around the heater and grew with heating time. Correspondingly, the tomographs showed a region of decreasing resistivity that was approximately centered around the heater. The size of this region grew with time, as did the resistivity. The results indicate that the changes in resistivity are caused mostly by the rising temperature of the rock mass pore water, although saturation changes also played a role. The drying region appeared to propagate upwards and sideways. The changes in resistivity were caused by changes in both temperature and saturation. The ERT results were consistent with other physical evidence.

- In FY 1998, ERT For Subsurface Imaging was demonstrated at Dover Air Force Base, Dover, Delaware, where it was used to monitor a full-scale test emplacement of a thin-wall grout barrier installed by high-pressure jetting and a thick-wall polymer barrier installed by low-pressure permeation injection (see Figure 5). Images of electrical resistivity before and after barrier installation were compared. Barrier materials were imaged as anomalies that were more electrically conducting than the native sandy soils at the test sites. Although the spatial resolution of the ERT images was not sufficient to resolve flaws smaller than a reconstruction voxel (50 centimeters on a side), the images did show the spatial extent of the barrier materials and, therefore, the general shape of the structures. To verify barrier performance, ERT was also used to monitor a flood test of a thin-wall grout barrier. Electrical resistivity changes were imaged as salt water tracer moved through the barrier at locations which were later found to be defects in a wall or the joining of two walls.

Results and Interpretations

The actual data that ERT provides are a series of tomographs (two- or three-dimensional images) taken at different times during the process monitored. Each tomograph shows the distribution of resistivity in the subsurface, represented either as a set of "slices" (cross-sections) or as a composite three-dimensional image. The analyst uses both the tomographs themselves and the changes from one tomograph to the next to make inferences about the spatial progress of the process being monitored. The process, naturally, is one that is expected to affect subsurface resistivity, such as heating, the use of steam or oxidizing materials to aid in removing DNAPLs, or detection of leaks involving ionic materials.

There is no baseline technology that provides comparable results in terms of resistivity distributions in the subsurface. Hence it is impossible to validate this technology with regard to resistivity using field subsurface data; the developers at LLNL have done that sort of validation in laboratory-scale models (See Boyd et al., 1994; Daily and Ramirez, 1984; Daily et al., 1992; and Daily and Ramirez, 1994). Rather, the sorts of comparisons with baseline technologies which can be made using subsurface data typically involve comparing inferences made about the process being monitored with inferences made using other techniques, including "post-mortem" excavation and/or soil boring in some cases. The LLNL investigators have a long string of both theoretical and application publications about ERT and its successor EIT; applications appearing in these papers include environmental restoration, environmental monitoring, and medical imaging. Some 80 or more papers may be found on the web at http://www.llnl.gov/tid/lof/, searching under names Daily, LaBrecque, and Ramirez. ERT was the subject of Douglas LaBrecque's 1989 Ph.D. thesis at the University of Utah; other papers have appeared in

Physical Review Letters, *Water Resources Research*, *Geophysics*, *IEEE Transactions on Biomedical Engineering*, *Communications in Pure and Applied Mathematics*, and *IEEE Transactions on Geoscience and Remote Sensing*.

ERT should be viewed as an enabling technology. It is difficult to quantitatively assess accuracy and reproducibility of conclusions reached when these are dependent on the skill and experience of the analyst, in the same fashion as the interpretation of medical tomographs depends on the skill and experience of the clinician. Therefore, in this ITSR forum we rely on the testimony of the analysts and users in the nine DOE applications presented above as well as the other published results cited in the previous paragraph as establishing the credibility of the technology. Doing so, one easily concludes that the technology does provide results that are useful in guiding environmental monitoring and environmental restoration efforts, subject to competent interpretation by skilled and experienced analysts. Since it is an enabling technology and, moreover, is typically used in conjunction with other sources of information (again, in a fashion similar to medical tomography), the question of efficiency compared with a baseline is moot.

The tomographs produced in a typical application are voluminous; it would be prohibitive to reproduce them here for all of the demonstrations. As an example of how inferences are made from ERT tomographs, nine tomographs generated during the Dover Air Force Base subsurface barrier integrity demonstration are presented in Figure 5. This set of tomographs clearly shows that the barrier was leaking and localizes the leak. A subsequent excavation, shown in Figure 6, validates the conclusion that the barrier was leaking as inferred from the tomographs. These figures are not intended to prove that the technology worked, but rather to demonstrate how the technology can be used and to illustrate that it did in fact lead to the correct conclusion in this particular application. For other applications the tomographs may be more complex, requiring a skilled interpreter to explain their significance in relation to data gathered by other technologies.

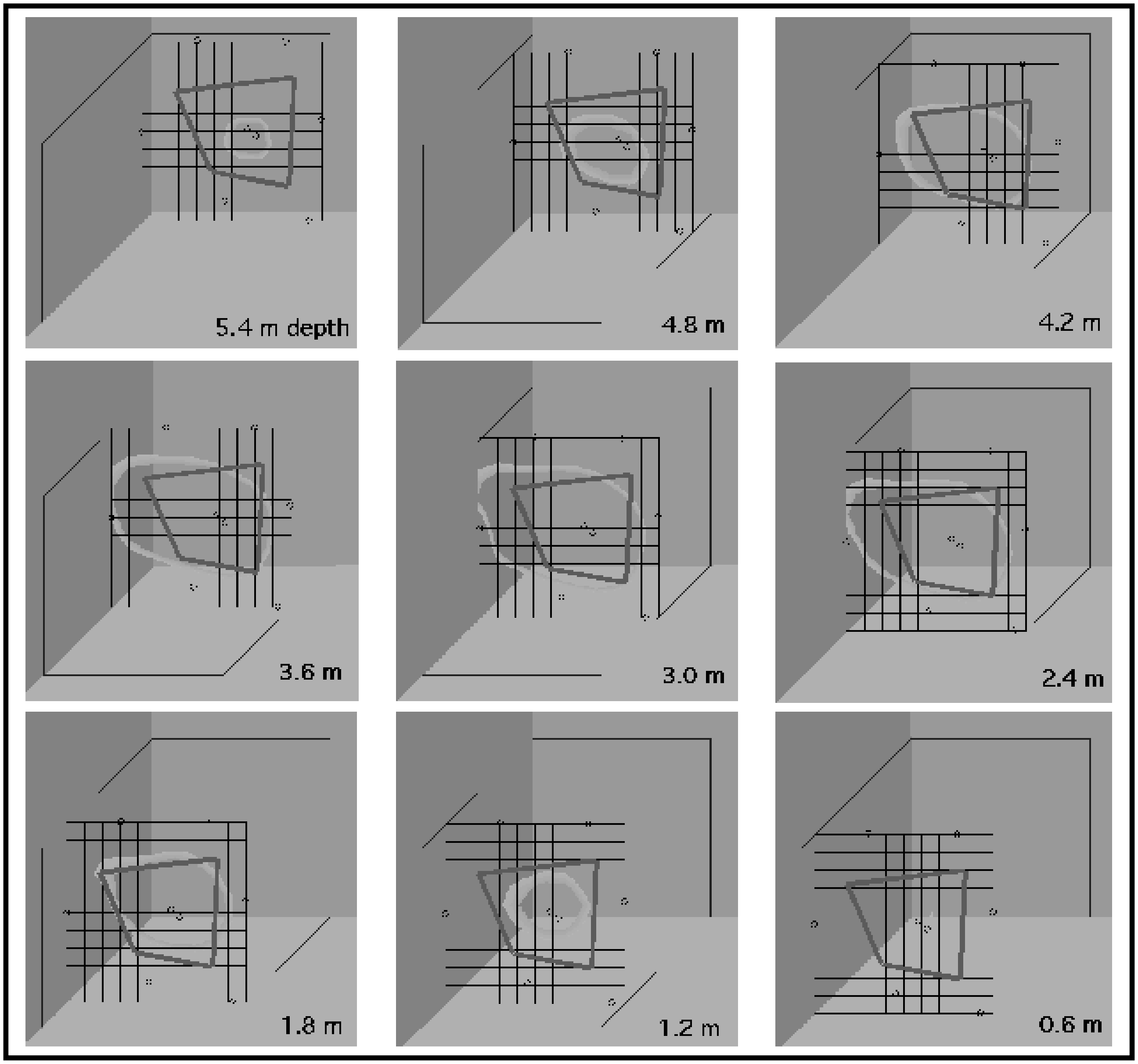

Figure 5. These cross-sections of a tomograph show the progress of a rapidly changing, electrical resistivity front (changing light shape) resulting from the movement of saltwater injected into the subsurface within a thin-wall grout barrier (unchanging dark shape). The images show the location of the resistivity front at nine depths at one point in time near the end of the full-scale demonstration at Dover Air Force Base, Delaware. The images at 2.4 to 4.2 meters in depth indicate that the barrier was breached around the center of the left corner. Excavation of that area of the barrier after the test revealed that the electrical resistance tomography images correctly showed the location of the leak. The next figure (Figure 6) shows the excavation made to verify the leak and determine its cause.

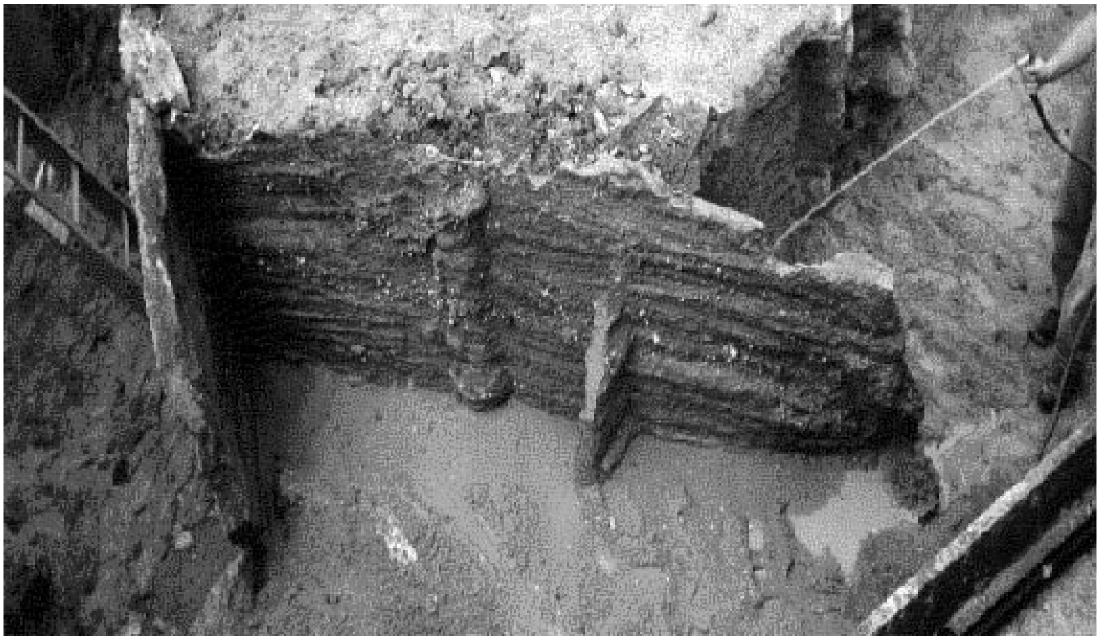

Figure 6. After examining three-dimensional ERT images at the Dover test site, a portion of a contaminant migration barrier was excavated for further evaluation. Electrical resistivity changes were imaged as salt water tracer moved through the barrier at locations later found to be defects in a wall or the joining of two walls.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

Electrical Resistance Tomography (ERT) For Subsurface Imaging produces electrical resistivity images of the subsurface. Other non-invasive geophysical technologies reveal other aspects of the subsurface. Some of these technologies are:

- Cross-Hole Radar
- Surface Radar
- Cross-Hole Seismic
- Surface Seismic
- Electrical Impedance Tomography

The above technologies are complementary to each other in the sense that each technology provides different information and has different performance properties, such as range and ease of use. These technologies can be used together with the baseline technology (conventional drilling and sampling) to characterize underground conditions.

Comparison With Baseline Technology

The baseline characterization approach relies primarily on sample collection and geophysical well logging along individual boreholes. The major technical limitation is that the samples generally provide hard data on the soil and water within only a few inches of the borehole. The major operational limitation is that the soil and water samples often need to be analyzed at off-site laboratories, and the analytical data may take a week or longer to obtain. Some geophysical well logging technologies are also limited to taking measurements that are representative of the subsurface within only a short distance of the borehole. Furthermore, running downhole geophysical logs is labor intensive.

With ERT For Subsurface Imaging, electrical resistance images of the subsurface can be produced on-site and can provide data that extends to the distance between the electrode arrays, which can be hundreds of feet apart. The major technical limitation is that other technologies are required to identify what the ERT images represent. The major operational limitation is the availability of skilled workers to install the network and interpret the results. As with the conventional approach, ERT For Subsurface Imaging requires the availability of boreholes or hydraulic push holes for most applications.

Complementary Approach

The baseline approach and ERT For Subsurface Imaging should be used together in a complementary fashion to reduce the costs and increase the efficiency of site characterization and monitoring. In a monitoring situation, ERT can efficiently and quickly detect changes in subsurface resistivity, which can then be investigated by baseline or other complementary technologies. In addition, ERT can image resistivity patterns related to geological and hydrological features.

While ERT can directly image some remediation processes by looking at changes in resistivities, it cannot identity the causes of resistivity anomalies. When the results from both ERT and the baseline approach are evaluated, inferences can be postulated on the chemical and physical nature of tomograph features. Therefore, tomographs can be used to better locate and minimize the need for more costly and environmentally invasive approaches to site characterization.

Patents/Commercialization/Sponsor

ERT technology is currently being used commercially (see page 16 for the commercial sponsors) for site characterization and remediation process monitoring. The initial deployment of ERT for monitoring tank leakage and the deployment of barrier emplacement is expected to be done by these companies with likely consultation with the LLNL principal investigators. Collaborators are testing, refining, and adapting ERT For Subsurface Imaging to meet their requirements in various applications as follows:

- Yucca Mountain Site Characterization Project - Quantitative moisture mapping in fractured hard rock.
- SteamTech - Automated, autonomous data collection and code development.
- University of Lancaster - Code development for leak detection and imaging.
- Westinghouse Hanford/Pacific Northwest National Laboratory - Vadose zone monitoring and leak detection in single shell tanks.
- U.S. Bureau of Reclamation - Characterizing earthen dams.
- California Transit Authority - Imaging of pavement structures.

U. S. Patents

- Using Electrical Resistance Tomography to Map Subsurface Temperatures, U. S. Patent No. 5346307
- Optimal Joule Heating of the Subsurface, U. S. Patent No. 5325918
- Dynamic Underground Stripping: Steam and Electric Heating for *In Situ* Decontamination of soils and Groundwater, U. S. Patent No. 5449251
- Methods for Detecting and Locating Leaks in Containment Facilities Using Electrical Potential Data and Electrical Resistance Tomographic Imaging Techniques, U. S. Patent No. 5661406
- Using Electrokinetic Phenomena and Electrical Resistance Tomography to Characterize the Movement of Subsurface Fluids, U. S. Patent No. 5495175
- Using Electrical Resistance Tomography to Map Subsurface Temperature, U. S. Patent No. 5346307

Pending U. S. Patents or In Process

- Design for Electrode Wells for Powerline Frequency Electrical Heating of Soils IL-9085
- Electrical Resistance Tomography Using Steel-Cased Boreholes as Electrodes IL-9667
- Electrical Resistance Tomography from Measurements Inside a Steel-Cased Boreholes IL-9571
- Electrokinesis Used to Stop Leaks in Geomembrane Lined Ponds and Landfills IL-9835

Commercial Sponsors

- SteamTech Environmental Services, Inc.
  1135 Terminal Way, Suite 109
  Reno, NV 89502
  (702) 329-6146/(805) 322-6478
  fax: (702) 329-6252
  Website: www.steamtech.com

- Blackhawk Geometrics
  301 Commercial Road, Suite B
  Golden, CO 80401
  (303) 278-8700
  fax: (303) 278-0789
  website: www.blackhawkgeo.com

- Applied Research Associates, Inc.
  4300 San Mateo Blvd NE, Suite A-220
  Albuquerque, NM 87110
  (505) 881-8074
  fax: (505) 883-3673
  website: www.ara.com

SECTION 5

COST

Methodology

The cost of deploying Electrical Resistance Tomography (ERT) For Subsurface Imaging, as with other site characterization and monitoring technologies, depends primarily on the nature of the site and on the mix of technologies deployed. In practice, ERT will be used in combination with other technologies, and the results of the combined approach are complementary.

Two separate cost savings analyses have been done for ERT. The difficulty in performing cost savings for many applications of ERT is that there is a lack of baseline costs. One of the largest cost savings for ERT is its use as a remediation process control, but these cost savings are associated with the overall remediation process rather than ERT itself. The cost savings analysis given later in this section was done by HAZWRAP; this analysis relates to the savings in site characterization costs using ERT. A second cost savings analysis (Appendix D) relates to locating and monitoring leakage from landfills or high-level waste tanks.

ERT has advantages that can reduce the cost of conventional site screening, site characterization, containment monitoring, remediation process monitoring, and other purposes. The cost savings are highly site dependent. Some ways in which cost savings can be realized include:

- Initial ERT surveys can delineate subsurface features or conditions that can be used to optimize the deployment design and thereby reduce the cost of fielding more expensive site characterization technologies.

- ERT can produce data on subsurface conditions at a lower cost than conventional technologies. The electrode arrays can be deployed underground as well as on the surface. The holes required for ERT arrays are generally smaller in diameter and can be more widely spaced than the holes used to accommodate conventional downhole logging and sampling technologies.

- ERT imaging provides the only means of guiding remediation operations in near real time, thereby substantially reducing remediation costs by minimizing worker downtime and unnecessary remediation of adjacent uncontaminated areas.

- ERT can provide remote, fully automatic, long-term monitoring of the subsurface and produce three-dimensional images of dynamic processes such as changes in a contaminant plume, gradual changes resulting from remediation technology applications, and monitoring contaminant barrier or waste tank integrity.

The major design considerations and variables affecting the cost of subsurface site characterization and remediation are:

- Regulatory Requirements.

- Site Geology.

- Areal Extent.

- Depth.

- Nature of Contaminant(s).

- Mix of Technologies/Methodologies.

- Safety Measures.
- Time Constraints.
- Funding Available.

The following is an example of what it might cost to purchase an ERT For Subsurface Imaging system for one-time use. The approximate costs and/or cost considerations (estimated by LLNL) for fielding an ERT network are as follows:

- The hardware costs for the data acquisition system are about $50,000.
- The cost for a powerful laptop computer to perform data inversions ranges between $3,000 to $5,000.
- The cost of licensing the data inversion algorithm is negotiated between DOE and the interested party.
- The life-cycle costs will depend on several factors, including the application of interest, frequency of use, degree of resolution desired, and flexibility to install electrode arrays in boreholes used for other types of measurements.
- It typically takes about 2 hours to install electrode arrays in each borehole or hydraulic push hole.
- Data collection times generally range between 40 minutes and 2 hours per measurement plane; this time depends on the number of electrodes installed in each borehole.
- Data processing times generally range from 20 minutes to several hours on a fast laptop computer; this time depends on several factors, including the area of the measurement plane being sampled, the number of measurements collected, and the presence of data noise.

Cost Analysis

There are many considerations involved in deciding how to cost-effectively characterize or remediate a particular site. Case studies would be needed to completely account for all of the costs involved in any individual situation. Of necessity, a generic cost comparison must be simple to scale. The following cost savings analysis was developed by HAZWRAP (DOE-OR). For purposes of the cost analysis, the assumptions used were:

- A moderate-sized site (3-4 acres).
- Fairly shallow depth to groundwater (15 to 25 feet).
- Contamination is trichloroethylene (TCE) released from an underground storage tank.
- Limited Remedial Investigation (RI) work already performed; i.e., the installation of a few monitoring wells that have detected dissolved chlorinated solvents in the water and some isolated soil samples around the tank.
- The goal is to develop detailed geology, hydrogeology, and contaminant distribution information so that an effective plan for removal of the contamination source area can be designed and implemented.

For both the conventional approach and the innovative ERT approach, boreholes are drilled to 50 feet in depth with a hollow stem auger with a split-spoon sampler. Drill cuttings are drained for disposal and tools are decontaminated between borings for both approaches. Drill holes are grouted when completed.

Conventional Close-Spaced Drilling and Sampling Without ERT

Most DOE sites currently use drilling as their baseline technology for sample collection and installation of monitoring wells. Direct push technologies exist and have been used at several DOE sites, but are unable to penetrate some difficult soils (e.g., consolidated and cobbles) and rock and are limited in the depth they can achieve in penetrable soils. The primary cost savings between the conventional approach and the ERT approach is a reduction in the number of wells needed to characterize the site geology.

For the case of a conventional borehole sampling investigation (i.e., drilling closely spaced boreholes and obtaining soil/water samples), the following assumptions were used:

- Install 15 test borings to 50 feet in depth to map the subsurface geology in enough detail to create a three-dimensional geological cross section.

- Nine of the borings are continuously sampled and the other six will be sampled every 5 feet.

Drilling two borings a day @ $1,200/day (rig and crew)	$ 9,000
Decontaminate equipment 16 hrs @ $125/hr	$ 2,000
Drums for cutting and disposal fee	$ 2,000
Grouting holes 16 hrs @ $125/hr	$ 2,000
Geologist oversight 80 hrs @ $75/hr	$ 6,000
Data interpretation 40 hrs @ $75/hr	$ 3,000
Total Cost	$24,000

Wider-Spaced Drilling and Sampling with ERT

The next investigation approach uses ERT electrode arrays placed on the surface and one array per drilled borehole to define site geology. The following assumptions were used:

- ERT is used to define site geology and hydrogeology instead of a high-density test-boring program. Consequently, only six drill borings to 50 feet in depth are needed because the ERT technique investigates a much larger area away from the boreholes.

- The ERT arrays installed in the boreholes collect electrical resistivity measurements and transmit the data into a computer for processing and data interpretation by a trained professional.

- Data interpretation simplifies the selection of sampling locations most likely to reveal soil and groundwater contaminant concentrations and reduces the number of samples to be analyzed.

- Three ERT surveys/day.

Drilling two borings a day @ $1,200/day (rig and crew)	$ 3,600
Field crew of two people for 2 days (30 hrs @ $150/hr)	$ 3,000
Decontaminate equipment 6 hrs @ $125/hr	$ 750
Drums for cutting and disposal fee	$ 800
Grouting holes 6 hrs @ $125/hr	$ 750
ERT and data display equipment	$ 2,000
Data interpretation, 10 hrs @ $75/hr	$ 750
Geologist oversight 24 hrs @ $75/hr	$ 1,800
Total Cost	$13,350

Using the assumptions noted above, the difference in cost of the ERT investigation is about $11,000 less (i.e., approximately 45% less) than the cost of the conventional investigation. Although the results obtained by each approach provide a generally equivalent level of data, the qualitative results are markedly different. While ERT can readily image relatively large subsurface areas in three-dimensions, the baseline technology can provide more specific localized characterization detail in two dimensions.

Cost Conclusions

The HAZWRAP cost savings analysis concludes that substantial savings can be realized by using ERT in several common scenarios. The cost savings will be achieved to the extent that the cost of implementing conventional technologies is avoided and the volume of soil remediated is reduced.

ERT can create subsurface images faster and at a lower cost, for an equivalent level of information, than conventional drilling, logging, sampling, and laboratory analysis. The automatic operation of ERT monitoring systems makes possible a relatively low-cost remediation-process and long-term contaminant-containment monitoring system; e.g., there are no probes to move within the boreholes (in contrast to other logging techniques).

While using ERT cannot entirely replace the conventional drilling and sampling approach, it can reduce the size of areas needing extensive penetration by identifying resistivity gradients that may define the location of contaminant fluids as well as subsurface conditions conducive to fluid migration. ERT For Subsurface Imaging can also be used as a basis for establishing remediation priorities and determining appropriate remediation strategies by delineating contaminant boundaries and subsurface conditions affecting contaminant migration.

Greater overall site characterization cost savings could occur when ERT is used in conjunction with cone penetrometer technology. The Cone Penetrometer Innovative Technology Summary Report (ITSR) contains a cost analysis of cone penetrometer technology; the Cost section of that ITSR is at the following web address: http://www.em.doe.gov/cgi-bin/parse/plumesfa/intech/conepen/cost.html. In general, while cone penetrometer holes are substantially less costly to drive than conventional boreholes, cone penetrometers have depth and soil property limitations that do not limit conventional drilling technology. In any case, ERT electrode arrays can be installed in cone penetrometer holes as well as the same holes used for conventional soil and water sampling and geophysical logging. When available, further cost reductions may be achieved by installing ERT electrode arrays in existing wells.

The mix of technologies to be employed to satisfy project objectives in the most cost-effective manner must be determined on an individual site basis.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

Currently, the U.S. Environmental Protection Agency has no system for certifying sensor technology for site characterization or monitoring. Potential worker health and safety hazards are associated with electrical, physical, and chemical hazards of electrode installation. The installation and dismantling of ERT electrode arrays may also expose workers to contaminants at some sites. Depending on site-specific conditions, regulatory considerations include:

- Site-specific regulatory/permitting issues (i.e., specific to state and local governmental authorities).

- Secondary waste stream regulatory considerations.

- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) evaluation criteria. If information has not been developed for a specific criterion, this fact should be stated. The nine CERCLA evaluation criteria are summarized below.

  —Overall protection of human health and the environment describes how existing and potential risks from pathways of concern are eliminated, reduced, or controlled through treatment, engineering controls, institutional controls, or by a combination of controls.

  —Compliance with ARARs (Applicable or Relevant and Appropriate Requirements) addresses whether an alternative meets its respective chemical-, location-, and action-specific requirements or can invoke a waiver for an ARAR.

  —Long-term effectiveness and permanence evaluates performance alternatives in protecting human health and the environment after response objectives have been met and includes magnitude of residual risk (untreated waste and treatment residuals) and adequacy and reliability of controls (engineering and institutional) used to manage untreated waste and treatment residuals over time.

  —Reduction of toxicity, mobility, or volume through treatment assesses performance of alternatives in terms of reducing toxicity, mobility, or volume through treatment and whether or not statutory preference for treatment as a principal element is satisfied.

  —Short-term effectiveness addresses the impacts of alternatives on human health and the environment during construction and implementation until response objectives are met and the length of time until protection is achieved.

  —Implementability assesses the degree of difficulty and uncertainties with undertaking specific technical and administrative steps and the availability of various services and materials.

  —Cost addresses costs of construction (capital) and necessary costs of operation and maintenance (present worth analysis assumes a 10 percent discount rate, and the periods of performance for costing purposes should not exceed 30 years).

  —State (support agency) acceptance of technical and administrative issues and concerns the support agency may have regarding each of the alternatives.

  —Community acceptance evaluates concerns the community may have for each alternative.

- For additional information on the above evaluation criteria, see the National Contingency Plan, 40 CFR 300.430(d).

Safety, Risks, Benefits, and Community Reaction

Worker Safety

Workers will be subject to the normal hazards associated with drilling into the subsurface and the installation of electrical instruments. The potential for exposure to environmental contaminants is expected to be site dependent.

Community Safety

The use of ERT to characterize and monitor the subsurface is not expected to adversely affect community safety. This technology permits onsite characterization and monitoring and, since it does not require the removal of physical soil and water samples, the potential for contaminants to be brought to the surface and leave the work site is substantially reduced. ERT is the only technology that can easily and cost-effectively monitor leakage from tanks, landfills and groundwater as well as monitor site conditions over large areas and long periods of time.

Environmental Impact

ERT will reduce the number of boreholes into the subsurface and the number of samples taken during site characterization, remediation, and post-remediation monitoring. This technology is less environmentally intrusive and is about 50 percent less likely to bring contaminants to the surface than the conventional technology.

Socioeconomic Impacts and Community Reaction

The use of ERT is not expected to result in any adverse socioeconomic impacts or community reaction. Since the technology is less environmentally intrusive than conventional technology, the community reaction to its use should be neutral to favorable. Furthermore, since the use of ERT makes possible a more accurate delineation of the area needing environmental remediation, and ERT can be used to verify the efficacy of remediation as well as monitor contaminant migration, the socioeconomic impacts and community reaction should also be favorable.

SECTION 7

LESSONS LEARNED

Implementation Considerations

ERT For Subsurface Imaging technology has advanced to the commercial application stage. It has already been deployed to monitor remedial processes. Fabricating the electrode arrays can be done inexpensively by taping the electrode pairs at the desired intervals to the supporting shaft or string. The supporting shaft or string can be whatever material is appropriate for the particular application; stainless steel is the preferred material for permanent emplacements. For deep holes, robust pieces of stainless steel are suitable for emplacement in the ground to depths of hundreds of feet. Electrode arrays can also be placed on or near the surface and still monitor the upper layers of the subsurface. The tomographs produced with the ERT technology developed by LLNL are true two- or three-dimensional images from computed tomography and not just a series of two-dimensional planes.

The LLNL-developed data acquisition system is computer-controlled and can be operated by personnel with minimal special training. Operation requires a technician to interact with the data collection system on a periodic basis to start the automatic program that performs data collection and to connect electrodes in other boreholes to the acquisition system. Further development of the LLNL data collection system will allow unattended data collection and unattended connection and disconnection of the electrodes in other boreholes. The tomographs resulting from LLNL data inversion algorithms need to be interpreted by professionals proficient in interpreting what the images mean. (An automated system that can be operated unattended is presently available commercially.)

The electrodes used are normally grouted permanently within the boreholes. These stainless-steel electrodes and attached wires can be left in the ground without harm to the environment. If electrodes are placed in radioactive soil or along a contaminated ground surface, they may need to be decontaminated upon removal.

Data inversions require the use of a fast laptop computer. Data collection times are longer than for the baseline technology (geophysical borehole logging) because more data are required.

Technology Limitations and Needs for Future Development

- ERT For Subsurface Imaging requires the emplacement of electrode arrays at the surface or in holes hydraulically pushed or drilled into a site. However, once emplaced, the electrodes can be used to continuously monitor the site for an indefinite period.

- ERT For Subsurface Imaging initially requires trained technicians to set up the electrode array network, operate the system, and interpret the images.

- ERT For Subsurface Imaging focuses upon relatively shallow features and can image small targets in this environment–even in surficial geologic units with relatively small contrasts in physical properties

- The precision of ERT images diminishes as the inverse square of the distance between electrodes.

- ERT For Subsurface Imaging can be used to evaluate the efficacy of barrier materials

- ERT For Subsurface Imaging works equally well in the vadose zone, saturated zone, unconsolidated soil, and fractured rock. The technology is near full development and is available for licensing.

Technology Selection Considerations

ERT For Subsurface Imaging provides electrical resistivity data that extends and supplements the data obtained by conventional and other site characterization and monitoring methods. The logging data and sampling analytical data obtained by the baseline technology can be used to corroborate and enhance the interpretation of ERT images. Therefore, these data provide a means to validate the corresponding ERT images. The use of both ERT and conventional logging and sampling are complementary and suitable for evaluating the subsurface of most sites.

Potential commercial applications of ERT For Subsurface Imaging include geologic mapping for the mining, petroleum, chemical, and waste management industries. It is commercially applicable for the environmental remediation applications such as monitoring soil heating, soil moisture during steam or gas injection/vacuum extraction, and aquifer perturbations during remediation activities. It can also be used for the nondestructive evaluation of large-scale structures such as dams.

APPENDIX A

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APPENDIX B

TECHNOLOGY MANAGEMENT SYSTEM DATA ELEMENTS

Technical Description

Electrical Resistance Tomography (ERT) For Subsurface Imaging can be used to produce two or three-dimensional images of electrical resistivity in the subsurface. It can be used on a scale from feet to hundreds of feet. ERT has been applied to mapping subsurface hydrogeological features including confining layers of various types. ERT has also been successfully demonstrated for use in near real-time imaging of remediation processes to provide process control. Remediation processes imaged include soil heating, pump and treat, steam injection, electrokinetics, Dynamic Underground Stripping, Hydrous Pyrolysis Oxidation and more. ERT was successfully engineered to allow rapid and inexpensive installation of electrodes with Cone Penetrometer Technology. This technology has been commercialized for site characterization and remediation process monitoring. It has been successfully deployed at DOE and commercial sites. ERT is essential for monitoring process control during steam injection to destroy all organic contaminants in the subsurface with two other LLNL-patented remediation technologies: Dynamic Underground Stripping and Hydrous Pyrolysis Oxidation. Other technologies applying ERT to other problems has been successfully demonstrated and commercialized and simply await initial implementation at a DOE site (e.g., waste tank leak monitoring and barrier installation monitoring).

Benefits

ERT can reduce the costs of site characterization by reducing the need for more costly technologies. Remediation monitoring using ERT can image in near real time processes in the subsurface such as groundwater pumping, soil heating, steam injection and simple geological features such as clay lenses and aquitards. ERT is critical as a process control for steam injection for two remediation technologies: Dynamic Underground Stripping and Hydrous Pyrolysis Oxidation (LaBrecque et al., 1996 and Ramirez et al., 1992). These technologies have shown large cost and schedule savings in remediating DOE sites.

Funding Source

This section provides cross reference information in regard to the OST Characterization, Monitoring and Sensor Technology Crosscutting Program contract established for development of Electrical Resistance Tomography For Subsurface Imaging. The U.S. Department of Energy Headquarters (DOE-HQ) Technology Management System (TMS) tracking number is provided as well as the specific Technical Task Plan.

TMS No./Title: 17 - Electrical Resistance Tomography For Subsurface Imaging

APPENDIX C

ACRONYMS AND ABBREVIATIONS

ARAR	Applicable or Relevant and Appropriate Requirements
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
DC	Direct Current
DNAPL	Dense Non-Aqueous Phase Liquids
DOE	U. S. Department of Energy
EM	DOE Office of Environmental Management
ERT	Electrical Resistance Tomography
FY	Fiscal Year
HPO	Hydrous Pyrolysis/Oxidation
HQ	DOE Headquarters
ITSR	Innovative Technology Summary Report
LLNL	Lawrence Livermore National Laboratory
NCP	National Contingency Plan
NV	DOE Nevada Operations Office
OAK	DOE Oakland Operations Office
OST	Office of Science and Technology
PCE	Perchloroethylene
RI	Limited Remedial Investigation
SCFA	Subsurface Contaminants Focus Area
TCA	Trichloroethane
TCE	Trichloroethylene
TMS	Technology Management System
TTP	Technical Task Plan
U.S.	United States of America