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Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Westinghouse
Hanford Company Richland, Washington

Management and Operations Contractor for the
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ELECTRICAL RESISTIVITY TOMOGRAPHY AT THE DOE HANFORD SITE

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ABSTRACT

Recent work at the DOE Hanford site has established the potential of applying Electrical Resistivity Tomography (ERT) for early leak detection under hazardous waste storage facilities. Several studies have been concluded to test the capabilities and limitations of ERT for two different applications. First, field experiments have been conducted to determine the utility of ERT to detect and map leaks from underground storage tanks during waste removal processes. Second, the use of ERT for long term vadose zone monitoring has been tested under different field conditions of depth, installation design, acquisition mode/equipment and infiltration chemistry. This work involves transferring the technology from Lawrence Livermore National Laboratory (LLNL) to the Resource Conservation and Recovery Act (RCRA) program at the DOE Hanford Site. This paper covers field training studies relevant to the second application for long term vadose zone monitoring.

Electrical resistivity tomography is a cross-borehole, imaging technique for mapping subsurface resistivity variations. Electrodes are placed at predetermined depths in an array of boreholes. Electrical current is introduced into one electrode pair located in one borehole while the resulting voltage change is detected between electrode pairs in other boreholes similar to a surface dipole-dipole array. These data are tomographically inverted to image temporal resistivity contrasts associated with an infiltration event. Thus a dynamic plume is spatially mapped as a function of time.

As a long-term vadose zone monitoring method, different field conditions and performance requirements exist than those for short term tank leak detection. To test ERT under these conditions, two vertical electrode arrays were constructed to a depth of 160 feet with a linear surface array between boreholes. The fielding was used to facilitate the technology transfer from LLNL to the Hanford RCRA program. Installation methods, commercial equipment and acquisition mode were evaluated to determine economic and technical feasibility to assist design of long-term monitoring networks. Preliminary results of the training test are presented.

Until recently, vadose zone monitoring techniques could provide only local point or linear coverage for leak detection and thus, are used primarily under liquid collection systems at land disposal units. As developed by LLNL, ERT can provide areal coverage under waste treatment and storage facilities given the right conditions. Advantages of ERT to groundwater protection programs are explored along with suggestions for future uses where ERT can be employed today.

INTRODUCTION

The Electrical Resistivity Technology approach relies on detection and mapping of electrical resistivity variations associated with migrating fluid. It is a geophysical imaging technique that maps liquids migrating through the subsurface. The fluid flow causes changes in the resistivity of the soil that can be detected by introducing an electrical current into the ground through an electrode or electrode pair and measuring the resulting voltage change between another electrode pair. The research and development aspects of the ERT technology are present in another paper in these proceedings (Ramirez and Daily, 1996). This paper will discuss the issues of importance in successfully transitioning ERT to an operational mode. It also describes an ongoing project to transfer ERT to DOE operations for direct application at all DOE locations. This technology transfer is funded by the RCRA program at the DOE Hanford Site to provide vadose zone monitoring for facilities where groundwater monitoring alone is not adequate.

As part of this transfer, a training exercise was conducted with a twofold objective. First, a field demonstration was designed to allow operations personnel to gain experience in all aspects of applying the ERT technology from electrode installation to data reduction. Second, the ERT technique has been developed and used primarily in a research mode since the initial fieldings (Ramirez et al., 1992; Daily et al., 1992; Daily and Ramirez, 1993). Acquisition systems and installation methods have been largely custom built by the developers. To encourage use by the commercial environmental community, standard equipment and procedures need to be available. Also for use as a routine monitoring method, different conditions of depth, installation equipment/design, acquisition mode/equipment and infiltration chemistry exist than those that apply for tank leak detection. The training exercise was used to evaluate these aspects of ERT readiness for commercialization.

The installation design and method with commercial vertical electrode arrays (VEA) and currently available tomographic acquisition equipment are presented, along with a discussion of the field results. Areas that need further development have been identified along with applications for which the technique can be immediately applied. Also shown are initial results from the infiltration test.

BACKGROUND

It is important to understand the philosophy behind vadose zone monitoring to gain a full appreciation of its value. The primary goal of any RCRA monitoring program is to prevent potable groundwater sources from becoming contaminated. However, once contamination is found by the groundwater monitoring network, the facility has been leaking for a number of years, and the drinking water quality is compromised. In the arid western states where groundwater is frequently deep, the extent of contamination may be extensive, requiring expensive, clean up operations if remediation is even possible. ERT has the potential to provide effective monitoring close to the facility in the vadose zone, thus providing an early leak detection warning system. By detecting and locating leaks early, steps can be taken to stop or mitigate contamination migration prior to degrading our drinking water supplies.

Durant et al., (1993) discusses the regulatory history of vadose zone monitoring in the RCRA program. Regulations of the U. S. Environmental Protection Agency (EPA) under RCRA have required soil-pore liquid and soil-core monitoring at hazardous waste land treatment facilities since 1980 and 1982. In fact, the original RCRA proposal in 1978 included vadose zone monitoring but was not promulgated because the applicable technologies required further development. A guidance document on design and operation of vadose zone monitoring networks was issued in 1986 to resolve technological difficulties, and in 1988 EPA proposed to require vadose zone monitoring on a case-by case basis at hazardous waste landfills, surface impoundments and waste piles. As yet this requirement has not been promulgated. From this history, it is would appear that the agency is in favor of unsaturated zone monitoring when the technologies can be demonstrated as viable.

To perform an ERT survey, a number of electrodes are placed vertically in two or more borings. Several hundred electrical resistance measurements are made between different electrodes on any two vertical arrays. Surface electrodes may also be included. The data are processed with a tomographic inversion code to produce a cross-sectional image between the borings of spatial resistivity variations monitored over time. Zones of increased saturation mark migrating liquids and appear as regions with low resistivity changes.

Field testing under various subsurface conditions of the ERT technology has been ongoing by the LLNL developers (Daily et al., 1992; Daily and Ramirez, 1993; Daily et al., 1995; Daily and Ramirez, 1995). These tests include monitoring steam floods and air stripping injection experiments plus conducting water leak tests. At the DOE Hanford Site, the ERT technique was field tested to evaluate applicability to leak detection monitoring under and around single shell tanks (SSTs) specifically and solely during sluicing operations for waste removal (Ramirez et al., 1995). As such, the tests did not address technical concerns pertaining to other uses for ERT, especially for long term monitoring and deep plume tracking.

LOCAL GEOLOGY

Training for Westinghouse Hanford Company (WHC) personnel was conducted at the 105A Mock Tank Demonstration Site on the 200 Areas Plateau in the north-central part of the DOE Hanford Site. This was the site of the processing plants that extracted high grade plutonium from irradiated fuel rods which was then used in the construction of nuclear weapons.

The subsurface geology was determined from mud logs constructed from air rotary cutting, gross gamma ray logs and neutron moisture logs. In general the 200 East Area, is underlain by an estimated 270 to 300 feet of slightly consolidated and generally uncemented gravel, sand and silt assigned to the informal Pleistocene Hanford formation.

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Two borings (B2469 and B2470) were drilled to 160 feet for the training test. An interpretation of the acquired drill cuttings indicated that a sand-dominated Hanford formation unit is present through the depth of interest. Up to 5 distinct lithologic types were identified as medium to coarse grained sands with basaltic pebbles and granules, fine to coarse grained micaceous sands, medium to coarse grained sands, granules and pebbles with silty interbeds and a coarser, pebble-rich sand with carbonate-rich silt. Fine grained carbonate beds were identified at about 15 feet and 82 feet in B2470.

In general Hanford sediments are extremely dry with moisture values as low as 4 % by volume. Calibration of the neutron moisture gauge for Hanford soils indicated in situ moisture values around 4 to 5 % with several local layers up to 10 %.

FIELD STUDY

Each phase of implementing an ERT deployment has different but important considerations. Because the goal is to make ERT available to the entire environmental community and not just to researchers, commercial equipment was employed whenever possible. This equipment is described with suggestions for changes discussed in the conclusions section.

EQUIPMENT/INSTALLATION

At present there is not a standard, economic method to emplace the VEAs for permanent installations. Previous VEAs at the test site were constructed of wire mesh soldered to electrical wiring and then attached to 1 inch PCV pipe. This results in thick bundles of wires extending from each VEA. Although this type of construction does not require expensive materials, it is labor intensive. Overall installation costs can be high when drilling and construction time are considered. For long term monitoring, electrode installations should be robust and economic. To use ERT commercially requires a standard installation design and equipment that can be varied and yet economically manufactured and easy to install.

Figure 1 shows the installation design employed for the training study. The assembly consists of downhole electrodes, an insulated cable similar to seismic land cables with standard Bendix connectors, a 1 inch PVC pipe and a 3.8 inch PVC pipe. The electrodes and cables, available commercially, were designed originally to hang is an open, fluid-filled hole and then to be retrieved and reused. Electrodes are detachable and can be replaced as needed if used in the intended manner. The 1 inch pipe conducts water to the electrodes once in place, and the 3.8 inch pipe adds stability to the assembly. It was originally planned to collect crosshole seismic data prior to infiltration, and the seismic sources are fluid coupled. Thus the 3.8 inch pipe was threaded and glued with a bottom cap to assure that it could hold water. Electrodes were located every 10 feet with 16 electrodes in each VEA. The electrodes were constructed of a single strand of stainless steel wire wrapped around a high-density polyethylene (HDPE) post. The post is encased in a HDPE shell that is mounted to the cable with a screw-on water-tight connector. The individual connections are marked on the cable to identify electrodes during testing and emplacement.

All drilling in Hanford sediments requires that a temporary steel casing be pulled behind the bit to avoid collapsing holes. The 3.8 inch and 1 inch PVC piping sections were suspended in 20 foot sections from the drill rig while the array wire was attached. The array was secured to the PVC section with cable ties, and the electrode was strapped to the casing section with several stainless steel hose clamps. Several 1/8 inch diameter holes were drilled in the one

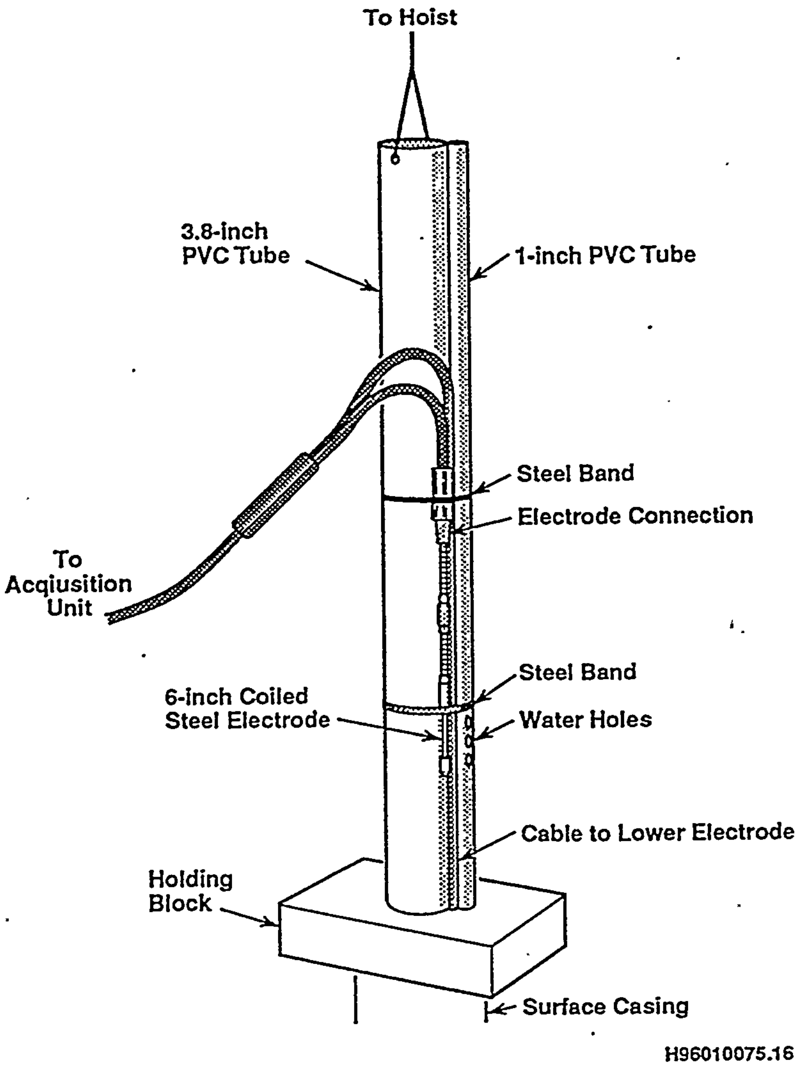

Figure 1. This schematic shows the installation configuration used for the training exercise. Each stand of 3.8 inch PVC pipe was suspended over the temporary casing as the one inch PVC pipe, electrode and cable were attached with steel bands. Holes were drilled next to the electrode to allow water to leak to the local sediments increasing electrical coupling.

inch PVC pipe next to the electrode. These holes allow the electrodes to be soaked with water to increase electrical coupling similar to wetting surface electrodes. The holes were covered with filters to avoid sediment obstruction to water flow. Once the entire assembly was in the hole, it was back filled with sieved drill cuttings producing a permanent installation. The temporary casing was pulled as the hole was filled. This operation requires some care to avoid removing the entire assembly. Although each electrode was tested for coupling with the soil as it was buried, it is not uncommon to have some nonfunctioning electrodes. Remote electrodes were places about 1600 feet out from each VEA.

The data acquisition system consists of a central transmitter and receiver with a constant output of 200 volts. The current is also constant during acquisition but can be set from 1 to 200 milliamps. Although the received voltages can be printed during acquisition, only the absolute values of the transfer resistances are saved to disk. Two scanner control boxes were used to control switching of the received signals. Up to 32 electrodes can be switched automatically. This commercially available unit has an automatic line check feature to assure connections are complete. It also has an internal algorithm that evaluates the number of array lines and poles in an array and generates the transmission and measurement schedule for acquisition. This file can be modified to meet particular circumstances.

DATA COLLECTION

Data sets were acquired between two boreholes 80 feet apart and a surface array. Each VEA had 16 electrodes spaced 10 feet apart beginning 10 feet below the surface. The infiltration point was placed half way between the VEAs with 8 surface electrodes spaced at 8 foot intervals. Remote electrodes were placed about 1600 feet from each VEA. Raw Columbia River water was infiltrated at 8 gallons per hour from August 16 to September 10. Almost 5000 gallons of water were released to the subsurface. Prior to data collection, both 3.8 PVC boreholes were filled with water to collect crosshole seismic data using fluid coupled sources. Both holes leaked, especially B2470 which rapidly lost water to 60 feet then slowly to several feet over 24 hours. At the time, it was believed that the water was leaking through the bottom.

Although previous ERT experiments employed a dipole-to-dipole method to acquire data, the commercial acquisition system was designed to use a pole-to-pole method for tomographic acquisition. The latter method was used for the training test. However, it is not clear at this time which acquisition mode is favorable. All data sets were collected with an array that required 2 1/2 hours to generate both the forward and reciprocal data sets. Every fourth electrode was used as a current electrode while voltage differences were measured at all electrodes to reduce the acquisition time.

RESULTS

From the measured transfer resistances, two dimensional tomographic inversion methods described by LaBrecque et al., (1995) were used to map the distribution of resistivity between the two boreholes. Each pixel size was 5 feet by 4 feet chosen as one half the electrode spacing. Smaller pixel sizes resulting in more nodes greatly increases computation time since the LLNL code is usually run on a workstation and not on a mainframe computor. However, this coarse grid limits the resolution of the resulting tomogram from 4 to 5 feet. It may also cause distortions in areas with high resistivity contrasts.

Cross borehole ERT is most sensitive to changes in the subsurfaces resistivity when data collected during an infiltration event are compared to data collected prior to infiltration. By differencing the two data sets, temporal and spatial resistivity changes can be mapped. The background or baseline data set acquired during the field training was collected after water leaked to subsurface through the 3.8 inch PVC pipes: Thus fluid migration was occurring when the data were acquired. Part of the training exercise was to learn not only how to operate the code but how to determine data quality and to perform noise analysis and advanced processing methods. This requires time and experience.

The baseline tomogram is shown in Figure 2 with the interpreted geologic section. The black rectangle in the top center represents the infiltration point. The geologic section from borehole B2469 is on the right while that from borehole B2470 is on the left. In general there is a fair correlation between the geology and the resistivity pattern in the tomogram. The coarser Hanford sediments correlate to the larger resistivity anomalies while the finer grained units have lower resistivity. There is a distorted zone located just under the uppermost silty carbonate bed at 15 feet. Carbonates may be very resistive up to 10,000 ohm-m, and at the Hanford Site are known to spread water laterally. Also the pixel size is too large to properly image this thin bed. The lateral extent of this bed is not known but in outcrop, these thin carbonate beds are very discontinuous. Thus the two dimensional requirement of the reconstruction algorithm may be violated contributing to the distortion.

The lower, coarse, pebbly, sand below 100 feet does not show the finer grained interbeds as a distinct unit with a lower resistivity although there is a hint of bimodel character in the slight hour-glass shape of this anomaly. Most likely these beds are masked by moisture increases caused by the water leaking from the boreholes. Absolute tomograms collected several months after infiltration ended, when sediments can be expected to have drained, show the separation into appropriate layers. All data sets collected during the controlled infiltration time period were compared to that shown in Figure 2.

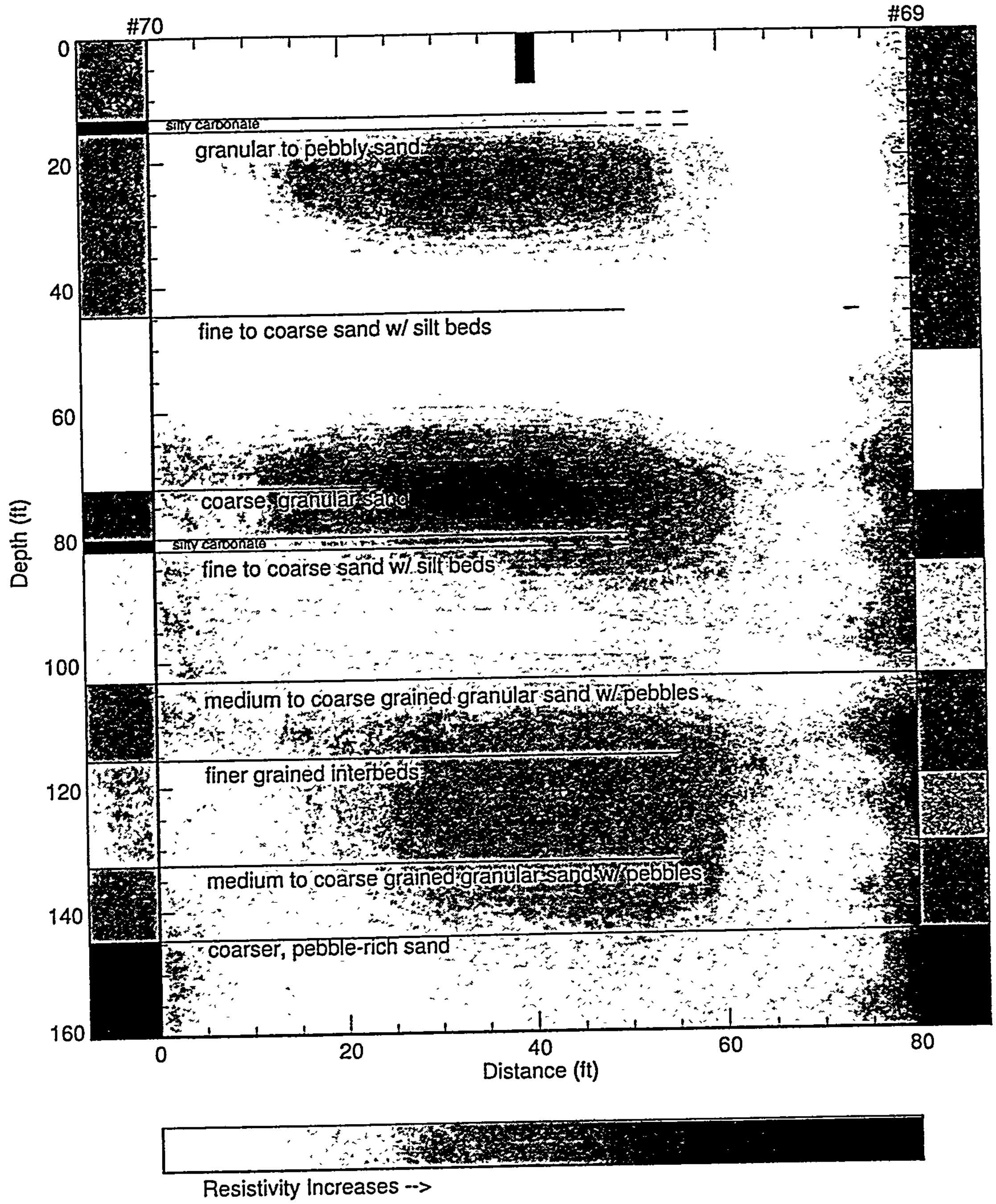

Figure 2. This baseline tomogram was acquired on August 11, 1995 after water leaked to the subsurface through the 3.8 inch PVC pipes. The scale gives absolute resistivity in ohm-m increasing towards the darker grays. The interpreted stratigraphic units at borehole #69 on the right and #70 on the left were determine from drill cuttings, gross gamma ray logs and neutron moisture logs.

Figure 3 shows percent differenced tomograms for days 8, 13, 16 and 21 after infiltration began. Only decreases in resistivity over time are displayed since these decreases correspond to saturation increases. Decreasing resistivity is shown with darker tones on the tomograms. The large, very conductive anomaly near the top of each image is the distorted region associated with the thin carbonate layer. Although advanced processing techniques may resolve this problem, this area of the images will not be included in analysis of the data at this time.

The magnitudes of the resistivity variations range from 100 to 4200 ohm-m. Although this may seem high, expected values can be estimated using the differentiated form of Archie's Law given in Daily et al., 1995. Initial in situ values of saturation were estimated from the neutron moisture logs that have been calibrated for Hanford soils. Values averaged about 5 % by volume. For an initial resistivity of 2600 ohm-m and a 2 % increase in saturation, the resulting resistivity variation is 1040 ohm-m. For the finer sands with an initial resistivity of 200 ohm-m, the estimated resistivity change is 80 ohm-m. These numbers correspond well with the observed results.

In general, the series of images over time present a complex picture of water migration in the subsurface as would be expected since there are multiple sources of water for flow. Yet the resulting tomograms give a reasonable picture of migration. As pointed out earlier, the tomograms are not well resolved above 25 feet near the infiltration point. However it can be seen that the maximum resistivity decrease for any of the days does occur in this region as expected. The other increases in saturation apart from this maximum are due primarily to water migrating through the sediments from the leaking 3.8 inch PVC pipes. The days prior to Day 8 display a similar pattern except that the lower anomaly centered at 135 feet increased in magnitude as the water collected in finer grained interbeds at that depth. As can be seen on images for Day 13 and 16, this water migrates out the bottom of the section with the resistivity anomaly decreasing in magnitude and size.

While these changes are occurring in the lower sections, saturation increases can be seen in the anomalies forming in the upper right part of the section at 20 to 40 feet. These resistivity variations form a pattern over time that suggests a flow migration path extending laterally to the end of the fine grained carbonate layer and then migrating down the right side of the section. It is possible that this carbonate layer caused lateral migration of the controlled infiltration water to the VEA holes which then provided a conduit for water to reenter the section at lower depths. The data suggest this scenario on Day 13 at a depth of 60 feet where the resistivity anomaly increases in magnitude eventually spreading again across the finer layer located at this depth. By the 21st day of infiltration, water appeared to have migrated into the finer grained interbeds in the lower coarse, granular sand bed.

Although the results present a complex pattern of resistivity decreases, this is not unexpected given the uncontrolled borehole leaks and the heterogeneous stratigraphy. If the pattern of flow can be discerned in the upper section close to the controlled infiltration point with advanced processing techniques, then a more complete picture may emerge.

CONCLUSIONS

For dry, arid regions, ERT can be very sensitive, possibly detecting saturation changes as low as a few percent by volume. This makes the potential of applying ERT for detecting or mapping small saturation changes very viable, especially at the arid DOE sites such as Rocky Flats, Sandia and Hanford. It may even be applicable to mapping fluid migration through fractured basalts at the Idaho National Engineering Laboratory. Figure 4 gives a schematic representation of the applications that the DOE community can apply with the current state of technology development. In particular, RCRA vadose zone monitoring for facilities and landfill caps is an important area for ERT users to focus since the application can be relatively straight forward and useful.

Although events prior to the training exercise resulted in uncontrolled leaks at the test site, the plume mapping abilities of the ERT technique were demonstrated. The results indicate that ERT may be successfully applied to mapping dynamic vadose plumes even without baselining in initial dry conditions. Of course, spatial saturation changes must be occurring with the temporal saturation variations resulting in both spatial and temporal resistivity variations. This may be an important assist for evaluation of a leaking facility even after the leak has occurred.

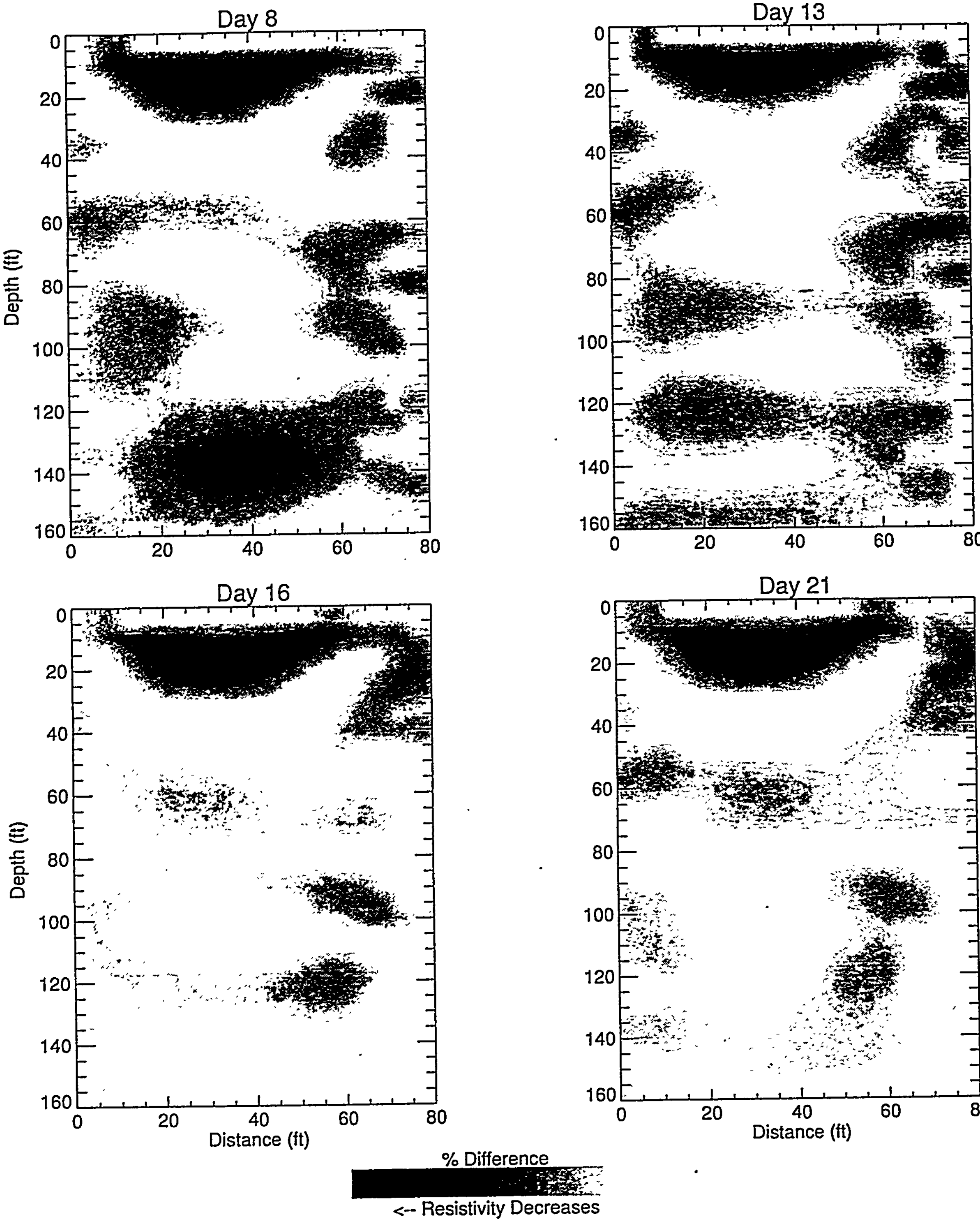

Figure 3. The 4 tomograms show percent differences between the day indicated and data collected on August 11, 1995 prior to releasing water to the subsurface. Gray areas indicate regions of increased saturation.

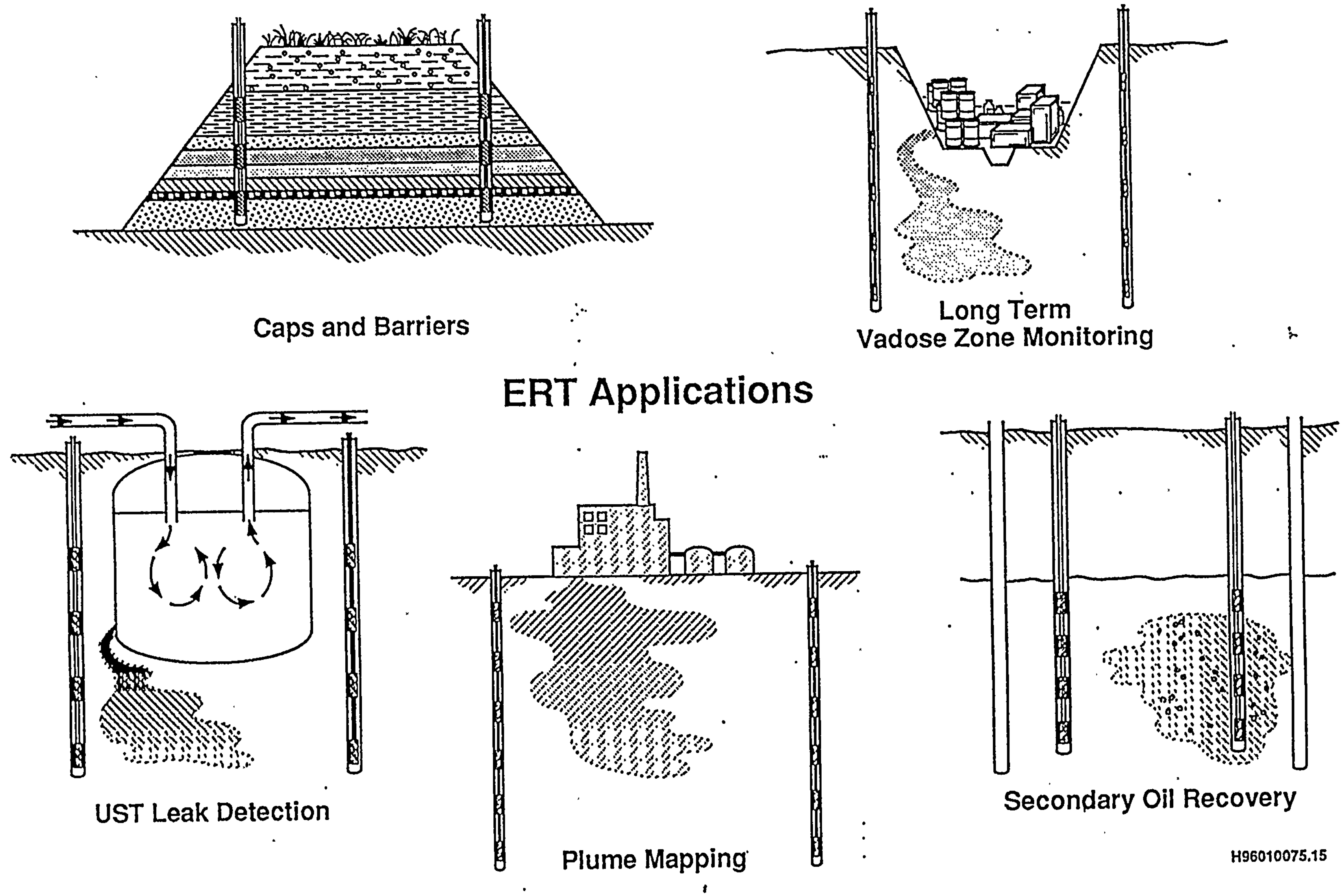

Figure 4. This schematic displays only some of the applications for the ERT technology. Of the shown applications, monitoring is the easiest to implement with the current level of technology development.

Certainly a strong need exists to have a standard, less expensive manner to emplace VEAs. For DOE sites across the country, reducing costs is a priority. For the commercial community, reducing costs is essential. Work is currently progressing on designing, building and testing a VEA that can be deployed with a cone penetrometer push rod apparatus. When development is finished, installation costs should make ERT an economic monitoring method for both DOE and commercial applications.

The commercial acquisition system used for the ERT training does not save the sign of the received transfer resistances. During the development of the ERT technique, the LLNL team has determined that important information is lost without knowledge of the appropriate sign change when attempting to image small saturation changes with respect to background noise. New ERT acquisition equipment designs should include this feature. Otherwise, when the speed of acquisition and the number of recording channels is not a priority, there are adequate acquisition systems available once the transfer resistance sign can be retained.

As with any other geophysical technique, the skill and experience of the processer should not be under rated. Therefore it will be important for clients or end users to evaluate the experience and ability of the individuals processing the data as well as the performance of the code that will be used to analyze the data. Track records will be important as the method finds a home in the commercial market.

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Recent work at the DOE Hanford site has established the potential of applying Electrical Resistivity Tomography (ERT) for early leak detection under hazardous waste storage facilities. Several studies have been concluded to test the capabilities and limitations of ERT for two different applications. First, field experiments have been conducted to determine the utility of ERT to detect and map leaks from underground storage tanks during waste removal processes. Second, the use of ERT for long term vadose zone monitoring has been tested under different field conditions of depth, installation design, acquisition mode/equipment and infiltration chemistry. This work involves transferring the technology from Lawrence Livermore National Laboratory (LLNL) to the Resource Conservation and Recovery Act (RCRA) program at the DOE Hanford Site. This paper covers field training studies relevant to the second application for long term vadose zone monitoring.