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Development of an Electrical Resistivity Imaging Program for Subsurface Characterization at Hanford

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ABSTRACT

Recent successes in subsurface plume imaging over waste storage and disposal facilities using electrical resistivity geophysics has prompted the expansion of the science into a full program for environmental characterization. Characterization using direct current electrical resistivity imaging (ERI) was first tested over liquid waste disposal trenches at the BC Cribs and Trenches (BCCT) site, south of the 200 East area of Hanford. The geophysical data were compared to borehole data with favorable conclusions. Since the initial deployment at BCCT, the method has been applied at several other facilities within the Hanford Nuclear Reservation and significant achievements have been made to solve the complex nature of the industrial environment, namely metallic infrastructure such as storage tanks, pipes, wells, and other objects that interfere with plume imaging. The solution was to directly include the infrastructure into the measurement strategy. Other achievements include placement of deep subsurface electrodes during decommissioning of small-diameter characterization boreholes, permanent electrodes on the surface to allow reoccupation for time-lapsed imaging, enhancements in computer hardware and software to solve larger problems with increased resolution, and the installation of a quality assurance program to ensure instrument and data integrity.

INTRODUCTION

The Department of Energy (DOE) has recognized the need for a comprehensive strategy to deal with environmental contamination resulting from Cold War-era production of fissile material. The need was met by creating the program office of Environmental Management (EM) in 1989 [1]. One major part of DOE-EM's strategy has been the focus on subsurface characterization to define the risks at the largest radiologically contaminated sites, of which the Hanford Site, Savannah River Site, and Idaho National Laboratory have been a few sites topping concerns [2].

Specifically, subsurface characterization became the subject of a number of programs, panels, and focus areas, including:

- Characterization, Monitoring, and Sensor Technology
- Contaminant Plume Containment and Remediation Focus Area
- Subsurface Contaminants Focus Area
- Hanford Site Groundwater/Vadose Zone Integration Project
- Committee on Subsurface Contamination at DOE Complex Sites
- The DOE Site Technology Coordination Groups
- Advanced Remediation Technologies

Each of the focus areas was established to identify particular aspects of subsurface characterization needs. The Characterization, Monitoring, and Sensor Technology (CMST), initiated immediately after the creation of EM program office, wanted technologies that characterize, monitor, and sense mobile contaminants and define mobile contaminant pathways. To accomplish this task, a thorough definition of transport properties of media, such as the continuity of clay layers or highly mobile sandy regions, was needed. A directive within this scope was given to non-intrusive and inexpensive methods. The DOE was essentially asking for improved high-resolution and surface-deployable geophysical methods to define shallow systems, but did not believe these methods currently produced satisfactory results.

Throughout the years since its creation, DOE-EM has produced other focus groups and restructuring programs to help address pressing environmental remediation and containment issues by working with research and development organizations. Site-specific programs emerged under the Groundwater/Vadose Zone Integration Project, with a plan to integrate site contractors, stakeholders, and national laboratories for rigorous technical review. The project attempted to integrate all site-wide vadose zone characterization, assessment, modeling, and monitoring. Additionally, the project developed a program to assess the cumulative long-term impact of contaminants on the local environment. Furthermore, to address critical site needs, science and technology efforts were supported by promoting field demonstration projects. One project at Hanford, for example, yielded an effective monitoring technology during tank waste retrieval based on electrical resistance monitoring using existing infrastructure [3]. The geophysical method was shown to be more effective and sensitive than other technologies.

The DOE has expended significant effort to define its needs and identify subsurface characterization solutions. Recommendations resulting from the various focus areas, committees, and panels range from detailed research to field monitoring. However, the scope of the needs determined by each of these groups is generally too broad to identify specific issues by the individual site contractors. Additionally, emerging technologies that are not well understood or documented have been marginalized, and focus has been on obtaining small incremental improvements in more traditional and well understood techniques. Regardless of these constraints, geophysical characterization and monitoring programs have emerged at the Hanford Site to solve real problems posed by the site contractors. Therefore, the objective of this paper is to demonstrate the process under which these programs[1] developed and describe the types of problems that the methods were meant to solve. The paper will also describe the evolution of the programs as the applicability of geophysics was pushed into areas previously thought to be off limits due to complexity. Lastly, the paper will show how the programs could expand even further to solve a broader class of problems that could potentially be used at other DOE sites.

BACKGROUND

The Hanford Site in eastern Washington is home to 177 underground storage tanks, which contain approximately 1.9x108 Ci in 2x105 m^3 of waste in a viscous liquid, sludge, and salt cake waste form [4]. The tanks were in use from 1943 to 1986 to store a fraction of the waste generated during the processing of uranium in one of nine reactors and the reprocessing of plutonium in one of five chemical plants [5]. The tanks are organized into tank farms; there are 18 tank farms on the Hanford Site.

Two types of tanks are on the Hanford Site: single-shelled tanks (SSTs) and double-shelled tanks (DSTs). The SSTs were in use from 1943 to 1964 and range in size from 208 m^3 to 4400 m^3. Of the 149 SSTs, 67 have been confirmed or assumed to have leaked, with approximately 3800 m^3 of liquid released to the soil [6]. To reduce the leak potential, DSTs are preferred since there are no known or assumed leaks from the DSTs.

The DOE is currently managing the waste in the SSTs by moving it to safer locations and eventually into a more secure waste form. Waste retrieval is a difficult process due to the engineering problems posed by the varied tank waste forms and the health and safety risks associated with workers. Waste retrieval methods differ by the amount of sludge and integrity of the tank. If, for example, the tank is structurally sound, the waste can be retrieved by a rapid and inexpensive method of high pressure jets and pumps. If, on the other hand, the tank is of questionable integrity, a more time consuming and expensive vacuum retrieval system in combination with a mobile retrieval system may be required [5]. On the Hanford Site, the more expensive retrieval system may be required on the 67 questionable tanks without regard to volume leaked or confirmation of leak.

Waste Site Monitoring

In support of liquid waste retrieval operations, DOE has agreed to conduct leak detection, monitoring, and mitigation (LDMM) to ensure that additional leaks to the vadose zone are minimized. To help the DOE in the LDMM program, the Pacific Northwest National Laboratory (PNNL) established the Vadose Zone Transport Field Studies [7,8] and Tank Leak Detection Demonstrations [9,10] to examine potential characterization and monitoring technologies that could be deployed in the tank farms and utilize, to the extent possible, existing infrastructure (e.g., more than 1,300 steel-cased wells). The list of candidates for initial testing in a mock tank leak injection experiment included electrical resistivity tomography (ERT), high resolution resistivity (HRR)-steel cased resistivity tomography (which was subsequently referred to as

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[1] The geophysical programs described in this paper are focused on those developed by hydroGEOPHYSICS, Inc (HGI) and strategic partners, and it is recognized by the authors that a significant amount of geophysical experiments have been conducted by other groups.

HRR-leak detection monitoring or HRR-LDM), cross-borehole radar, cross-borehole seismic, cross-borehole electromagnetic induction, and subsurface airflow and extraction.

Of the geophysical methods, it was found that those based on direct current electrical resistivity, i.e., ERT and HRR-LDM, were better suited for LDMM within the mock tank environment. Subsequent rigorous testing, including a 110-day double-blind leak injection test [3], revealed that the HRR-LDM method was capable of meeting the performance evaluation criteria for all nine valid leaks using existing infrastructure (i.e., available wells). The patented HRR-LDM process [11], could determine leak volume, leak onset, and leak cessation quite accurately based on time-series analysis of recorded transfer resistances.

The initial mock tank leak injection experiments suggested that the HRR-LDM method was superior to existing baseline monitoring using gamma and neutron logging of the steel-cased dry wells surrounding the tanks [3]. This potential superiority led to further testing of HRR-LDM by the CH2MHill Hanford Group in an actual SST farm to 1) determine the performance of the HRR-LDM system in a full-scale SST environment, 2) provide data to support developing costs assessments for deployment on other SSTs, 3) provide data to compare leak detection and monitoring performance with the current drywell logging baseline methods, 4) demonstrate that HRR-LDM data can be generated to support waste retrieval operations, and 5) provide a basis for future use of the HRR-LDM system [12].

The final leak injection test was conducted between tank S102 and S103 in the S tank farm, where a series of 10 injections of at least 3600 L were pumped into the vadose zone. The injection procedure utilized a modified steel-cased drywell to deliver an electrically conductive sodium thiosulfate solution to the base of the tank, which was designed to simulate the liquid waste during a leak. The results of the testing revealed that the HRR-LDM method is capable of detecting a leak of approximately 8000 L, 95% of the time, with less than 5% chance of false alarm, and is therefore a suitable alternative to drywell monitoring during waste retrieval [13].

Waste Site Characterization

In June 2004, ERI combined with other geophysical methods such as electromagnetics and magnetic gradiometry, was tested as a waste site characterization method [14,15]. The combined methods is referred to collectively as surface geophysical exploration (SGE). The BC Cribs and Trenches Site, located south of 200 East, has 26 waste sites (unlined trenches and cribs) that received a total of 115,000 m^3 of liquid waste, comprised mostly of sodium nitrate solution. Ionic salts such as sodium nitrate are highly electrically conductive. When these salts are introduced to sands of the Hanford formation, they produce plumes that are good targets for geophysical methods based on electrical and electromagnetic techniques. A borehole placed through the center of a trench confirmed the presence of conductive material at a depth of 25-44 meters below ground surface and the ERI characterization mapped the conductive anomaly in three-dimensional space near the borehole. The ERI characterization technique was applied to the surface only, and without the aid of infrastructure or sensors buried deeply in the subsurface. This geophysical mapping technique extended the usefulness of the borehole data by extrapolating the information away from the immediate location of the borehole.

Due to the success of the initial survey, a broader coverage of BC Cribs was initiated shortly after the completion of the initial survey [16]. The broader survey included the collection of ERI data along 45 additional lines, totaling over 24 line-kilometers of data. The ERI field data acquisition included working in areas of radiological soil contamination, while also exploring more deeply in the subsurface. The final analysis showed a spatial distribution of low resistivity (or high conductivity) values that could be correlated to the footprint of the waste trenches. It also showed that the sodium nitrate plume is likely contained within the vadose zone well above the water table. Currently, a comprehensive drilling and sampling program has been initiated to broaden the validation of the geophysics. Completion of the drilling is targeted for the end of FY08.

After showing the applicability in a relatively easy test case, the ERI technology was used to map contaminant plumes beneath waste tanks in the T Tank Farm [17]. The T Farm consists of 12 single-shell tanks with capacities of approximately 2000 m^3 and four single-shelled tanks of 2000 m^3. Several of the tanks are known or suspected leakers. The site is overlain by a distributed network of metal pipes, electrical conduit, wells, and other electrical noise sources that make resistivity methods difficult. Subsurface characterization in the single-shell tank farms has historically been performed using characterization wells to collect soil samples or perform well logging. These techniques provide localized data (~ 0.45m) around the wells. The interest in evaluating resistivity methods is that they can be used to extend the current level of understanding associated with subsurface contamination by providing spatial distributions that can be correlated with other characterization data.

Due to the complex nature of the tank farm, two deployment strategies of the resistivity method were tested. The first relied on the traditional use of surface electrodes placed along linear transects and oriented orthogonally to ensure complete coverage. The transects covered both tank areas and nearby disposal cribs and totaled approximately 12 line-kilometers. Surface resistivity was successful outside the tank farm fence over the cribs and trenches. The method was highly successful outside the farm, but was not successful through the farm. The failure was likely the result of near-surface metallic infrastructure used to transport waste from the chemical processing plants. The metal is more electrically conductive than the waste, thereby channeling current preferentially away from the contaminated soil.

The results of the surface resistivity data over the cribs showed areas of low resistivity that can be linked to past waste disposal activities. In the area over the western cribs, where approximately 1.35×10^5 m^3 of liquid waste was disposed, a large volume of soil has been affected by the waste. From the modeling, it appears that the waste has reached the water table, which can be corroborated by groundwater monitoring data.

The second deployment method used the wells within and around the tanks to map the distribution of resistivity. The wells allowed the electrical current to penetrate below the infrastructure. The direct use of site infrastructure in the resistivity measurements proved to be successful. Locations of low resistivity matched hydrologic expectations of known tank leak locations. Additionally, the method confirmed the low resistivity interpretations from the surface resistivity method over the western cribs. Lastly, the distribution of low resistivity values may have identified other areas of concern around tanks that have been previously thought of as non-leakers. These include tanks T-110 and T-112. A corroboration of other techniques capable of measuring electrical properties should be used to confirm the model results, including electromagnetic induction. These other techniques could, in theory, be used together with the DC resistivity data to help constrain the inverse model and add vertical resolution to the resistivity anomaly. At the very least, the method can help site borehole locations for a follow up comprehensive characterization through drilling.

MOVING FORWARD

A time line of electrical resistivity development projects can be seen in Figure 1. The top of the time line shows the process of development for ERI characterization and the bottom demonstrates the process for monitoring. After the leak injection testing, little has been done to advance the HRR-LDM monitoring capabilities at Hanford. However, the characterization has seen much improvement with each project, extending the capabilities of the method to obtain more robust data sets over broader areas. In the 200 West area of Hanford, for example, several tank farms have been investigated for potential leaks from unintentional (tanks) and intentional (cribs and trenches) releases of liquid inorganic waste (see Figure 2 for the waste site locations) to the vadose zone. In 200 East, three tank farms and several additional waste areas have been investigated. In each case the science of electrical resistivity geophysics, as applied to large industrial complexes, has moved forward to increase the understanding of the results in terms of current and future environmental risks. Table 1 lists all major characterization sites and the incremental improvement associated with the projects. The table also shows that a total of 91 line-kilometers of ERI data have been collected at Hanford with an aerial coverage of approximately 170 hectares.

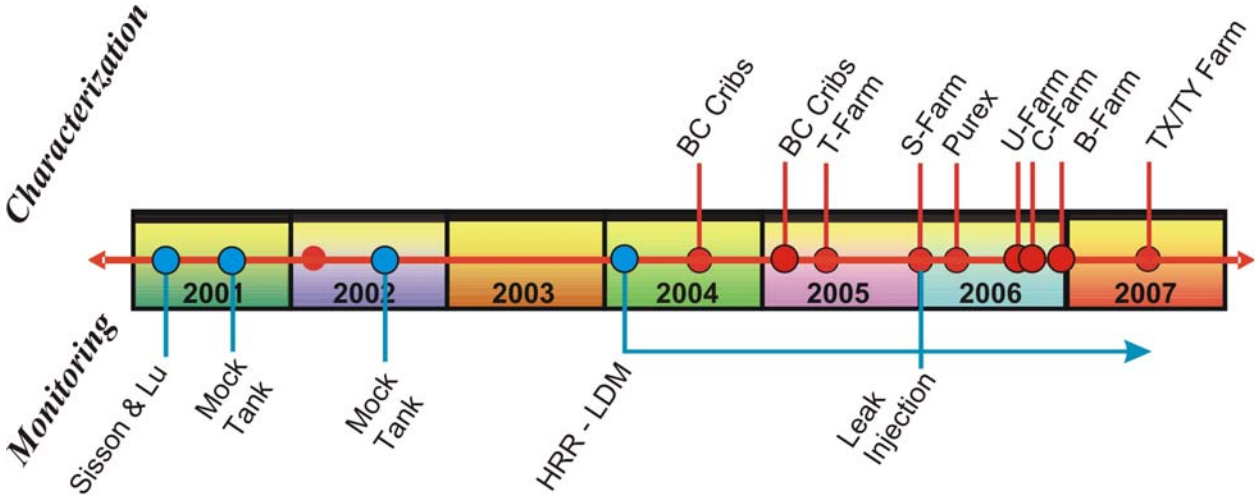

Figure 1. Time Line of Electrical Resistivity Usage at Hanford.

Table 1. Listing of ERI improvements for characterization of Hanford's waste sites.

Site Name	Date	ERI Line Coverage (km)	Wells Used for ERI	Coverage Area (hectares)	Advancement
BC Cribs FY04	July 2004	2.7	-	-	Initial ERI deployment at Hanford for characterizing a known waste site.
BC Cribs FY05	February 2005	20	-	40	Upscaling of data acquisition, logistical improvements

Site Name	Date	ERI Line Coverage (km)	Wells Used for ERI	Coverage Area (hectares)	Advancement
BC Cribs FY06	February 2006	1.7	-	-	Full 3D inversion of ERI data. Proper interpretation of many waste sites in close proximity
PUREX Plant	December 2005	2.5		9.7	Successful ERI data collection with significant infrastructure
T Farm	April 2005	12	110	23	First tank farm, logistics, involving infrastructure (i.e., wells) in data acquisition
S Farm	May 2006	4.0	42	3.6	Temporal ERI characterization of simulated tank leak. Placement of permanent electrodes
U Farm	August 2006	1.6	66	5.6	Strategic data acquisition for initial assessment
C Farm	September 2006	1.4	78	7.3	First use of buried electrodes (modified sacrificial tip from cone penetrometer)
B Complex	November 2006	20	224	40	3D and mixed array data acquisition, parallel processing of inversion code. Development of QA procedures
T Complex	September 2007	25	156	40	Testing of well-to-surface electrodes. Full production application of ERI under QA documentation. GIS data storage and retrieval.

Another main achievement of the ERI technique has been the incorporation of electrode sensors placed deeply within the subsurface. Typically, boreholes on the Hanford site are costly, and to drill a borehole for the sole purpose of resistivity electrodes makes the geophysical technique prohibitively expensive. A compromise has been the use of an electrode that is left behind following characterization using direct push techniques. Direct push is a sampling method based on established push technology, where the drill stem is pounded into the subsurface. Drill cuttings are not brought to the surface and the technique proves to be less expensive than rotary drilling. The sacrificial tip is left behind and an electrode is placed through the drill stem with a wire connection that is brought to the surface. It is then incorporated with the other surface sensors and wells during ERI measurement. The data from the deep sensor can provide higher vertical resolution than could be normally obtained from surface-only measurements. It seems to be especially useful when combining the data with the wells, as vertical information is totally lost on well-only measurements.

QUALITY ASSURANCE

Quality assurance (QA) is an important aspect to programmatic technology development for any government site. For the tank retrieval monitoring technology, the QA documentation for HRR-LDM was established as soon as the testing phase in the mock tank environment had ceased. However, only recently has the characterization technology moved beyond the test phase into an accepted technology, thereby warranting its own QA procedures and documentation. Starting with the B Complex site at the beginning of FY07, many procedures have been developed to ensure that the information prescribing layout of sensors, measurement strategies, software enhancements, and storage of data are recoverable.

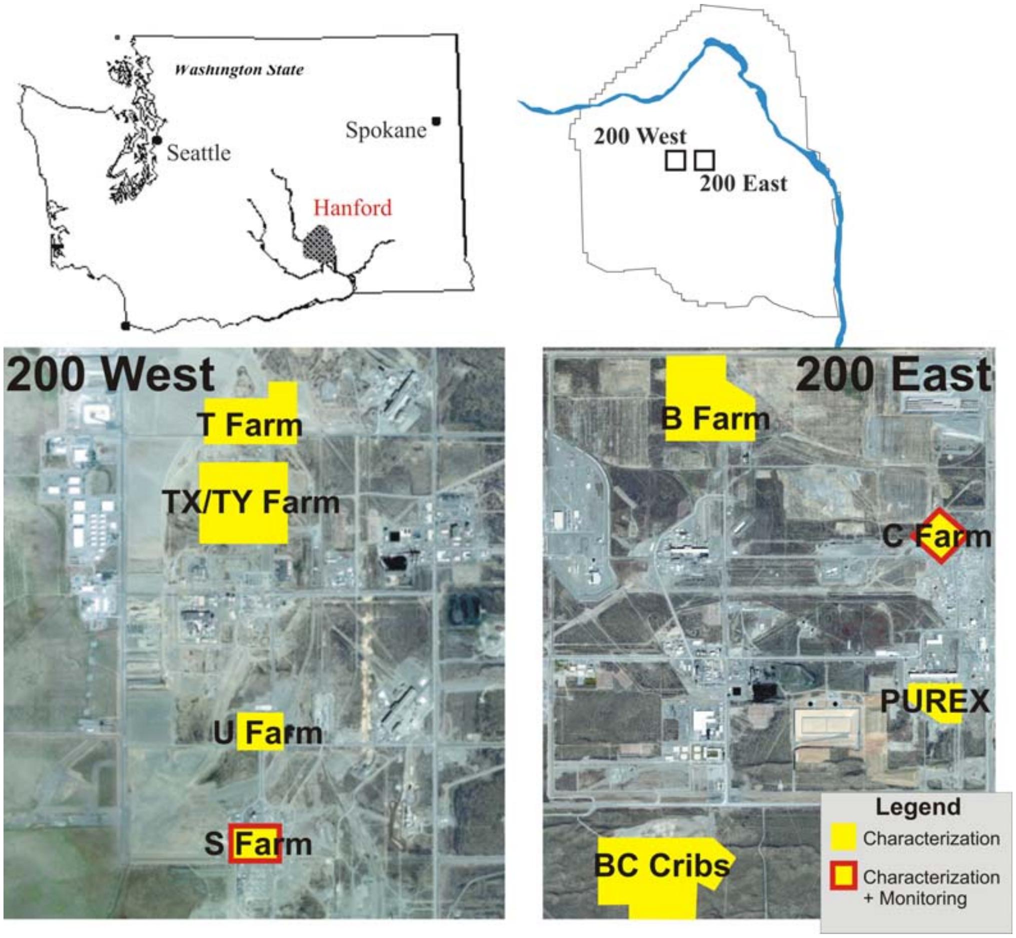

Figure 2. Locations of Resistivity Applications in the 200 Areas of Hanford.

Specifically, the collection and analysis of ERI characterization data is performed under a project specific QA plan using a graded QA approach that conforms to applicable requirements. The procedures implement the requirements of *Quality Assurance Requirements for Nuclear Facility Applications* [18] and the DOE order 414.1C *Quality Assurance* [19]. Work not covered in the QA plan conformed to accepted industry standards for geophysical methodologies and sound engineering principles.

The ERI quality assurance plan implements the criteria of DOE O 414.1C and the following requirements from ASME NQA-1:

- Organization (Requirement 1)
- Quality Assurance Program (Requirement 2)
- Instructions, Procedures, and Drawings (Requirement 5)
- Document Control (Requirement 6)
- Corrective Action (Requirement 16)
- Quality Assurance Records (Requirement 17).

In addition, a project specific software management plan was prepared to implement a graded approach to software management.

Data Collection

The setup, operation, and maintenance of the geophysical characterization equipment used in collecting and analyzing resistivity data at Hanford is described the System Design Description (SDD). This document identifies the requirements for the hardware and software used for data collection and analysis and provides a rationale for the hardware and software selected for use. It also prescribes calibration procedures

The SDD also describes the calibration requirements for the hardware used to collect geophysical data. As an example, the manufacturer (Advanced Geosciences, Inc.) of the resistivity data acquisition instrument (SuperSting R8) recommends a yearly calibration of internal calibration resistors. The calibration is performed at the manufacturer's facility and a certificate of calibration is provided. A copy of the calibration documentation, serial numbers, and expiration dates are maintained in project files. In addition, daily inspection of the receiver calibration is performed onsite using the manufacturer-supplied calibration resistor test box. The supplied test box is connected to the SuperSting R8 before commencing the daily survey. A specific calibration test firmware is provided within the SuperSting and provides the operator with a pass/fail indication for each of the 8 receiver channels. If any of the channels fail, a recalibration or repair is required.

Data Processing

Data processing is performed using a number of software packages. The requirements and responsibilities for the identification, evaluation, development, testing, and maintenance of quality affecting software acquired, developed, or modified in support of the characterization efforts are defined in the Configuration Management document. Recent addition and modification of the processing code for resistivity inverse modeling was documented in the Verification and Validation document. These recent changes to the code were necessary to analyze the entire area of interest at B Complex. Prior to B Complex, project areas were divided into smaller domains and combined in the end or visualization. The EarthImager3D resistivity inversion software was modified by restructuring the code to run on a 64-bit Windows platform using an unlimited number of processors on a multi-processor computer.

FUTURE POSSIBILITIES

In anticipation of an expanded role of ERI at Hanford, permanent electrode sensors were installed at several waste sites. Installation of permanent electrodes include the S Tank Farm, B Complex, and TX/TY Tank Farms. The permanent electrodes allow reoccupation of previously characterized locations for temporal discrimination of changes in electrical properties. The change could result from, for example, leaking tanks during waste retrieval operations or movement of waste plumes downward through the vadose zone. This new strategy would combine the roles of the two current programs of characterization and monitoring into one coherent program with a much larger scope.

To understand the magnitude of the permanent electrode strategy and the potential impact for temporal characterization at very large scales, Figure 3 shows the layout of the electrode locations at TX/TY Tank Farms. Over 5000 electrodes are currently being installed along a grid pattern that covers areas outside and inside the tank farm fence. The figure, for clarity, only shows approximately one-sixth the total number of permanent electrodes, and one can simply envision the regions between adjacent points filled in with electrodes at higher densities. The permanent electrodes offer distinct advantages over the current characterization project by providing 3D data acquisition in focused areas that may be important for retrieval or long-term monitoring of sources zones. The temporal characterization strategy could be structured in a way that allows high resolution either in time or space within regions of particular interest while other areas are sampled at lower resolution.

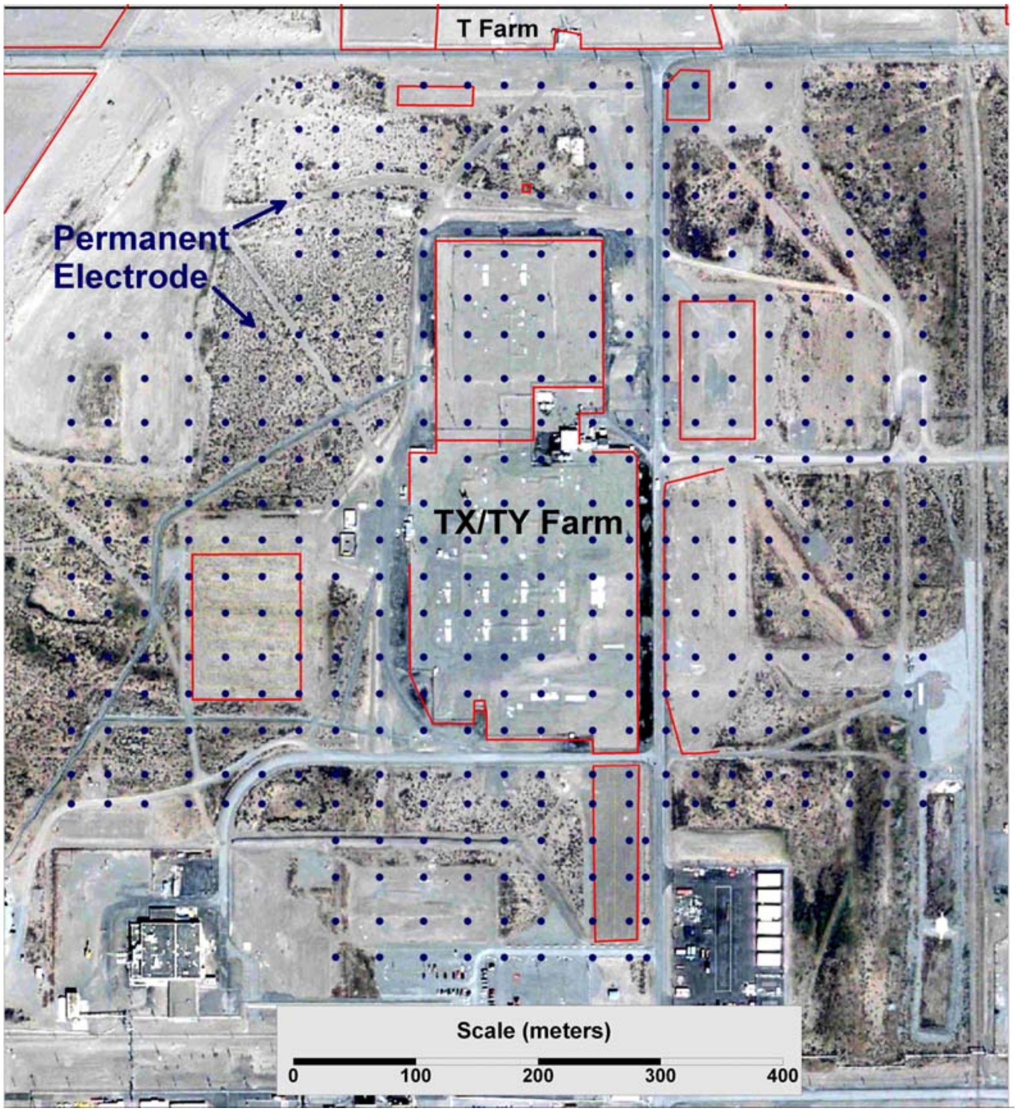

Figure 3. Permanent electrode layout at TX/TY Tank Farm, Hanford

Other DOE Sites

Several other DOE sites offer suitable environments for ERI characterization. These sites were identified by their similarity to Hanford in regards to the type of liquid waste released to the vadose zone and in sufficient quantities to provide contrasts in electrical properties relative to the background. At Los Alamos, the canyons and mesas offer an opportunity to help identify the footprint, source, and potential pathways of plumes resulting from disposal activities. The subsurface disposal area at INL may also prove to be an area suited for geophysical characterization. The Savannah River Site has several aging tank farms and the ERI technology could determine which tanks are of the highest integrity.

CONCLUSIONS

The electrical resistivity geophysical method has been applied in a number of applications at the Hanford Site to solve challenging problems in both characterization and monitoring. The imaging technique has extended the usefulness of the borehole sampling program by extrapolating the information away from the immediacy of the hole. The technology has gone through a maturity, from simple usage and testing to determine applicability to a full development of QA procedures. During this time, the resistivity method has been able to expand its role at Hanford due to the progressive nature by which it is applied. By incorporating metallic infrastructure into its measurement strategy for both characterization and monitoring, the method has overcome limitations set forth in other technologies. Other advancements in geophysical measurements, including the addition of deep subsurface electrodes from modified cone penetrometer tips, installation of permanent electrodes, redesigned software to model multi-farm characterization projects approximately one square kilometer in size, have shown that resistivity can adapt to many other potential limitations. The adaptation may prove useful if it is determined by site contractors at other DOE sites that ERI should be tested for a host of other problems.

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