ESTCP
Cost and Performance Report

Electromagnetic Surveys for 3-D Imaging of Subsurface Contaminants

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ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

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LIST OF ACRONYMS

1,2-DCE	1,2- dichloroethylene
3-D	three-dimensional
A	amperes
AFB	Air Force Base
AWAC	Airborne Warning and Control System
bgs	below ground surface
BRAC	Base Realignment and Closure
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CPT	cone penetrometer testing
CVOC	chlorinated volatile organic compounds
DCA	di-chloroacetic acid
DCE	1,1 dichloroethane
DNAPL	Dense Non-Aqueous Phase Liquid
DOD	Department of Defense
EM	electromagnetic
EOL	Electromagnetic Offset Log
EPA	Environmental Protection Agency
ESOH	Environment Safety and Occupational Health
ESTCP	Environmental Security Technology Certification Program
ESTRG	Environmental Security Technology Requirements Group
FID	flame ionization detector
ft	feet
GC/MS	gas chromatography/mass spectrometry
GP	Geoprobe®- installed microwell
Hz	Hertz
IDL	instrument detection limit
IDW	investigation derived wastes
LNAPL	light non-aqueous phase liquid
mA	milliamps
MCL	maximum contaminant limits
mL	milliliters
mV	millivolts
NA	not applicable

LIST OF ACRONYMS

NADEP	Naval Air Depot
NAS	Naval Air Station
NAPL	non-aqueous phase liquid
ND	not detected
NFESC	Naval Facilities Engineering Service Center
O&M	operation and maintenance
ohm-m	ohm-meters
PCE	tetrachloroethylene
ppb	parts per billion
ppm	parts per million
PVC	polyvinyl chloride
QA/QC	Quality Assurance and Quality Control
RCRA	Resource Conservation and Recovery Act
RHOA	resistivity horizontal affect
ROD	Record of Decision
SCAPS	Site Characterization and Analysis Penetrometer System
TCA	1,1,1-Trichloroethane
TCE	Trichloroethylene
TPH	total petroleum hydrocarbon
U of M	University of Missouri, Center for Environmental Technology
UST	underground storage tank
VOA	volatile organic analysis
VOC	volatile organic compound

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- Mr. Scott Wright from the Naval Facilities Engineering Service Center (NFESC)
- Mr. Tom Maxwell from GEHM Environmental Corporation
- Dr. Lee Peyton from the Center for Environmental Technology
- Mr. Ken Spielman from Alameda Point
- Mrs. Sara Sayler from Tinker AFB

1.0 EXECUTIVE SUMMARY

This report presents cost and performance data for a demonstration sponsored and funded by the Department of Defense's (DoD) Environmental Security Technology Certification Program (ESTCP). GEHM Environmental Corporation and the Center for Environmental Technology at the University of Missouri (Columbia) were contracted by the Naval Facilities Engineering Service Center (NFESC) to investigate the use of quasi-static electromagnetic (EM) resistivity surveys to detect dense non-aqueous phase liquid (DNAPL) contamination in the subsurface at two U.S. DoD installations. This EM resistivity survey technique is a surface to borehole geophysical method that generates a three-dimensional (3-D) image of subsurface features based on their contrasting resistive properties.

The two sites selected were the former Naval Air Station Alameda, renamed Alameda Point, and Tinker Air Force Base. They were selected for this pilot study on the basis of having a previously well-documented DNAPL problem, and the fact that they reside in two distinctly different types of geologic settings. These sites also have typical limitations with respect to drilling restrictions and with respect to the high degree of uncertainty in knowing where free-phase DNAPL currently occurs in the subsurface. Alameda Point's subsurface consists of saturated unconsolidated clastic sediments, while Tinker AFB consists of interbedded sands and shales.

The primary objective of this investigation was to verify that the EM technique could consistently, rapidly and accurately perform high resolution site characterization and DNAPL source delineation. By having a more thorough understanding of the subsurface conditions, monitoring wells can be located and screened at the most effective interval for evaluating DNAPL presence. Recovery wells can be located and screened for optimum free-product removal. Given significant improvements in the performance of these wells, lended by successfully applying this method, substantially fewer wells and sample analyses would be required for a given site, and greater quantities of free-phase DNAPL could be removed more quickly and economically.

The project goal involved successfully predicting the location and extent of subsurface anomalies of suspected DNAPL contamination with the EM technique. However, because all geophysically based subsurface characterizations carry uncertainty, the 3-D EM resistivity method must be accompanied with drilling and sampling to ground-truth the occurrence of DNAPL. As a result, after the geophysical predictions were made, validation drilling and sampling was conducted to verify the presence of DNAPL, thus indicating the accuracy of 3-D EM characterization.

The EM technique images highly resistive fluids and materials, and requires chemical analysis of physical samples to verify subsurface contamination. The verification process is accomplished after acquiring, processing and analyzing the EM resistivity data and generating 3-D computer models of suspected areas of hydrocarbon contamination. A cone-penetrometer truck or drilling rig then samples the subsurface soil to confirm that high concentrations of DNAPL are present in the subsurface. The borehole results are thus used to validate the EM geophysical model. Although one objective of any geophysical survey is to provide the type of subsurface information that is derived from drilling holes, some variation between these methods is expected and they seldom agree completely.

A number of data anomalies were selected as targets for evaluation by conventional drilling and sampling techniques. Groundwater samples were collected and analyzed for the presence of volatile organic compounds (VOCs). DNAPL was considered to be present in the groundwater at a site if the solubility of a groundwater sample met or exceeded 10 percent of the solubility limit for any DNAPL constituent thought to be present.

The results from the two study sites indicate that EM survey techniques do not adequately predict where significant subsurface DNAPL is located. Results from Tinker AFB indicated that only groundwater results matched EM predictions. At Alameda Point, an alarming number of "false-negative" findings were discovered. That is, EOL imaging reported little to no concentrations of DNAPL in specific areas. However, later subsurface investigations using laser-induced fluorescence and video microscopic methods revealed significant quantities of mixed NAPLs in these same studied areas. A possible source of error that may have led to these discrepancies was a result of the level of subsurface DNAPL being too diffuse to significantly alter the resistivity of the sediments. Due to the inconsistent results of this project, this technology has not demonstrated the required performance capabilities enabling it to be compared to the more conventional methods currently used to characterize DNAPL sites.

This study clearly shows that EM technology will not successfully detect low concentrations of DNAPL in soil and sediments. Based on the results of the demonstration, it appears doubtful, given the types of conditions that DNAPL are thought to typically accumulate and reside in the subsurface (e.g., in small, scattered pools and ganglia), whether the EM resistivity method can distinguish between aqueous media and the DNAPLs and/or their dissolved-phase constituents.

The estimated survey costs to perform an EM resistivity survey over one acre at Alameda Point and Tinker AFB were $154,209 and $134,262, respectively. It is important to note that, project costing for the EOL technology is very site-specific and depends on a number of variables such as: depth of contamination; site interference due to traffic, buildings, and surface covering; quantity of drilling and sampling required to adequately evaluate the presence of DNAPL; local market conditions and rates; and the availability and quality of site-specific pre-survey information. However, the EOL technology does have the benefit of seeing increased cost effectiveness with larger surveyed areas. Contributing cost factors to a typical EM survey include site review, mobilization, EM resistivity well installation, data acquisition, data processing, survey verification boring and sampling, and data display and reporting. Since the results of this technology demonstration were inconclusive with respect to the direct detection of DNAPL, a detailed and accurate cost comparison and/or relation between alternative characterization technologies was difficult to present.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY BACKGROUND

This report describes a demonstration sponsored and funded by the DoD's Environmental Security Technology Certification Program (ESTCP). The following demonstration investigated the use of quasi-static EM resistivity surveys to detect and generate 3-D images of subsurface DNAPL contamination. This EM resistivity survey technique is a surface to borehole geophysical method that generates a 3-D image of DNAPL-contaminated subsurface zones based on their high resistive properties as contrasted with non-contaminated subsurface soil, rock and groundwater.

GEHM Environmental Corporation and the Center for Environmental Technology at the University of Missouri contracted with the Naval Facilities Engineering Service Center (NFESC) under Contract Number N47408-97-C0213 to conduct the 3-D EM survey application at two DoD installations known to have subsurface DNAPL contamination. The objective of this demonstration was to prove that the EM survey technique could be a viable method to consistently, rapidly, and accurately perform high resolution DNAPL source delineation and significantly assist in the direct remediation of source zone contamination.

The challenges of site characterization and remediation are further complicated by the presence of DNAPLs. The complex nature of DNAPL transport and fate often inhibits its detection by direct methods, leading to incomplete site assessments and sub-optimal remedial design. High specific gravity, low viscosity, and very low solubility in water characterize these separate-phase hydrocarbon liquids which sink to the bottom of aquifers. The movement of free-phase DNAPL is strongly dependent upon the subsurface stratigraphy, particularly the distribution of zones of high permeability, such as faults, bedding planes, and sand channels, which act as preferential pathways for DNAPL migration.

Usually, most of the contaminant mass at a DNAPL site is centered in the source zone. In addition, DNAPLs undergo only limited degradation in the subsurface, and persist for long periods while slowly releasing soluble organic constituents to groundwater through dissolution. As a result, the trapped DNAPL that remains in the soil/aquifer matrix acts as a continuing source of dissolved contaminants to the groundwater. Because of this, it is necessary that the contaminant mass be removed from the source zone in order to restore the aquifer to drinking water standards. Unfortunately, conventional methods such as drilling and sampling do not accurately characterize the heterogeneities through which DNAPL may migrate; nor have conventional aquifer remediation approaches, such as pump-and-treat, removed more than a small fraction of trapped residual DNAPL (Pankow and Cherry, 1996).

2.2 THEORY OF OPERATION

The quasi-static EM resistivity survey is a surface source to an in-hole receiver geophysical technique used to generate 3-D images of subsurface features by measuring variations in resistivity within a medium. For example, all free hydrocarbons are highly resistive while subsurface waters are much lower in resistivity. By measuring resistivity contrasts within the subsurface, one can predict the presence of hydrocarbon plumes. The resistivities are displayed and visualized in three dimensions to give interpreters a "CAT Scan" type of image of the subsurface.

This technology has been used successfully in exploration of natural resources (i.e., mining, oil and gas, subsurface freshwater) since the 1960s (Pritchard, 1995; Maxwell, 1995). Recent advances in instrumentation have enabled this technique to be used in relatively shallow applications. Presently, Electromagnetic Offset Log (EOL) models cannot be used to document soil and water contamination, as a stand-alone process. The EOL process merely images highly resistive and low resistive features related to fluids and materials. The results of the EOL project must undergo a comparative analysis with existing truth data (i.e., soil chemical data) and with post-EOL process data. However, the amount of post-EOL truth data that is required will always be much less than that which would be required if EOL was not performed. The objective of an EOL site survey is to provide on-site program managers with a quicker, and much less expensive depiction of the vertical and horizontal extent of a contaminated plume.

The presence of fuel contamination in the subsurface produces high resistivity anomalies due to the presence of high resistive hydrocarbon molecules. The 3-D image in Figure 1 shows high resistive regions detected beneath a fuel pipeline. These regions are likely to contain hydrocarbon contamination.

A minimum resistivity contrast of 1.5 is required to distinguish between different subsurface features. DNAPLs and LNAPLs have resistivity properties exceeding 1 x 10^6 ohm-meters. The following table lists resistivity values, in ohm-meters, for various saturated lithological materials. Vadose zone (unsaturated) soils have resistivities that are 10-50 times the resistivity of saturated soil.

Saturated Soil	Ohm-Meter	Saturated Rock	Ohm-Meter
clay/mud	2-5	Shale	1-10
silt	5-20	Sandstone	10-50
sand	10-50	Volcanic rock	100-500
gravel	20-50	Metamorphic rock	300-1,000
		limestone	50-10,000

The process of conducting a 3-D EM resistivity survey consists of the following steps:

- Conduct a complete review of all available geologic/hydrogeologic information and site specific sources of DNAPL contamination, as well as sources of cultural and electrical noise.
- Install two or more instrumentation wells to allow redundant signal paths and to ensure good data quality. Installation consists of constructing wells with 2-inch polyvinyl chloride (PVC) casing. Due to physical limitation, maximum well depth cannot exceed 300 feet.
- Place an EM receiver sensor in the instrumentation well.
- Induce a magnetic field into the earth at points located around the well.
- Record the EM signal at the sensor. These data can produce a cross-sectional view of the subsurface between the sensor and the point of induction. For each point, the sensor is positioned at 0.1 foot increments from the bottom of the well up to ground level. As the point and sensor are moved, a 3-D matrix of data is generated of the EM intensity.
- Process the data and generate a 3-D representation of relative resistance.
- Locate the subsurface DNAPL contamination by identifying localized regions of increased relative resistivity (a resistive anomaly).

- Identify stratigraphic features by differentiating zones of smaller systematic resistivity differences.
- Collect three physical samples of media (low, medium, and high contamination predictions) for ground truth. Verification samples are collected by the technology demonstrators after each prediction.

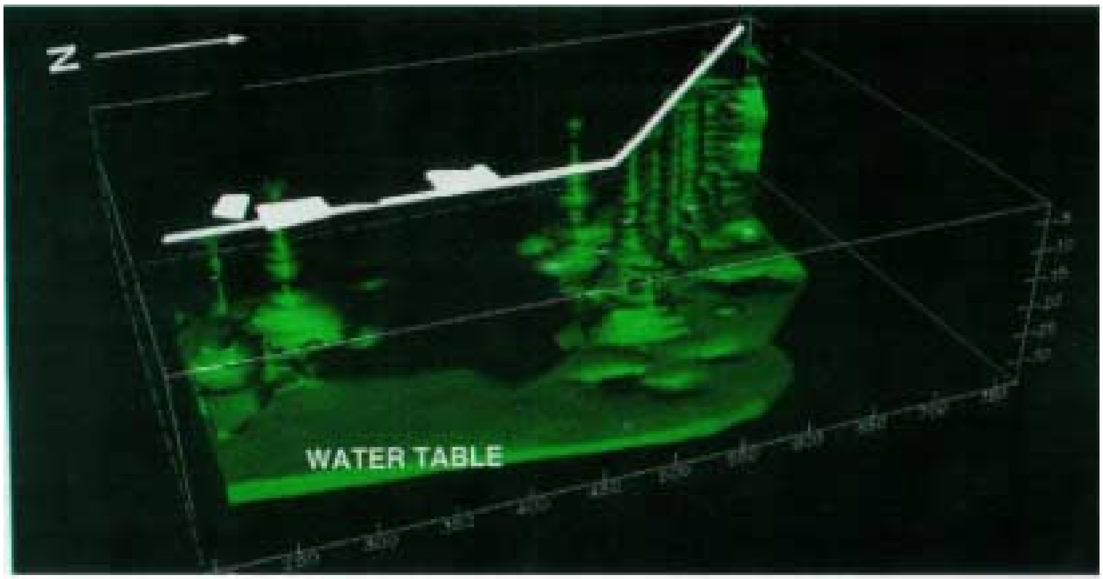

Figure 1. West Texas Pipeline Area High Resistivity Anomalies in the Vadose Zone and at the Water Table.

The primary electromagnetic field consists of a large, long wavelength signal (1,400 amp-meter^2 EM moment at the surface, 263 hertz (Hz)). The primary signal response is strongly influenced by regions of very high resistivity. Superimposed on this primary source signal response are the much smaller amplitude signal responses from the secondary subsurface currents, which are generated at the boundaries and within the bodies of resistivity change. The primary and secondary fields are converted to apparent resistivity (from voltage to ohm-meters) to identify the presence of highly resistive anomalies (i.e., contamination) and the physical properties in the earth, respectively.

The transmitter coil and receiver are tuned to a narrow bandwidth of 263 Hz. This tuning procedure, along with optimizing receiver well locations based on low noise levels, is designed to filter out electrical noise. This allows the EM resistivity surveys to be conducted in and around man-made structures and other sources of electrical noise.

Other potential noise generators such as buried man-made objects, the locations of which are often unknown, produce unwanted secondary currents and an undefined attenuation of the amplitude in the expected primary field strength; an effect known as “amplitude static”. The shape of the signal’s amplitude from a metal object often helps an analyst to identify and eliminate its effect. Without careful consideration, the secondary current depths of such metal features become depths of no-record, and these volumes are omitted from the processed data. However, the zones below often provide valid data, and are included in the survey results.

Naturally occurring subsurface ferro-magnetic materials do not impact measurable resistivity changes, and do not affect this technology. Also, since the instrumentation is located either down-hole or in a sheltered enclosure, weather conditions do not affect the data collection process. Fieldwork is stopped during electrical storms.

The resolution of the survey data can vary depending on the transmitter location grid spacing. For surface grid spacings of 20 feet, the survey results are typically accurate to within 2 feet vertically and 10 feet laterally. Although its location may not be finely resolved, a film of free-product contamination can be detected with this EM resistivity technique (Pritchard, 1995).

Each survey and analysis is based on tens of thousands of sampled data points. The processed data can be presented either in three dimensions or as depth-specific slice and cross-section images. Contours of relative resistivity in either of these formats can be developed and used to track the resistivity patterns of the soils or other near-surface materials. Higher contaminant concentrations will be represented by higher resistivity values. This relationship is not always linear, however, due to unrelated changes in geology within a contaminated area that may also impact resistivity readings

2.3 ADVANTAGES AND LIMITATIONS OF EM SURVEYS

2.3.1 Advantages

The data collection process for EM resistivity surveys is only slightly invasive. Hence, site characterizations can be accomplished at high traffic and inaccessible areas with little or no impact to the site activities.

This EM resistivity method may provide detailed 3-D images of subsurface hydrocarbon contamination and geologic features. The accurate imaging of subsurface site contamination enables focused subsurface source zone remediation. The direct treatment of the contaminant source zone is significantly more effective than the current methods of treating or containing the dissolved constituents generated by the source zone.

Accurate subsurface images provide a more thorough understanding of the subsurface environment, so that monitoring wells can be located and screened at the most effective interval for evaluating DNAPL presence. In turn, recovery wells can be located and screened for optimum product removal. With such significant improvements in recovery well installation and performance, substantially fewer wells are required to remove the DNAPL at a site.

2.3.2 Limitations

The 3-D EM resistivity method is not a stand-alone means of effective site characterization. This technique is interpretative, as it images any highly resistive fluids and materials in the subsurface. It requires confirmatory (validation) sampling and chemical analyses to verify that subsurface contamination is present. The validation process is accomplished after acquiring, processing and analyzing the EM resistivity data and generating 3-D computer models and images of suspected areas having contamination. A drilling or cone penetrometer testing (CPT) rig advances soil borings in the surveyed areas believed to have high concentrations of DNAPL in the subsurface. The bore hole results are used as truth data for comparative analysis of the EM geophysical model. Although the objective of any geophysical survey is to provide information similar to that from drill holes, some variation is expected and they seldom agree completely.

The survey area is limited to a radius of approximately 300 feet around each instrumentation well, so that a survey encompasses a circular area that is about 1.6 acres in size. Hence, the "general" location of a suspected surface source is needed to focus the EM resistivity survey. The depths imaged by this EM resistivity survey are constrained to that of the instrumentation well, which can reach a maximum depth of approximately 300 feet. Hence, the maximum depth of interest needs to be identified before starting the survey, or known to be no more than 300 ft. bgs.

There has also been some concern regarding the technology's capability to detect DNAPL configurations, e.g. residual globules, ganglia, and small pools, that are potentially out-of-range of the instrument's spatial resolution. This is believed to be a significant source of error when delineating areas with low levels of DNAPL saturation.

There are certain types of settings where data collection is not possible. For example, an EM resistivity transmitter coil is not effective when situated too close to a large metal object (e.g., a dumpster), or when it is located adjacent to railroad tracks. In these situations, the transmitter coil must be relocated to a more effective position to enable quality data collection.

The companies that provide EM resistivity surveys are very limited in number. The personnel that design the survey and collect resistivity data in the field must have a strong understanding of the technology to ensure that high quality data is obtained. Personnel interpreting survey results must be very experienced and must understand how certain resistivity anomalies relate to site-specific geologic features.

2.4 TECHNOLOGY SPECIFICATIONS

2.4.1 Contaminants

This project was directed towards locating subsurface DNAPL contamination source zones. Of particular interest are TCA, TCE, DCA, DCE, 1,2 DCE, PCE, chloroethane, and vinyl chloride compounds. For the validation effort, an analytical result of a target sample was considered a positive DNAPL presence if the cumulative level of contamination in a sample, or Σ[DNAPL constituents], was at least 10% of the free-phase solubility of the contaminant TCE. Therefore, since TCE = 1,100 mg/L (Pankow & Cherry, 1996) the presence of DNAPL was indicated by a concentration greater than or equal to 110 mg/L (ppm). For example, an analytical result of 30 ppm TCE and 80 ppm TCA would indicate the presence of DNAPL. An analytical result was considered a negative DNAPL result if: 1) the cumulative concentration of the DNAPL constituents was less than 110 ppm; or 2) none of the constituent concentrations exceeded their maximum contaminant limits (MCLs) as established by the EPA.

2.4.2 Process Waste

There was no process waste generated during EM resistivity data collection. IDW consisted of the washdown water used to decontaminate the well drilling equipment, the Geoprobe® and SCAPS probes, and the samplers after use, as well as the cuttings generated from drilling the receiver wells.

All IDW was contained in 55-gallon drums and was disposed of in accordance with RCRA regulations.

2.4.3 Reliability

Equipment necessary to collect and store 3-D EM resistivity data is designed for field use. If an equipment failure were to occur, the failed component could be replaced within 24 hours.

2.4.4 Ease of Use

The use of this EM resistivity equipment requires three qualified individuals. The actual operation is typically facilitated by a source operator who moves the transmitter coil from grid point to grid point to allow for the flux to be generated in the subsurface below the grid point. A second individual, the recording engineer, located in the vicinity of the receiving well some distance from the transmitter, performs the collection and logging of the data from the grid point. Both functions are essentially trouble-free once up and running, and can be configured in a variety of ways to accomplish the logging for a particular site. The EOL data interpretative analysis is performed by a third, highly qualified geophysicist with considerable experience in reviewing geological/hydrogeological information and interpreting and modeling EM resistivity data.

2.4.5 Versatility

This method could be used for imaging subsurface components with high resistive characteristics as well as imaging subsurface stratigraphic features. Additionally, it could be used for remediation monitoring and post-remediation verification. Other features that make this technique extremely versatile are: it is nonintrusive except for one or two borings which must be drilled in noncontaminated areas; it greatly reduces the amount of drilling and sampling; it is less disruptive; and, it can be performed in most structures and over most surfaces.

2.4.6 Maintenance

For the most part, very little maintenance is required for the operation of the EOL technology. Most of the field components rely on solid-state electrical equipment that is durable and trouble-free. Some of the surveying components are disposable and easily replaceable. All of the equipment is continually monitored for optimum performance.

2.5 MOBILIZATION, OPERATION, AND USE OF DATA

This technology demonstration effort consists primarily of conducting two 3-D EM resistivity geophysical surveys and correlating these survey results with conventional physical samples.

A 3-D EM resistivity survey incorporates a complete review of all available and relevant geologic/hydrogeologic information as well as consideration for site-specific sources of cultural and electrical noise interference. This review is necessary to determine the most effective geophysical survey design with respect to source pattern and to placement of receiver wells in the surveyed area.

The EM resistivity survey method uses a surface source coil that transmits a very low frequency signal. This induces a long wavelength and time-varying magnetic flux below the source coil's location. The EM source is an optimally tuned coil having 32 turns of low resistance wire which create an area of 4 m^2. A current of up to 11 amperes runs through the coil, thus creating a maximum EM moment of 1,408 ampere-meters.

The induced magnetic field is remotely detected by the EM receiver located down-hole. The receiver is tuned to the specific source-signal frequency being used. This frequency is relatively low, 263 Hz, and is found at one of the minimum-amplitude spectral points of the noise spectrum to contend with cultural and industrial noisy sites. Figure 2 illustrates the data collection process. The signals from the receiver probe are passed through a High-Q inverted notch filter specific to the source-coil frequency. The collective effect of this system enhances the signal over noise. The filtered signal is then passed to an integrator, which performs additional signal-to-noise enhancement by summing and averaging the signal over many tens of cycles.

Shown below are some general specifications of the basic system components.

Transmitter Loop	Receiver Probe	Data
Area = 43.1 $feet^2$	Length = 2.5 feet	16-byte A/D converter
32 turns	Diameter = 1.6 inches	1/100-scale resolution
11 amperes	30,000 turn; 28-gauge wire	263 Hertz

The voltage signals received at different depths in the well are the result of the superposition of time-varying magnetic fields from the surface coil and induced currents created in features of differing resistivity. The magnetic flux from the source coil is known as the primary flux, and the magnetic flux from the "eddy currents" is known as the secondary flux.

After a complete set of vertical offset log data representing the formations below the coil is recorded, the source coil is moved to another surface location and the process is repeated. Data acquisition at a site continues until the 3-D matrix of resistivity data collected is sufficient to meet the survey objectives.

The final phase of the field processing effort involves digital sampling of the integrated voltage output, plotting, and review of field records of the output for quality control. This is then followed by field evaluation of existing anomalies.

The digital data is stored on disc, and then undergoes the following processing off-site by GEHM Environmental:

- Automated editing and removal of extreme noise from the unusable data sets
- Automated amplitude static corrections to eliminate variations in the individual logs caused by changes in source strength in and around metal noise features (such as buried metal tanks, pipelines and plates).

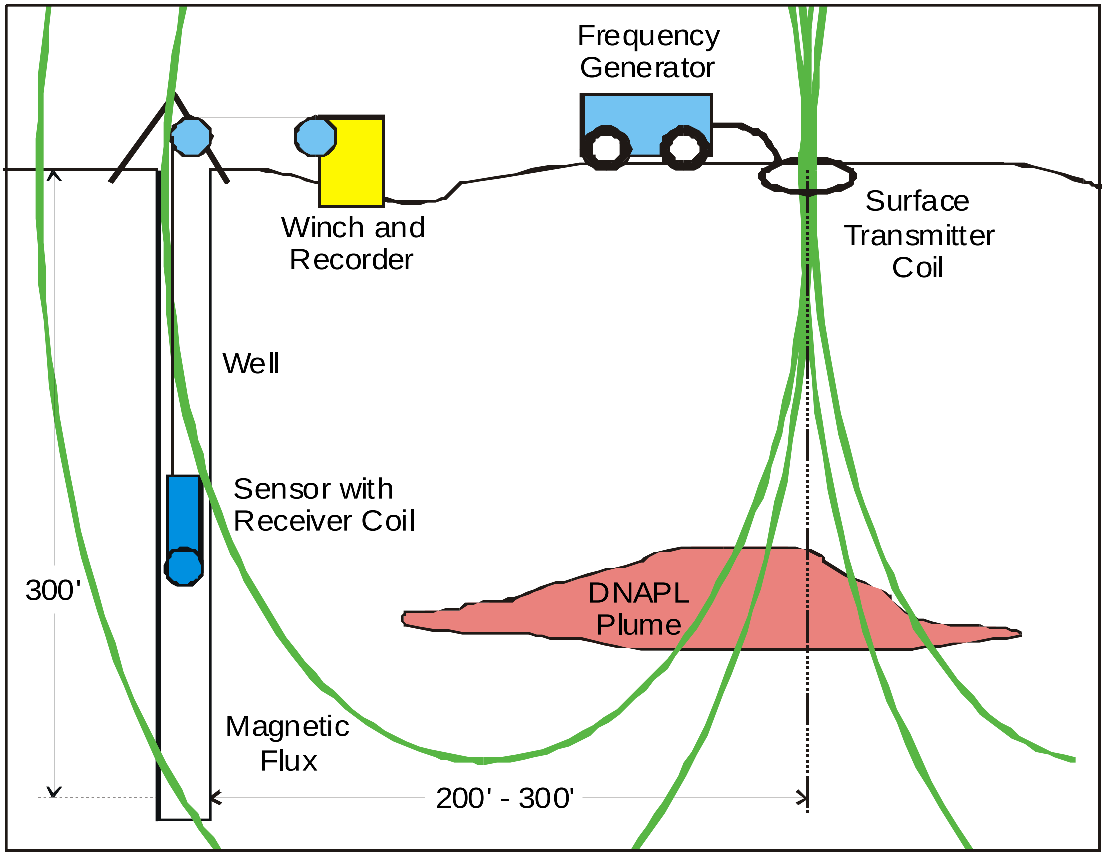

Figure 2. 3-D EM Resistivity Transmitter and Receiver System.

- Adjustments to all data sets from each receiver well to conform to a data set that would have been acquired from a single receiver well. These adjustments are predicted by overlap data recorded from two or more receiver wells.
- Automated signal-to-noise enhancement using 0.1-foot samples to generate resolution for the final 0.5-foot offset logs that are input into the model process.
- Generation of one-dimensional log models, prior to three-dimensional processing.
- Bisect the one-dimensional logs into first-order (gross character) resistivity logs and second order (refined character, usually associated with geologic stratigraphy) residual logs.
- Design of two-dimensional and three-dimensional model weights.
- Three-dimensional surface-integral modeling.

The final data processing effort consisted of developing 3-D images, maps, and cross sections using Dynamic Graphics' software and annotation using Silicon Graphics' Showcase software.

A high-resolution 3-D EM resistivity survey was conducted at Site 5, Alameda Point, and at Building 3001, Tinker AFB, in September 1997 and January 1998, respectively, by GEHM Environmental Corporation. GEHM Environmental Corporation's name for these 3-D EM resistivity surveys is an Electromagnetic Offset Log (EOL).

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The objective of this project was to assess the effectiveness of 3-D EM resistivity surveying as a method for performing site characterization and subsurface DNAPL source delineation. The 3-D EM resistivity method has been successfully used in the past to image subsurface light, non-aqueous phase liquid (LNAPL) plumes (Pritchard, 1995; Maxwell, 1995; GEHM, 1996). This project's effort involved demonstrating the ability of this EM method to generate 3-D images of subsurface DNAPL contamination. Collecting subsurface physical samples within the surveyed region validated the accuracy of the survey results and predictions. Soil and groundwater samples were collected using direct-push and rotary drilling methods.

EM survey-based DNAPL source delineation was deemed to be successful if 90% of the predictions for DNAPL contamination could be verified, based on physical and chemical analyses of samples taken from within the surveyed regions.

Where present as a separate phase, DNAPL compounds generally are detected at less than 10% of their aqueous solubility in groundwater. Typically, dissolved contaminant concentrations greater than 1% of the aqueous solubility limit are highly suggestive of NAPL presence. This relatively low value is the result of the effects of non-uniform groundwater flow, variable DNAPL distribution, the mixing of groundwater in a well, and the reduced effective solubility of individual compounds in a multi-liquid NAPL mixture. In addition, concentrations less than 1% solubility do not preclude the presence of NAPL (Cohen et al., 1993).

Validation is the process of confirming that a target identified by the EM survey as potentially containing DNAPL does in fact actually contain DNAPL. A target location is selected in this area, and drilling, groundwater sampling, and chemical analyses of the soil and groundwater are performed to validate the EM survey prediction.

Sampling data indicated the presence of DNAPL if the cumulative level of contamination in a sample, or Σ[DNAPL constituents], was at least 10% of the free-phase solubility of the contaminant TCE. Therefore, since TCE = 1,100 mg/L (Pankow & Cherry, 1996) the presence of DNAPL was indicated by a concentration greater than or equal to 110 mg/L (ppm). An analytical result was considered a negative DNAPL result if: 1) the cumulative concentration of the DNAPL constituents was less than 110 ppm; or 2) none of the constituent concentrations exceeded their maximum contaminant limits (MCLs) as established by the EPA. This measurement value is an order of magnitude greater than the established 1% "rule-of-thumb" value for DNAPL detection.

3.2 SCHEDULING FOR SETUP AND OPERATION

The activities and approximate time-frames shown below were followed in the demonstration and validation of the EM resistivity survey method at both project sites:

Task	Task Start-Task End	Organization
approval to begin field activities	week 0	ESTCP
collect 3-D resistivity Data	week 5-6	GEHM
process and evaluate survey data	week 7-8	GEHM
submit site survey report	week 10	GEHM
generate list of predictions	week 11	CWM
conduct field validation sampling/analyses	week 13-14	CWM
provide initial field validation results	week 17	NFESC

3.3 SAMPLING PROCEDURES

3.3.1 Sample Collection

Groundwater and soil samples were collected to support the validation of the EM resistivity survey results. Because soft unconsolidated sediments are found in the upper fill layer at Alameda, it was possible to replace the more disruptive rotary drilling method with a much more productive hydraulic push probe for sample collection. This also enabled collection of discreet, representative samples at the locations and depths of interest. At Tinker AFB, the company AEI/B. Graham, Inc., was the drilling company under contract to JMB Associates of Owasso, OK. At Tinker AFB, rotary drilling was used to sample subsurface soil and groundwater.

The *Three-Dimensional Resistivity Survey EOL Reports* produced by GEHM Environmental provided subsurface interpretive analyses, with conclusions and recommendations for target validation locations based on anomalously high (indicating DNAPL) resistivity features. A select number of these target locations were chosen for verification drilling and sampling.

At Alameda, each sampling push location was identified in the field by referencing the EM survey grid points, which were marked on the ground. Each push location was measured to within ±0.5 foot from the target location. The depth of the collected sample was measured by the instrumented CPT rig. Each sampling depth was measured to within ±0.1 foot of the target depth. At Tinker AFB, samples were collected using conventional drilling techniques. Locations were accurate to within 1 foot.

3.3.2 Water Sampling

Water sampling was performed with the BAT® water sampler, which consists of a 40-milliliter (mL) tube with a rubber cap. This chamber (under vacuum) was pushed down into the ground to the desired depth, at which point a syringe needle punctured the lid and allowed groundwater within the aquifer present at that depth to flow into the tube. The needle was then retracted, and the sealed tube was brought back to the surface. All samples collected in this manner were sent to the laboratory sealed in their original collection tube.

3.3.3 Soil Sampling

At the Alameda site, soil samples were obtained by driving a 1.5-inch-diameter, 24-inch-long split spoon sampler into the ground at the designated depth. Upon recovery of the split spoon sampler to the surface, a small amount of soil was removed from the sample core and put into a 40-mL volatile organic analysis (VOA) vial. The vial was pre-filled with 15 ml of reaction-grade methanol in order to minimize the amount of volatilization that could occur in the sample container. This allowed for a more accurate analytical result. The vial sample taken from the core section was selected on the following criteria:

- Section contained visible staining (from contamination)
- Section had a high, localized flame ionization detector (FID) reading
- Section had an interface between coarse-grain material and fine-grain material
- Taken 1 cm from the bottom of the sample core.

All samples collected in this manner were sent to the laboratory in their sealed VOA vials.

The sampling method at Tinker AFB involved collecting samples from drill cuttings at pre-assigned depths. Neither the FID instrumentation nor the methanol preservation methods were used. All soil samples were placed in vials and stored in a small refrigerator and then transferred to an ice-chilled cooler prior to overnight shipment to the lab.

3.3.4 Experimental Controls

Rigorous quality assurance practices are required when evaluating contaminant concentration levels near their maximum contaminant level thresholds (i.e., 5 ppb for TCE). However, due to the gross nature of the criteria for identifying DNAPL (i.e., constituent concentration >110 ppm), such measures are not necessary. The following Quality Assurance and Quality Control (QA/QC) measures were followed for each sampling interval at the two sites.

The rinseate water from the sample collection equipment was analyzed prior to investigation at each new validation location. This ensured that no residual contamination from a previous sample remained on the apparatus.

One duplicate sample was made from one of every ten samples collected that was associated with a high confidence prediction for containing DNAPL. This ensured adequate repeatability and resolution of the laboratory analytical results, using samples that most likely had contamination.

Also, for each high confidence target, a duplicate sample was collected and analyzed at the on-site laboratory and at an off-site laboratory. This provided an indication of the accuracy of the on-site lab's results.

One trip blank was included with the samples sent to the off-site laboratory. Due to the proximity of the on-site laboratory and the gross nature of the criteria for identifying DNAPL constituents in most of the samples (i.e., 110 ppm), trip blanks were not included with samples analyzed on-site.

3.4 ANALYTICAL PROCEDURES

3.4.1 Selection of Analytical Laboratories

Tetra Tech was selected to subcontract with analytical laboratories for the chemical analyses of physical samples collected in the field at Alameda Point. They are local contractors to Alameda Point, and have been used successfully in the past to provide analytical services in support of base investigation efforts. Tetra Tech subcontracted with American Environmental Network to perform the analyses. Southwest Laboratory of Oklahoma was selected for performing chemical analyses of soil and groundwater samples collected in the field at Tinker AFB. They are local to central Oklahoma, and have also been used successfully in the past to provide analytical services in support of Base investigation efforts at Tinker AFB.

3.4.2 Analytical Methods

The primary method used to validate DNAPL predictions based on the EM resistivity survey was to compare the predictions to results derived from chemical analyses of samples taken at the site. Samples analysis was performed using a gas chromatography/mass spectrometry (GC/MS) in accordance with EPA Method 8260, capillary column technique. This method identifies the presence of DNAPL compounds in the physical samples and quantifies their level of contamination.

Water samples are analyzed in accordance with EPA Method 8240, while soil samples were analyzed by EPA Method 8260/8270 VOC by gas chromatography/mass spectrometry (GC/MS): capillary column technique. Since the contaminant levels of interest are in excess of 110 ppm concentration, this application only requires an instrument detection limit (IDL) of >1 ppm.

Water samples received at the lab were transferred to a separatory funnel and allowed to sit for 10 minutes. Afterwards, 10 mL was drained from the bottom and used for chemical analysis. For soil samples, approximately 10 g of soil was taken from the storage vial and used for chemical analysis.

The lowest instrument range for the GC/MS method is 5-200 ppb. This range was scaled up by diluting the samples. The instrument range for analyzing the samples associated with high confidence of DNAPL encompassed 10-400 ppm concentrations. This corresponds to an instrument resolution of +/- 5 ppm on the upper end of the scale.

Samples were also inspected visually for DNAPL. This was accomplished by adding a small amount of hydrophobic dye (Sudan IV or Oil Red O) to the remaining sample water (for soil samples: soil sample + equal volume water). The mixture vial was shaken by hand and observed for signs of separate phase product.

3.5 DEMONSTRATION SITE/FACILITY BACKGROUND

3.5.1 Background

Two sites were selected for this project in order to demonstrate 3-D EM resistivity surveys in different geologic conditions. The two sites were chosen because they each have a well-documented

DNAPL problem and reside in different types of geologic settings. The sites chosen for this demonstration and a general description of their geologic settings are:

Alameda Point, California – saturated, unconsolidated, clastic sediments
Tinker AFB, Oklahoma – interbedded, partially lithified sandstone and shale.

Information from previous site investigations (Alameda, CA- Naval Complex; Integrated Environmental Team of Tinker AFB, 1997) was used to design each EM resistivity survey. These site investigation data sets were considered to be typical for most DNAPL-contaminated sites. These data were used to better target the areas likely to have highest DNAPL levels.

Listed below are the highest DNAPL contaminant concentrations in samples collected at the two sites by on-site Remedial Investigation contractors as of the time of this study:

Alameda Point – 1,1,1-Trichloroethane (TCA): 790 parts per million (ppm)
Tinker AFB – Trichloroethylene (TCE): 250 ppm.

Based on overall site characterization and these specific analytical results, the two sites appeared to be appropriate candidates for the EM survey to detect DNAPL.

The EM resistivity survey site at Alameda Point was located in and around Building 5, a former depot maintenance facility with underground tanks and sewers that were used to contain industrial solvents and wastewaters. Although there was a significant amount of utilities and cultural features at this site, they did not adversely affect the survey data.

The EM resistivity survey site at Tinker AFB was located in and around Building 3001, part of an industrial complex where industrial solvents and wastewaters were contained in unlined subsurface pits and trenches. Despite the presence of buried utilities and various surface impediments, EM survey data were still successfully collected.

3.5.2 Site History - Alameda Point

Alameda Point is located on Alameda Island, in Alameda County, California. The island is located along the eastern side of San Francisco Bay as shown in Figure 3. Alameda Point occupies 2,634 acres, partially on land and partially submerged, and is approximately 2 miles long and 1 mile wide. Land use in the area includes shipyards, maintenance supply centers, residences, retail businesses, schools, and a state beach. The U.S. Army acquired the area now occupied by Alameda Point in 1930, and construction at this installation began the following year. In 1936 the base was transferred to the U.S. Navy, and in 1941 more land was annexed to the air station. The primary mission of the former Alameda Point was to maintain and operate maintenance facilities and provide services and material support to naval aviation activities and operating forces. The 1993 Base Realignment and Closure (BRAC) commission listed Alameda Point for closure. In April 1997 the base was closed, turned over to the public, and renamed Alameda Point. BRAC cleanup is now underway, with cleanup to be completed in fiscal year 2007. The Naval Facilities Engineering Command, Western Division, is overseeing the cleanup activities.

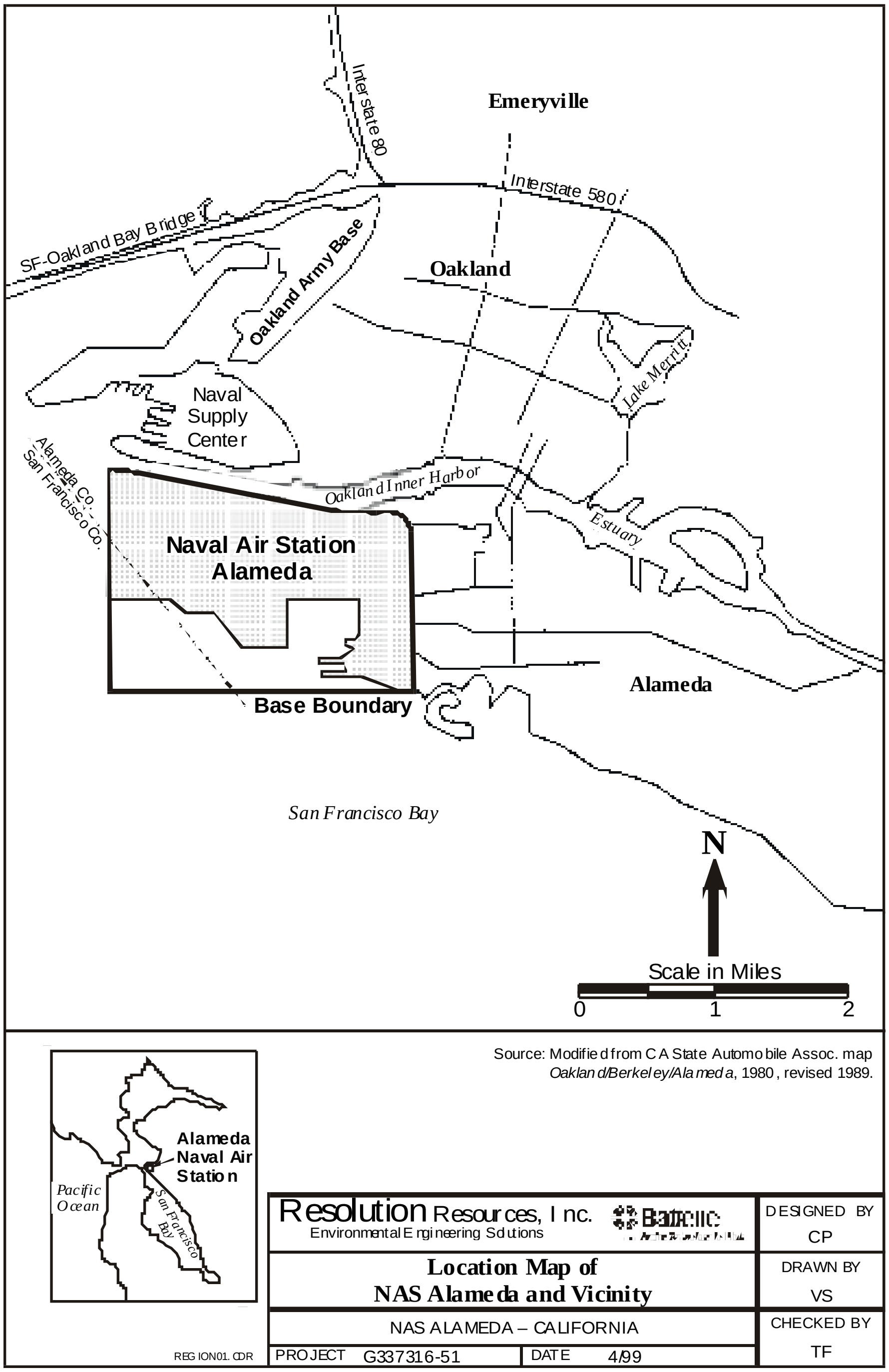

Figure 3. Location Map of Alameda Point and Vicinity.

The Installation Restoration Program has identified 23 potentially contaminated sites for investigation and cleanup. Site 5 (Building 5 area) was chosen to host the EM subsurface DNAPL imaging demonstration. This site is located in the center of the base, and covers 18.5 acres. It has been in operation since 1942, but has recently been vacated. Shops in the building were used for cleaning, reworking, manufacturing metal parts, tool maintenance, and for plating and painting operations. Figure 4 shows the location of Site 5 within Alameda Point.

The plating shop inside Building 5 has been identified as an area of concern, due to the high concentrations of VOCs in groundwater samples. Processes in the shop included degreasing, caustic and acid etching, metal stripping and cleaning, and chrome, nickel, silver, cadmium, and copper plating. A groundwater sample collected in 1992 from a boring located inside Building 5 at the plating shop showed concentrations of 790 ppm of TCA, indicating that the site was contaminated with significant levels of DNAPL (PRC Environmental Management, Inc., 1994).

Another area of interest is to the east, near the flagpole, where an underground solvent storage tank is located. TCA was detected in soil samples collected from areas adjacent to the east side of Building 5. The depths of contaminated soils span from 3 to 14 ft bgs, with concentrations ranging from 0.008 to 39 ppm (PRC Environmental Management, Inc., 1996). Also found in the soil were 1,1 dichloroethane (DCE), chloroethane, tetrachloroethylene (PCE), and vinyl chloride, all at relatively low levels. TCE was also encountered on the east side of the site in concentrations from 0.053 to 2.2 ppm. Water samples from 11 wells screened in the first water-bearing zone, mostly around the perimeter of Building 5, showed relatively low levels (below 0.5 ppm) of VOCs. One well, however, located on the east side of the building, was tested for TCA, DCE, 1,2-dichloroethylene (1,2 DCE), chloroethane, and TCE and found to have a total VOC concentration of nearly 60 ppm (Naval Facilities Engineering Command, Western Division, 1995).

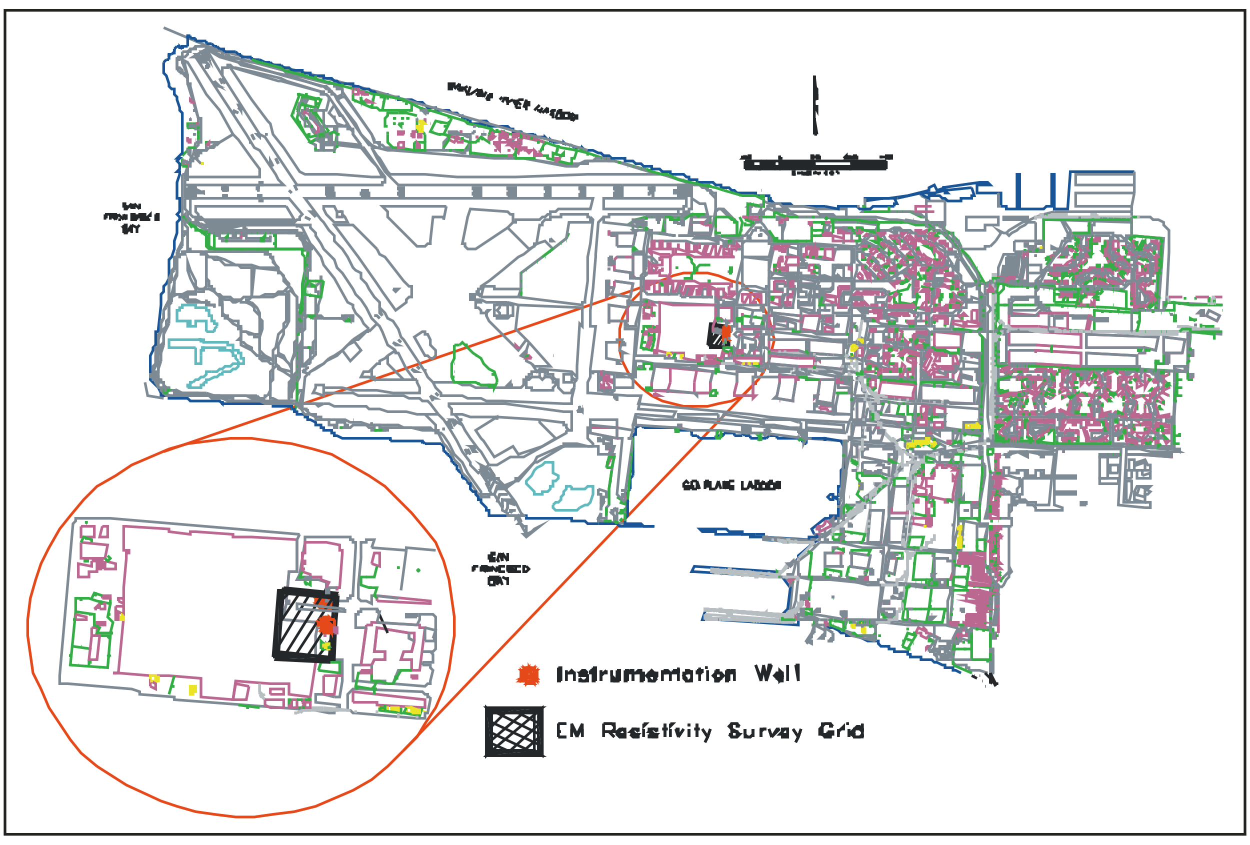

Figure 4. Alameda Point – Site 5.

3.5.3 Site History - Tinker AFB

Tinker AFB is located in central Oklahoma, in the southeast portion of the Oklahoma City metropolitan area, in Oklahoma County (see Figure 5). The Base is bounded by Sooner Road to the west, Douglas Boulevard to the east, Interstate 40 to the north, and Southeast 74th Street to the south. Building 3001 is located in the northeast portion of the Base, east of the north-south runway.

The Base encompasses 4,541 acres and contains approximately 500 buildings. Tinker AFB, is a worldwide repair depot. Tinker's mission is to manage and maintain the following aircraft: B-1B, B-2, B-52, E-3, and the multipurpose 135 series. Also managed at the Base are the SRAM, SRAM II, ALCM, and GLCM missile systems, as well as the United States Air Force Harpoon Missile. The Base houses the Air Logistics Center and two Air Combat Command units. Tinker is also the main operating Base for aircraft equipped with the Airborne Warning and Control System (AWACS).

The sources contributing to groundwater contamination beneath and adjacent to Building 3001 include the former solvent pits, industrial waste lines, improper tie-ins between storm sewers and wastewater lines, the North Tank Area, and Southwest Tanks. The former solvent pits within the northern end of Building 3001 are thought to be the main source of TCE contamination. Figure 6 shows the layout of Tinker AFB, and the location of Building 3001, in the northeast sector.

From the 1940s through the 1970s, unlined subsurface pits and trenches within Building 3001 were used as storage reservoirs to contain industrial solvents and wastewater. During their 30-year period of operation, the pits and trenches leaked, perhaps continuously, allowing percolation of contaminants into subsurface soil, bedrock and groundwater. Downward migration of the contamination reached the top of the regional aquifers. The contaminant plumes reach a maximum depth of 175 ft and extend laterally over an area of about 220 acres within the groundwater. Primary contaminants at the site are TCE, chromium, benzene, PCE, lead, and nickel.

The Building 3001 complex houses an aircraft overhaul and modification complex to support the mission of the Oklahoma City Air Logistics Center. The primary industrial activities conducted in the building (since operations began in the early to mid-1940s) are aircraft and jet engine service, repair, and/or upgrading. Some industrial processes use or generate solutions containing solvents and metals similar to contaminants found in the underlying groundwater. Organic solvents were used for cleaning and degreasing metal engine parts. TCE was the predominant solvent used from the 1940s until the 1970s. The degreasing operations were conducted in concrete pits set below the floor level.

In the early 1970s, PCE began to replace TCE as the predominant degreasing solvent, and the pits were replaced with aboveground degreasing systems (pit, piping, pumps, etc.). The subsurface pits were emptied and abandoned, typically by backfilling with sand and capping with concrete. Wastewater from the plating shop and paint stripping operations contained high concentrations of solvents and heavy metals, particularly chromium. Other waste materials generated from plating, painting, and heat-treating activities contain both solvents and metals. Subsurface contamination occurred primarily by leakage from the subsurface pits and trenches, erroneous discharging of solvents or wastewater into storm drains, accidental spills, and/or improper connections between wastewater and storm drains.

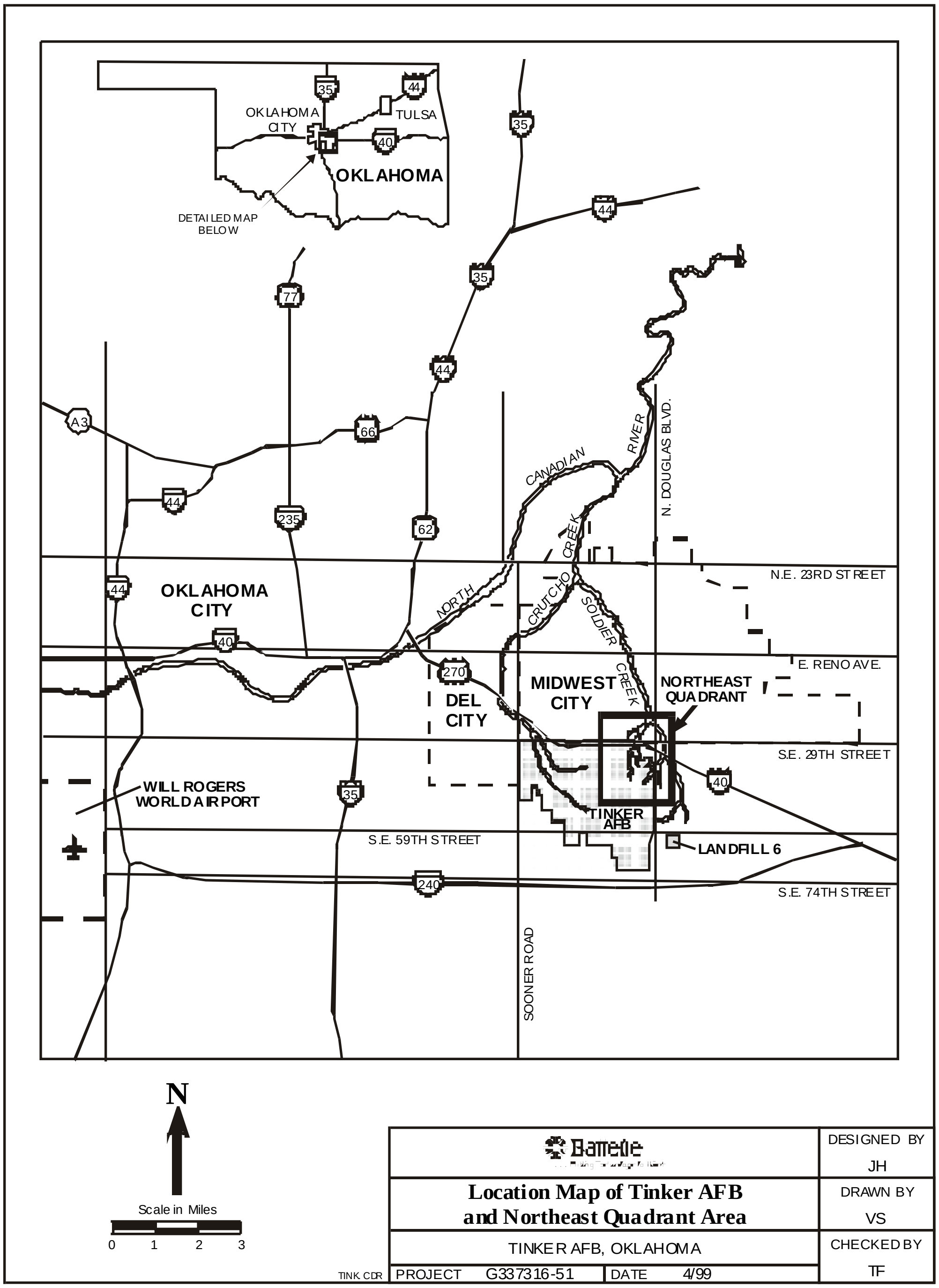

Figure 5. Location Map of Tinker AFB and Northeast Quadrant Area.

In 1987, the Environmental Protection Agency (EPA) placed the site on the National Priorities List because of the contaminated groundwater and soil. A remedial investigation was conducted in 1980 in accordance with CERCLA. The remedial investigation, completed in January 1988, found that the primary contaminants at the site are TCE and chromium. However, PCE and 1,2 DCE have also been detected. The highest concentrations of contaminants beneath the building are in the upper saturated zone, where 330 ppm of TCE and 80 ppm of chromium were detected.

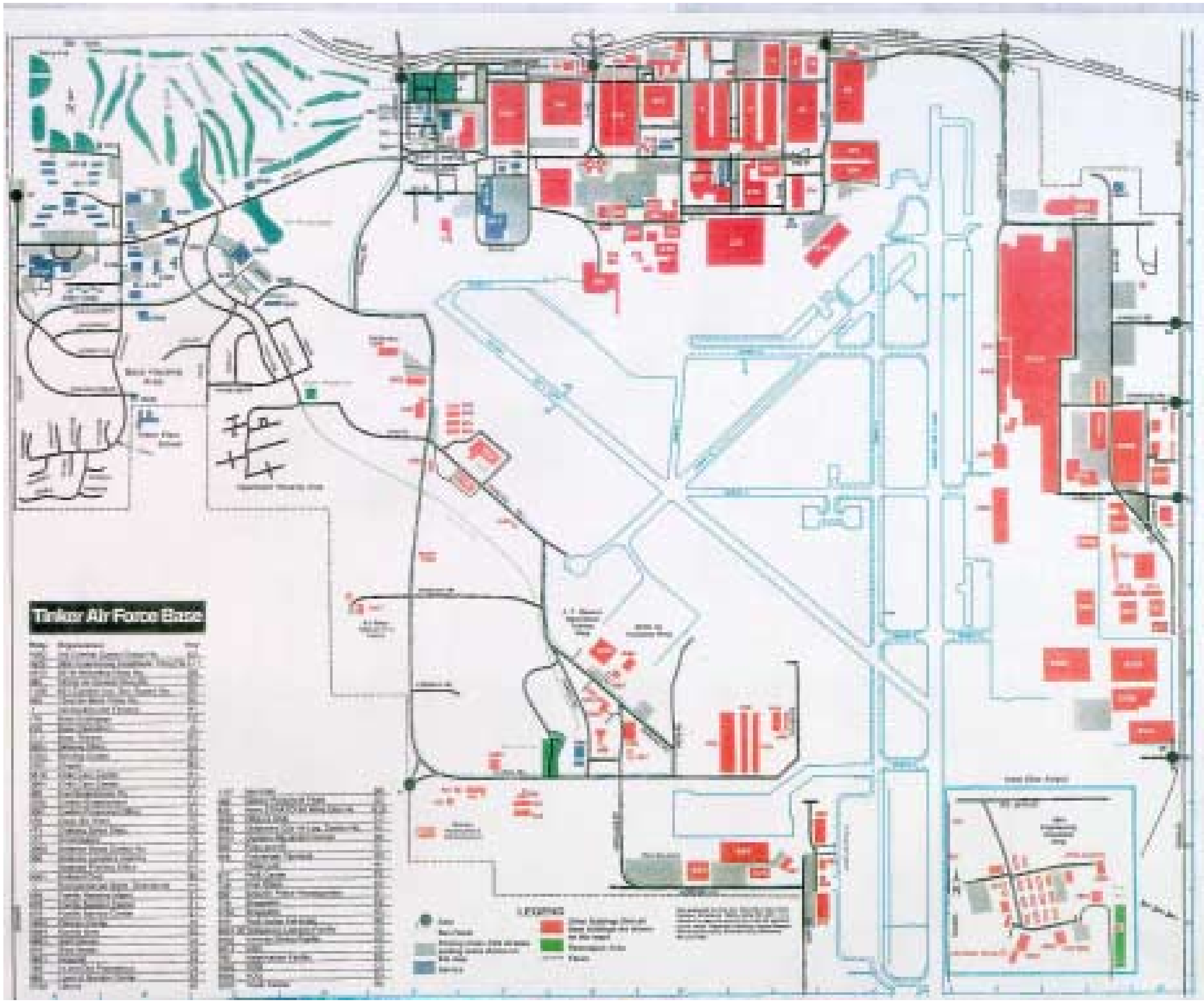

Figure 6. Location of Tinker AFB and Building 3001.

3.6 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

3.6.1 Alameda Point - Site Characteristics

Most of Alameda Point was built on artificial fill material dredged from San Francisco Bay, the Seaplane Lagoon, and the Oakland Channel. The hydraulically placed fill is comprised mostly of silty sand to sand, with clay and/or gravel, and contains wood, concrete, and metal. It was placed on Holocene Bay Mud. The fill is up to 40 feet thick in the western portion of the base, and thins to the east. About 400 to 500 feet of unconsolidated sediments overlie Franciscan bedrock, according to boring logs from water supply wells installed as early as the 1940s. The Bay Sediment is the youngest of the naturally occurring formations, and consists of Bay Sand and Bay Mud. The Bay Sand is gray with green or blue colors, and is fine to medium-grained sand or sandy silt, loose to medium dense with shells. The Bay Mud is also gray with green or blue hues, grades from clay to clayey silt, is soft to medium stiff, and has a minor amount of shells. The Bay Sediments are 130 feet thick, and are thickest in a paleochannel that trends nearly east to west across the middle of Alameda Point. This channel cuts across the northern part of Building 5, and is north of the source areas of concern in this investigation. Bay Sediments are thin or absent in the southeastern part of the base.

The Merritt Sand is older than the Bay sediments and was deposited in the late Pleistocene to Holocene Age. The medium-grained sands are brown, with yellow and red iron oxide stains, and sometimes having minor clay deposits. They are dense to very dense. This aeolian unit is up to 70 feet thick, and has been partially eroded by the paleochannel.

Groundwater is encountered in borings between 5 and 10 feet deep, and flow is generally to the west and southwest. Two aquifers, which are continuous, underlie Alameda Point. The first water-bearing zone occurs in the dredge fill, about 5 or 6 feet deep. The deeper aquifer is found in the Merritt Sand. The Bay Mud is considered to be an impermeable layer that isolates the upper aquifer from the lower aquifer. Both aquifers are influenced by tidal fluctuations and are characterized by water problems associated with nitrates, saltwater intrusion, and naturally occurring mercury contamination from the bedrock formation. As a result, groundwater is not presently used as a water supply on Alameda Island.

3.6.2 Tinker AFB - Site Characteristics

Tinker AFB is located in the Interior Lowlands physiographic province on gently westward-dipping Permian redbeds. Bedrock units encountered at Tinker AFB include the Garber-Wellington Formation and the overlying Hennessey Formation. The Garber-Wellington Formation outcrops in Central Oklahoma and supplies much of the drinking water for residents of Oklahoma and Cleveland counties. The recharge area covers the eastern half of Oklahoma County including Tinker AFB, and the formation dips to the west about 15 feet per mile. The Garber Sandstone and Wellington Formations are hydrologically interconnected formations that are not easily distinguished from each other based on rock type, key beds, fossils, or hydrologic properties. The Garber-Wellington is about 900 feet thick in the study area, and consists of lenticular and interbedded sandstone, shale, and siltstone. Sandstone is orange-red to reddish brown, fine-grained, and poorly cemented. Shale is reddish brown and silty. Although present beneath all of Tinker AFB, the Garber-Wellington is overlain by the Hennessey Formation over the southern half of the Base. Sediments of the Garber-Wellington are deltaic in origin. Stream-deposited sands interfinger with marine shales, and individual beds vary from a few feet to about 40 feet in thickness. Sandstone averages about 65% of the formation, as determined from borings drilled at the Base. Because of shifting channels and changing currents during deposition, detailed correlation of lithologic units is only possible over short distances.

In the eastern portion of Tinker AFB and Building 3001 there are three major water-bearing and transmitting units that underlie the northeast quadrant and the study area. Various hydrogeologic and modeling studies done at Tinker designate them as the upper saturated zone, lower saturated zone, and production zone. These zones are separated by two distinct shale units, the Upper and Lower Shale, that represent the most significant semi-confining units beneath the northeast quadrant of the Base. A series of interbedded and interfingered shale and siltstone lenses comprise the two distinct shale units. Together, all these units form the five primary hydrostragraphic units occurring within the northeast quadrant.

Previous studies also indicate decreasing TCE concentrations with increasing depth below ground surface. The subsurface shale layers have prevented contaminants from migrating into the drinking water zone. The contaminants that migrated into the upper zones of the Garber-Wellington traveled through possible cracks or discontinuities in the shale layers. Overall, the shale layers are effective in slowing the migration of contaminants into the producing zone.

There are several wells in the area producing minor amounts of water from the Hennessey Formation, which are developed from one of the thin sandstone beds or from joints and fractures in the shale (Integrated Environmental Team of Tinker AFB, 1997).

3.6.3 Summary of Site Analytical Results

An overall review of the results validating the EOL technology show that, at Alameda Point there were no true positives, 20 true negatives, 18 false positives, and 1 false negative. At Tinker AFB there were no true positives, 4 true negatives, 14 false positives, and 2 false negatives. In summary, not once was the EOL technology able to predict and then confirm the presence of DNAPL in the subsurface. In 32 cases, a high or medium confidence rating was predicted for locating DNAPL, yet validation sampling revealed little to no chlorinated constituent concentrations and no NAPL. In 24 attempts, the technology accurately predicted the absence of DNAPL in a specified area. And in 3 cases, greater than 110 ppm chlorinated hydrocarbon constituents were identified in a location predicted to have little to no chlorinated hydrocarbon contamination. Table 1 reflects the overall performance of the EOL technology.

Table 1. Summary of EM Resistivity Performance Results.

Project Site	# of Target Locations w/ High Probability to Have DNAPL[(a)]	Percent Accuracy	# of Target Locations w/ Low Probability to Have DNAPL[(b)]	Percent Accuracy
Alameda Point	18	0	21	95
Tinker AFB	14	0	6	67

(a) As predicted by GEHM Environmental. Total solute concentration in soil/groundwater verification samples taken from target locations must measure > 110 ppm.

(b) As predicted by GEHM Environmental. Total solute concentration in soil/groundwater verification samples taken form target locations must measure < 110 ppm.

4.0 PERFORMANCE ASSESSMENT

The objective of this task was to evaluate the likelihood that 3-D EM resistivity technique is capable of consistently finding DNAPL.

A validation process was applied to confirm that a target identified by the EM survey as potentially containing DNAPL did in fact actually contain DNAPL. Target locations were selected in surveyed the area, and drilling, groundwater sampling, and chemical analyses of the soil and groundwater were performed to validate the EM survey prediction.

Sampling data indicated the presence of DNAPL if the cumulative level of contamination in a sample, or Σ[DNAPL constituents], was at least 10% of the free-phase solubility of the contaminant TCE. Therefore, since TCE = 1,100 mg/L (Pankow & Cherry, 1996) the presence of DNAPL was indicated by a concentration greater than or equal to 110 mg/L (ppm). An analytical result was considered a negative DNAPL result if: 1) the cumulative concentration of the DNAPL constituents was less than 110 ppm; or 2) none of the constituent concentrations exceeded their maximum contaminant limits (MCLs) as established by the EPA.

The EOL technology was to be considered successful if 90% or more of the predictions validated by "truth sampling" were proven to be accurate.

4.1 EM RESISTIVITY DATA ACQUISITION AND ANALYSIS

The exact positioning of each survey grid was chosen based on review of all existing site characterization information, and discussions with the site environmental representatives. This ensured that each EOL survey was being performed in areas suspected or known to have significant concentrations of DNAPL in the subsurface. These surveys were accomplished with two instrumentation wells at each site, and each survey encompassed an area of approximately 2 acres. The EOL application provided 3-D resistivity data that was used in identifying the location of suspected DNAPL contamination within each survey grid. Contrasts in the resistivity data were measured and used to rank the probability of finding DNAPL contamination within a particular region. "Anomalous" areas represented regions of very high resistivity contrast. This large contrast was believed to be directly associated with the spatial distribution of DNAPL and/or other hydrocarbon based compounds within the vicinity. On the other hand, "average" resistive zones showed little to no resistivity contrast and were considered to be background areas having no DNAPL contamination. The accuracy of the predicted locations of DNAPL anomalies was validated with a physical soil and groundwater sampling program.

4.2 EOL SITE SURVEY REPORTS

Following GEHM's application of the EOL technology at each site, an EOL resistivity site survey report was provided for each of the two demonstration sites. These reports contained analysis and conclusions inferred and interpreted from the resistivity distribution and patterns of models and images developed from the raw data. The reports included: 1) site maps displaying the survey footprint with EOL transmitter stations and receiver well locations; 2) EOL resistivity image maps displaying resistivity contrasts at depth intervals; and 3) an EOL resistivity image map indicating suggested confirmation/ validation boring locations for a particular depth.

4.3 VALIDATION SAMPLING SELECTION

Using GEHM's conclusions and recommendations, NFESC and the University of Missouri selected field validation targets to conclusively establish the accuracy of the EOL technology for each surveyed region. These target locations (with [x, y, z] location and depth coordinates) were selected based on their potential for validating the survey results with physical sampling proven to contain DNAPL or chlorinated volatile organic compounds (CVOC) contamination.

4.3.1 Validation Data

The areas (anomalies) proposed for investigation were referred to as targets or target sample locations. Site survey grids were used to illustrate the location of a target sample. A sample location was defined by coordinates from a designated benchmark and depth below ground surface.

The targets were assigned a high, medium, or low confidence of encountering DNAPL. This qualitative ranking was based primarily upon the measured resistivity contrasts of anomalies visible at the site. The proximity of an anomaly to a source, fill, and any man-made structures or features was also considered. The EM Resistivity Image Maps provided by GEHM displayed resistivity contrasts at varying depth intervals below ground surface. The resistivity contrasts were displayed as Anomalous/High Resistivity regions, Above Average resistivity areas, and Average or background resistivity. The anomalously high resistivity zones were believed to be directly associated with the presence of DNAPL solvent compounds, and therefore given a high confidence prediction of finding contamination in that area. Average or background resistive zones were associated with the absence of compounds and thus labeled with a low confidence level. The following chart summarizes this classification process.

Confidence of Finding DNAPL	Size of Resistivity Anomaly
High	Anomalous/High
Medium	Above Average
Low	Average

4.4 VALIDATION SAMPLING ANALYSIS

Groundwater and soil samples were collected at each target location. Analytical results from these physical samples were used to determine the presence of DNAPL by applying the "10% solubility" rule mentioned described earlier in this section.

4.5 COMPARATIVE ANALYSIS

The accuracy and efficacy of the EOL technology was established by comparing the EM resistivity survey results to the field validation results. Findings from this correlation were categorized as true/false positives and true/false negatives. For example, a true positive reflects an EOL prediction that indicated the presence of DNAPL and was confirmed by a validation target sample at that location, to have DNAPL contamination. A finding of false negative occurred when an EOL prediction indicating little to no DNAPL in a specific area was proven incorrect by a target sample taken from that area. The target sample had to have either a chlorinated concentration greater than 110 ppm or a visual confirmation of DNAPL presence.

The last three relationships correspond to sites that are not contaminated with DNAPL. A false positive reflects a case where the EOL prediction indicates a medium or high level of contamination in an area known to have no DNAPL. A true negative corresponds to a low EOL-predicted DNAPL value for a sampling area that actually has little to no DNAPL. These relationships are shown in the list below:

Predicted EOL Resistivity Contrast[a]	Validated DNAPL Concentration[b]	Correlation
Anomalous	>110 ppm	true positive
High/Above Average	>110 ppm	true positive
Average	>110 ppm	false negative
Anomalous	<110 ppm	false positive
High/Above Average	<110 ppm	false positive
Average	<110 ppm	true negative

(a) The following resistivity categories were interpreted to reflect a range of DNAPL saturation.

Anomalous	> 110 ppm
High/Above Avg.	= 10 - 110 ppm
Average	= 0 - 10 ppm

(b) Represents the total chlorinated hydrocarbon solute concentration.

4.6 DATA ASSESSMENT

During the data acquisition process in the field, the 3-D EM resistivity logging operator viewed a computer monitor which simultaneously showed voltage, depth, and the logarithm of 1/voltage. An ASCII file was generated from each data log, which consisted of depth (feet), receiver speed (feet/minute), receiver voltage (millivolts, mV), transmitter current (milliamps, mA), and the logarithm of 1/V. Each of these logs was associated with a transmitter location (X, Y coordinates) and a particular receiver well.

The ASCII files were edited in the field by the logging operator who generated a set of data log files. These logs consisted of an X,Y,Z coordinate location (feet), resistivity horizontal affect (RHOA) measured in ohm-meters (ohm-m), RHOA1 (ohm-m), and RHOA2 (ohm-m). The RHOA was taken from the original logarithm of 1/voltage. RHOA1 is a first-order apparent resistivity, which describes significant resistivity changes. RHOA2 is a second-order apparent resistivity, and is the difference between the original RHOA and the RHOA1.

The final data log processing consisted of generating second-order resistivity (RHOA2) and smoothed second-order resistivity (SRHO2) values. This was then incorporated into the final database of the resistivity logs consisting of the following information:

X, Y, Z location	LOG_{10} of 1/V	RHOA1 (ohm-m)	RHOA2 (ohm-m)	RHO2 (ohm-m)	SRHO2 (ohm-m)	current (mA)	transmit location	receiver well

This final data set was then incorporated into a 3-D visualization process. This was accomplished using Dynamic Graphics, of Alameda, CA, 2D/3D reservoir modeling software for final 3-D modeling and imaging.

4.7 PERFORMANCE RESULTS

4.7.1 Alameda Point Building 5 and 5A

A 3-D model was generated for the Alameda site based on the subsurface resistivity properties found within the surveyed volume. Figure 7 contains a horizontal slice from the 3-D site model showing the resistivity contrasts found at 27 feet below ground surface (bgs). This image contains the most significant high resistivity anomalies found at this site, situated at a depth of 27 feet.

Based on this information, target points were selected to determine the technology's capability to identify the presence of DNAPL. The sampling target points shown in Figure 8 represent the actual locations selected by the University of Missouri and NFESC to perform validation/truth sampling and analysis. These post survey sampling targets were completed with SCAPS and GeoProbe microwell techniques. Validation sampling locations were selected based on EOL resistivity contrasts that indicated regions of anomalous properties situated at the depth of the confining layer.

Table 2 compares total chlorinated hydrocarbon solute concentrations in the target samples to the EOL confidence predictions for finding DNAPL in the subsurface. Concentrations for all EOL samples, except for one, were very low, ranging from 0 to 0.990 ppm. For 9 different locations, the EOL survey predicted the presence of DNAPL contamination with a strong level of confidence (medium or high). However, in each case, truth sampling revealed little to no DNAPL. On the other hand, 14 EOL confidence predictions indicating the absence of DNAPL were determined to be accurate based on their respective target sample results. One sample taken from the UST area revealed a relatively high concentration of DNAPL at 109 ppm. However, the EOL survey predicted this location to have little contamination.

Results of chlorinated hydrocarbon solute concentrations in sediment samples compared with EOL confidence predictions are shown in Table 3. These sampling locations are also shown in Figure 8. The analysis in Table 3 compares concentrations in the sediment samples to the respective EOL prediction for the presence of DNAPL. The results show that in 8 separate locations, the EOL survey predicted a strong likelihood of there being DNAPL contamination. However, in each case, validation sampling of these target locations failed to reveal solute concentrations greater than 110 ppm. In contrast, the EOL survey accurately predicted the absence of DNAPL at 6 separate locations.

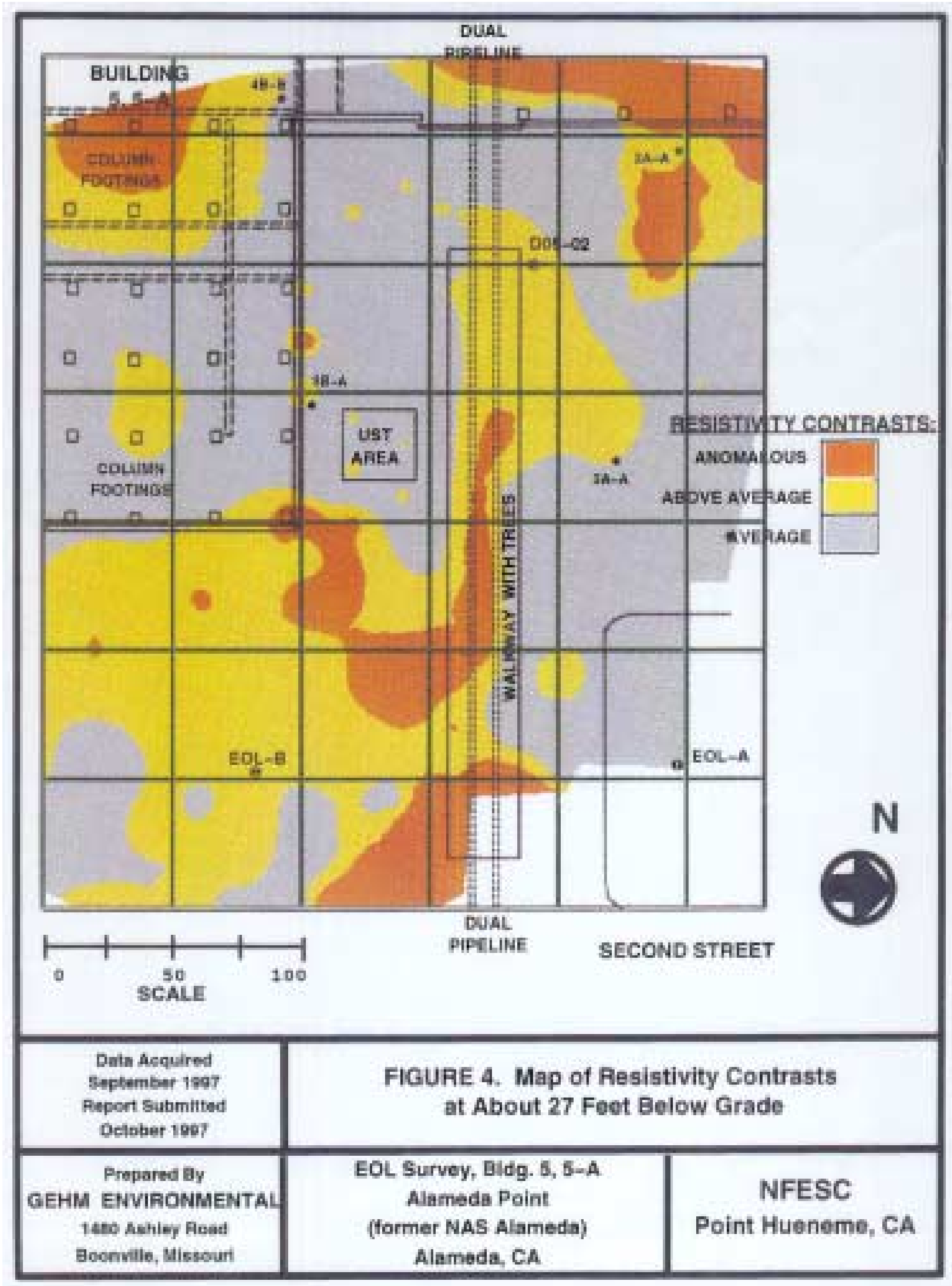

Figure 7. Map of Resistivity Contrasts at ~27 Feet Below Grade EOL Survey, Alameda Point, CA.

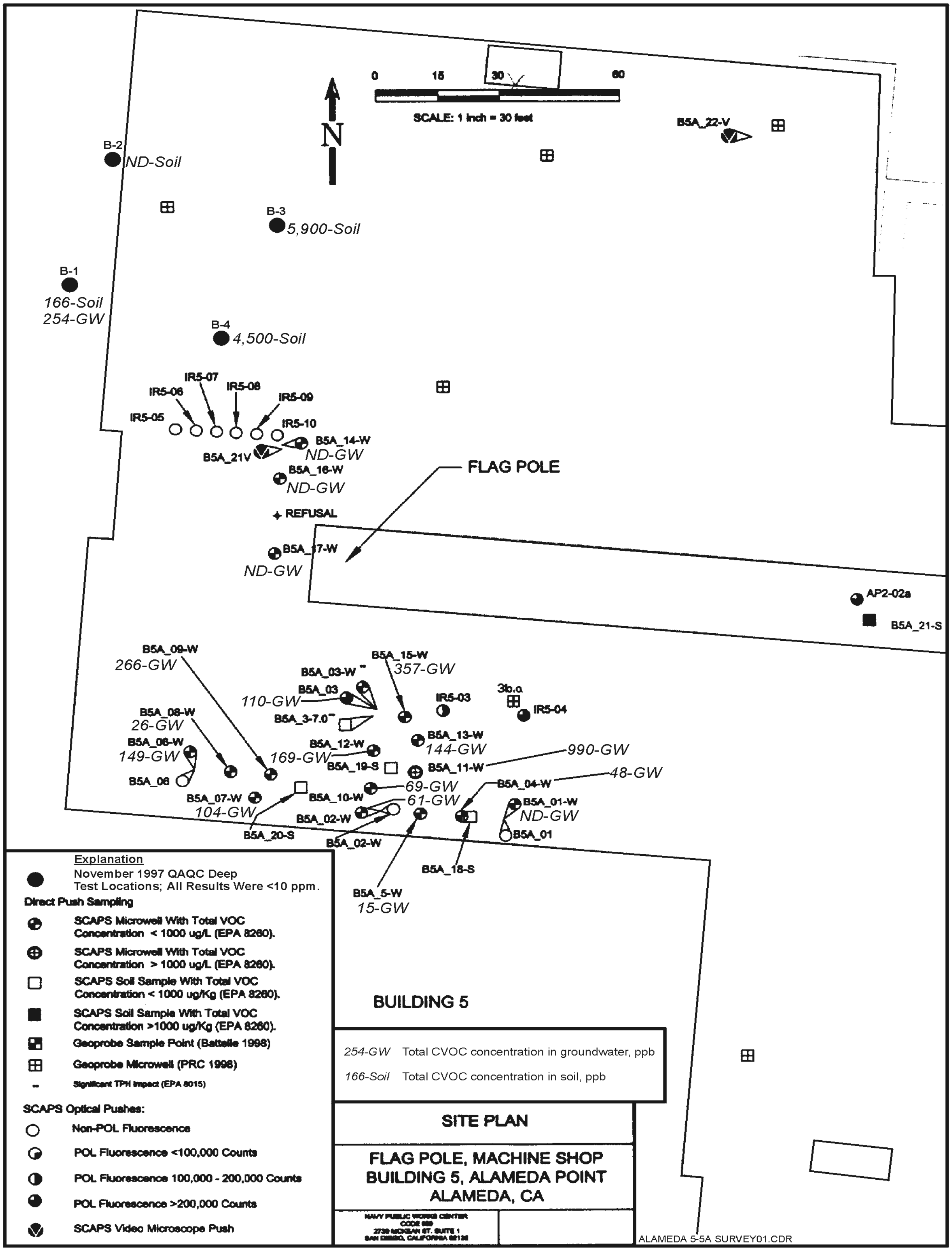

Figure 8. Map of Validation (Target) Sampling Points at Alameda Building 5.

Table 2. Comparison of EOL Predicted DNAPL Presence to Validated Target Sample Concentrations at Alameda Point, Building 5*.

Sample Location	Sample ID	Sample Depth (ft)	CVOC Concentration (ppm) in Sample	EOL Confidence Prediction for DNAPL Presence
B5A-01	B5A01-30	30	ND	Medium
B5A-02	B5A02-27.5	27.5	.006	High
B5A-03	B5A03-16	16	.110	Low
B5A-04	B5A04-17.5	17.5	.048	Low
B5A-05	B5A05-15	15	.015	Medium
B5A-06	B5A06-12.5	12.5	.149	Low
B5A-07	B5A07-12.5	12.5	.104	Low
B5A-08	B5A08-25	25	.026	Medium
B5A-09	B5A09-12.5	12.5	.266	Low
B5A-10	B5A10-12.5	12.5	.069	Low
B5A-11	B5A11-25	25	.990	Medium
B5A-12	B5A12-12.5	12.5	.169	Low
B5A-13	B5A13-12.5	12.5	.144	Low
B5A-14	B5A14-35	35	ND	Low
B5A-15	B5A15-7.5	7.5	.357	Low
B5A-16	B5A16-41.5	41.5	ND	Low
B5A-17	B5A17-41.5	41.5	ND	Low
B5A-18S#	B5A18S-30.5	30.5	ND	Medium
B5A-19S#	B5A19S-28.5	28.5	ND	Medium
B5A-20S#	B5A20S-26.5	26.5	ND	High
B1-S	B1S-7.5	7.5	30	Low
B3-S	B3S-26	26	.055	High
GP-10	GP10-7.5	7.5	109	Low

Environmental Laboratories Inc. Report March 16, 1998.
ND = Not detected.
* Groundwater SCAPS samples collected from depths ranging from 7.5 to 41.5 bgs.
# Soil sample

Table 3. Comparison of EOL Predicted DNAPL Presence to Validated Target Sample Concentrations at Alameda Point, Building 5*.

Sample Location	Soil Sample ID	Sample Depth (ft)	CVOC Concentration (ppm) in Sample	EOL Prediction for DNAPL Presence
B-1	B1-17	17	ND	High
B-1	B1-17D**	17D	.182	High
B-1	B1-24	24	ND	Medium
B-1	B1-27	27	ND	Low
B-2	B2-17	17	8.270	High
B-2	B2-24	24	ND	Low
B-2	B2-27	27	ND	Medium
B-3	B3-17	17	6.240	High
B-3	B3-24	24	ND	Low
B-3	B3-27	27	ND	Low
B-4	B4-17	17	4.980	Low
B-4	B4-23	23	.006	Low
B-4	B4-27	27	ND	High
B-1	B1-17W (water)	17W	.254	High
B-2	B2-17W (water)	17W	.031	High

TetraTech EM Inc. Report December 16, 1997.
* Analysis of sediment samples and groundwater taken from rotary drill borings.
** Duplicate sample

In the Alameda EOL survey grid, a combination of four post-survey split-spoon locations (four wells), and 21 post-survey SCAPS sample locations, all of various screening depths reaching as deep as 30 feet bgs, were tested for DNAPLs.

All samples were found to be below the 110 ppm constituent concentration criteria used to indicate the existence of free-product DNAPLs. This indicated that quantities of residual and free-phase DNAPLs were small in the studied area. Therefore any current prediction model would fail to detect an area <10 feet across, which is the resolution of the EOL method in its current configuration. This was evident when sampling at SCAPS location B5A-11 and the 5-foot step-out locations around it, B5A-01, B5A-02, B5A-03, and B5A-04. The water sample at location 11 showed 990 ppb DNAPL constituent concentration, ~1.0 ppm, usually a clear indication of DNAPLs in the Bay Mud Sediments. However, SCAPS samples 5 feet away, B5A-01 through B5A-04, did not detect any constituents >0.110 ppm. This suggests that the method cannot detect DNAPLs in current migration path configurations.

Although significant resistivity contrasts were apparent in the 3-D survey model, the technology apparently could not differentiate between resistive properties due to contamination and resistivity values caused by naturally occurring elements.

4.7.2 Tinker AFB, Building 3001, Air Logistic Center (West Side and Adjoining Land)

A 3-D model and imagery was generated for the Tinker AFB site, based on the subsurface resistivity readings and distributions found within the volume surveyed. A list of predicted target locations for Tinker AFB were developed and included within the EM resistivity site survey reports provided by GEHM Environmental. Each target location reflected the confidence of DNAPL presence, at a particular location and depth, as interpreted from the EM resistivity surveys. From this "prediction list," actual target sampling locations were selected and are depicted in Figure 9. As reflected in Figure 9, the anomalous, high, and above average resistivity contrasts, indicated in red, orange and yellow, represent the zones predicted to have significant chlorinated hydrocarbon solute concentrations in the subsurface. The green and blue colored formations represent average or background resistive contrasts, and are predicted to have minimal to no contamination.

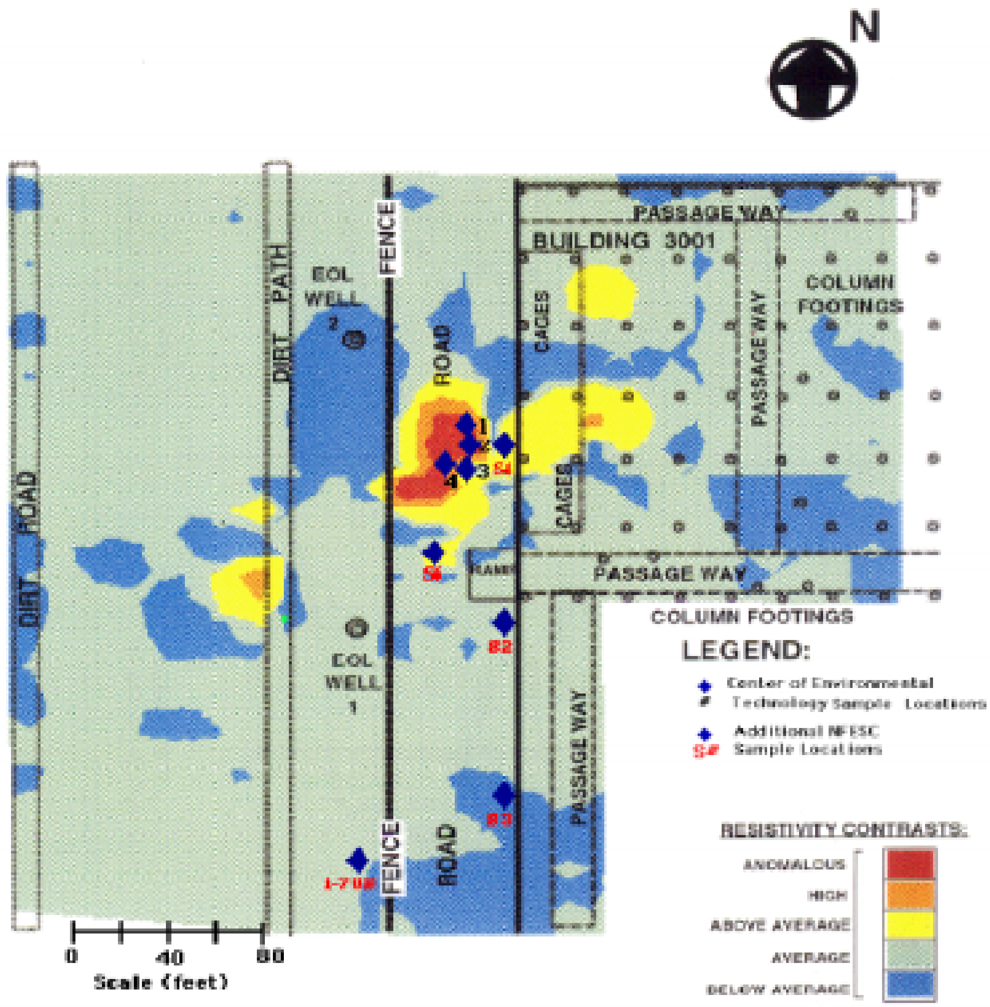

Figure 9. Composite Map of Resistivity Contrasts Above the Static Water Table and Above the Shale- CET Sample Locations, Tinker AFB, OK. *(Prepared by the Center of Environmental Technology, University of Missouri, Columbia MO)*

Sampling locations (#'s 1-4) for the post EOL survey validation drilling are shown in Figure 9. They are identified in this figure as "Center for Environmental Technology Sample Locations." This sampling effort was performed in April 1998 and concentrated on target locations predicted with a high level of confidence.

Additional post survey validation samples were obtained within the survey grid in November 1998 validation drilling for a seismic demonstration. These sample locations are also shown in Figure 9, and are denoted with a red "S". These additional samples will be referred to as "NFESC" samples. The locations of the EOL receiver wells are also shown on Figure 9, identified as "EOL Well 1" and "EOL Well 2."

The comparative results between validation sample chlorinated hydrocarbon concentrations and the EOL confidence predictions are shown in Table 4. This table compares post survey, measured chlorinated solute concentrations in the sediment samples to the initial probability of finding DNAPL at that particular point, as interpreted from EOL resistive anomalies. The results presented in Table 4 indicate there is poor correlation between high and anomalous EM readings and high Chlorinated Volatile Organic Constituents (CVOC) concentrations in subsurface soils.

In 14 cases, the EOL survey predicted a strong level of confidence in finding DNAPL in particular regions. However, in every case measured CVOC concentrations were significantly less than 110 ppm. In the two cases where CVOC concentrations did exceed the 110 ppm, the EOL prediction indicated little to no hydrocarbon contamination in that area. Overall, there was no apparent correlation between CVOC concentration and EOL predictions.

The CVOC sample concentrations shown in Table 4 represent the total DNAPL constituent concentration for each sample. For example:

$$\text{Total Measured Concentration} = x\text{ DCE ppm} + y\text{ TCE ppm} + z\text{ TCA ppm}.$$

Very low concentrations of DCE and TCE were found in subsurface soil samples collected in the validation borings (Laboratory results from Southwest Laboratory of Oklahoma included in Appendix B). Very low concentrations of TCE were found at sample depth (20-25 feet) at validation sites #1 and #2 as well as at sample depth (35-36 feet) for validation sites #3 and #4. Very low concentrations of DCE were found in the second sample depth (23 feet) at validation site #1 and the lowest depth (36 feet) at validation site #4. These low concentrations generally agree with the modeled 3-D image (GEHM 1998b). However, concentrations of the contaminants are too low to have significantly influenced the EOL resistivity or the survey results.

NFESC groundwater sample S3, taken at 40 feet bgs, was highly contaminated (150-170 ppm of CVOC). The region around S3 lies within the EOL footprint, and was measured with a below average EOL resistivity at 37 and 41 feet. EOL failed to detect this contamination. A possible reason for this missed detection is that the water in EOL-Well 1 was contaminated, thereby significantly reducing the measurement accuracy. A more likely reason for this failure is that migrating DNAPL typically produces regions of diffuse contamination that are of relatively low mass per unit of volume (mass is distributed over large volume of media). This lowers the solute concentrations well below the resolution capability of the technology.

Table 4. Comparison of EOL Predicted DNAPL Presence to Validated Target Sample Concentrations at Tinker Air Force Base, OK.

Sample Type	Sample Location	Sample ID	Sample Depth (ft)	CVOC Concentration (ppm) in Sample	EOL Confidence Prediction for DNAPL Presence
Soil	CET-2	CET2-20	20	.040	High
	CET-4	CET4-20	20	ND	High
	CET-1	CET1-21	21	.009	High
	CET-3	CET3-21	21	.004	Medium
	CET-1	CET1-23	23	.016	High
	CET-2	CET2-25	25	.007	High
	CET-3	CET3-25	25	.004	Medium
	CET-4	CET4-25	25	ND	High
	CET-4	CET4-26	26	ND	High
	CET-3	CET3-27	27	ND	Medium
	CET-3	CET3-35	35	.014	Low
	CET-4	CET4-36	36	ND	Medium
Water	EOL-Well2	EOL WELL2-35	35	3.480	Low
	CET-3	CET3-35	35	6.500	Low
	CET-4	CET4-40	40	7.400	Medium
	NFESC-S2	NFESCS2-40	40	.860	Low
	NFESC-S3	NFESCS3-40	40	151.000	Low
	NFESC-S3	NFESCS3-40	40	172.000	Low
	NFESC-S4	NFESCS4-40	40	1.250	Medium
	NFESC-S6	NFESCS6-40	40	3.310	Medium

Note: Below 110 ppm, samples are considered to have no DNAPL concentration
CET-# = U of MO Confirmation Boring taken from sample location #1,2,3, or 4

The EOL survey grid had more than ten well locations that were tested. This included a combination of two EOL-receiver wells, several wells and soil boring locations inside Building 3001, and 4 split-spoon target sample well locations. All samples tested from these wells were <110 ppm; the criteria used to indicate the existence of free-product DNAPLs.

4.8 CONCLUSIONS

One main conclusion can be drawn by comparing the measured chlorinated hydrocarbon constituent concentrations and the EOL-predicted resistive anomalies of the two sites. That is, the criteria for success was not met.

The EOL failed to detect DNAPL at the Alameda site where post-project verification sampling, and laser induced fluorescence/videoing characterization revealed significant quantities of mixed NAPL constituents in sediment and water samples taken exactly where the investigation was focused. A U.S. Navy and University of California, Berkeley, study recovered approximately 525 gallons of mixed NAPLs in the Alameda EOL study zone after the project was completed (Kram, 2000).

This study clearly shows that EOL technology will not successfully detect small chlorinated hydrocarbon solute concentrations in soil and sediments. Results of the Alameda study imply EM resistivity may not be applicable for detecting even anomalous CVOC concentrations or free-phase DNAPL in the subsurface.

Results from the two study sites indicate that EOL does not adequately predict where significant subsurface DNAPL is located. One suggested source of error was that DNAPL saturation zones were insufficiently large enough for detection by EM resistivitiy. Another possibility is that the level of subsurface DNAPL is too diffuse to significantly alter the resistivity of the sediments.

5.0 COST ASSESSMENT

5.1 COST PERFORMANCE

The EOL technique has been developed for detecting LNAPLs to the point that commercial services are offered. Hence, there are no further startup costs associated with setting up this technology. In addition, demobilization costs are relatively insignificant for easily accessible sites. The majority of the costs associated with this technology involve operation and maintenance (O&M) of the system.

This technology measures cost performance per unit of surveyed area. It is important to note that environmental project costing is very site specific and may vary significantly depending on a number of variables and factors. Costs can reach upward to several thousand dollars per day depending on the number of the variables associated with the particular project site. These variables include, but are not limited to: depth of contamination; site interference due to traffic, buildings, and surface covering; complexity of the site (i.e., number of buildings and other obstructions on the site); the amount of drilling and sampling required to adequately evaluate if DNAPL is present; depth of the wells; availability and quality of site-specific pre-survey information; local market conditions and rates to perform drilling and sampling; and the location and accessibility of the site.

Since the same EOL technique used to detect LNAPLs is used to detect DNAPLs in the subsurface, cost performance data can be appropriately drawn from the more commercialized and frequently applied LNAPL studies. However, since the results of this technology demonstration were inconclusive with respect to the direct detection of DNAPL, a detailed and accurate cost comparison and/or relation between the two applications is difficult to present.

5.2 COST COMPARISONS TO CONVENTIONAL AND OTHER TECHNOLOGIES

Shown below are the costs associated with performing a typical 3-D resistivity survey encompassing approximately a 2-acre grid. (This information has been provided by GEHM Environmental.)

Site Review	$ 1,000
EM Resistivity Well Installation	$ 8,000
Data Acquisition	$18,000
Data Processing	$10,000
Survey QA/QC Verification Boring	$ 6,000
Data Display and Reporting	$ 1,500
TOTAL	**$44,500**

Note: Mob/DeMob costs will depend on the location of the site.

Table 5 presents a breakdown of the cost of key activities related to the surveys and validation performed at Alameda Point and Tinker AFB.

Table 5. Project Cost Breakdown per Site*.

Activity	Alameda Point ($)	Tinker AFB ($)
Drill Wells for EOL Survey	12,484	26,840
Samples for EOL Survey	800	800
Conduct EOL Survey	39,804	18,293
Generate EOL Survey Report	8,327	8,526
Conduct verification drilling and sampling	64,403	51,412
Mob/De-Mob	8,000	8,000
Generate Project Summary Report	20,391	20,391
Approximate survey cost per acre	154,209	134,262

* Surveyed area is 1 acre.

The following details related to costs and activities for the work performed at the demonstration sites may be useful for planning future EM resistivity surveys:

- Advantageous cost benefits are most frequently found in the reduction of wells required to perform a given site characterization.
- EM resistivity surveying becomes much more cost-effective at sites that require extensive well drilling and sampling.
- EM resistivity eliminates costs associated with site disruption and disturbance that would be unavoidable with conventional drilling and sampling techniques.
- Drilling and sampling costs were strongly influenced by each site's geologic setting. For example, sites with subsurface geologic conditions favorable to direct push methods are less expensive than those that require conventional drilling methods.
- The cost of demobilization was relatively insignificant. It consisted of the minimal effort for personnel to pack up the 3-D EM resistivity instrumentation and leave the site.
- Given that 3-D EM resistivity surveys are services provided by commercial agencies, any costs for maintenance and replacement of system components are included in individual project costs.

Aside from site characterization savings, the greatest contributor to the overall savings is having a technology that provides more detailed information in less time.

Table 6 below, provided by GEHM Environmental, shows a cost comparison for a traditional drilling approach verses a drilling approach that includes EM resistivity surveys for the characterization of an LNAPL site at Naval Air Station North Island. This project's cost data shows a 24% savings in total cost by using the 3-D EM survey technique. In addition, it is important to note that this cost comparison did not take into account additional time and costs that would be incurred to apply conventional site characterization methods. The EM survey technique's cost-effectiveness becomes clearly apparent at sites that require extensive well drilling and sampling. For example, the 2 acres at NAS North Island adjacent to the LNAPL EM surveyed area, required 62 wells and six months to completely characterize using conventional drill and sample methods. Larger sites help offset the higher cost to operate the EM system. Cost Comparison for Traditional Drilling Approach to EOL with Drilling Approach analyze the complex data. A final hidden cost savings of using EM resistivity, not depicted in Table 5, is the fact that EM surveys are minimally disruptive to normal site operations. In this case, EM did not disrupt ongoing engine overhauls at the Naval Air Depot (NADEP) or block the adjacent street that carried critical NADEP traffic.

Table 6. Cost Comparison for Traditional Drilling Approach to EOL with Drilling Approach.

Comparison Category	Traditional Approach	EOL with Drilling Approach
1. Background information known prior to comparison	2 acres with known hydrocarbon contamination; 2 acres unknown	2 acres with known hydrocarbon contamination; 2 acres unknown
2. Typical monitoring well construction	40-foot, 2-inch diameter PVC/Schedule 40	40-foot, 2-inch diameter PVC/Schedule 40
3. Monitoring wells needed outside buildings	20 wells (10 wells per acre) = $20,000	8 wells (3 EOL receiver wells; 3 wells for data correlation model validation; and 2 wells for contingency) = $8,000
4. Monitoring wells needed inside buildings	2 wells = $3,000	0 wells
5. Mobilization/Demobilization (drill rig)	= $4,000 ($2,000/rig) 1 rig outside, 1 low-profile rig for in building	= $2,000 (1 rig for outside)
6. Drilling costs (includes rig, drill crew, materials, and incidentals)	= $1,000/well (outside) = $1,500/well (inside)	= $1,000/well (outside)
7. Well logging, development, and investigative derived waste disposal	$370/well (2 hours labor at $60/hr + $50/drum + $200/drum disposal cost) = $8,140	$370/well (2 hours labor at $60/hr + $50/drum + $200/drum disposal cost) = $2,960
8. Sampling and analytical costs (4 samples collected per well; 4 TPH-diesel and 1 SVOC analysis)	$600/well = $13,200	$600/well = $4,800
9. EOL costs (2 days field work, mobilization/demobilization, prepare report)	= $0	= $17,800 ($7,000/day for 2 days + $3,800 mob/demob)
Total Estimated Costs	**$48,340**	**$36,560**

Notes: TPH = Total Petroleum Hydrocarbons
SVOC = Semivolatile Organic Compounds

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6.0 IMPLEMENTATION ISSUES

If the EOL technique can be adapted and improved to accurately and consistently characterize and image subsurface anomalies in 3-D, it has the potential to be an economical technique that can provide much more detailed and useful imaging models than many other currently available technologies.

It was initially believed that the EOL technology's success in delineating LNAPLs in the subsurface would be easily carried over in the subsurface characterization of DNAPLs. The results of the Alameda Point and Tinker AFB demonstration found this no to be the case. It is presumed that though LNAPLs and DNAPLs are similar in resistivity, their difference in density can significantly impact mass distribution in the subsurface. LNAPL tends to collect in a narrow vertical range in the capillary fringe at or just above the water table forming a layer of low electrical conductivity just above the more conductive water and saturated sediments. DNAPLs can be found in regions of relatively low mass per volume. Here, mass is concentrated within a small volume of media. This can contribute to their ability or inability to be detected by an EM survey.

NFESC is currently evaluating the capabilities and limitations of using 3-D EM resistivity surveys to locate DNAPLs. A fact sheet will be developed that describes the appropriate uses and expected benefits of EOL technology, particularly with respect to DoD needs. This most recent demonstration of EOL technology has shown that it is not ready for transfer and implementation at DoD sites. However, if after further development the technology proves to be accurate and consistent, NFESC will play a critical role in transferring information on the system throughout the DoD.

6.1 COST OBSERVATIONS

Contributing cost factors to a typical EM survey include site review, mobilization, EM resistivity well installation, data acquisition, data processing, survey verification boring and sampling, and data display and reporting. Project costing for the EOL technology is very site specific and depends on a number of variables such as: depth of contamination; site interference due to traffic, buildings, and surface covering; quantity of drilling and sampling required to adequately evaluate the presence of DNAPL; local market conditions and rates; and the availability and quality of site-specific pre-survey information.

The most significant factor making EM resistivity surveys more cost effective than traditional subsurface DNAPL characterization drilling approaches, is the smaller quantity of wells that need to be drilled in a specific area. A considerable amount of money is saved in drilling, mobilization/demobilization, well installation and development, IDW disposal, and sampling and analysis costs with the EOL technology as compared to conventional drilling.

6.2 PERFORMANCE OBSERVATIONS

A significant problem observed in this demonstration involved the large number of false negatives in the survey results. Areas within the EOL survey zone that were predicted to have little to no subsurface contamination, have since been identified as actually having considerable DNAPL concentrations. SCAP LIF, SCAPS GeoVis, and SCAPS soil sampling characterization methods were used to truth sample these areas. Visible verification coupled with analytical results (3000+

mg/kg TCE in soil) gave strong support for the presence of DNAPL at the site. In addition, a recent steam enhanced extraction method demonstration project at the site removed over 500 gallons of NAPL.

It is possible that complications related to DNAPL source zone configuration may render this method unsuccessful under many conditions. The current conceptual models for DNAPL transport which describe residual phased materials as globules and ganglia imply that the material resides in narrow elongated configurations in which the mean saturation of DNAPL is potentially small. Unless pooled by some structural feature, the overall resistivity contrast posed by DNAPL presence and distribution appears to be imperceptible by the EOL technique at these sites. If a pool does exist and is caused by a structural feature, the EOL method may be capable of illuminating this attribute, but this does not support the claims that DNAPL can be directly detected.

The premise of the EOL technology is that "large volumes" of DNAPL are required for successful implementation. Due to the nature of DNAPL migration and plume configuration, it may be speculated that even "large" sites will pose challenges. Sufficient configuration (e.g., large, continuous plumes with high DNAPL volume per soil volume ratios) may be more important than sufficient volumes. If true, these sites may be categorized as typical, since DNAPL plume configuration is dictated by hydrodynamic constraints which prevent accumulation of large plumes. An exception to this would occur if the plume encounters structural or hydrogeological barriers which exceed fluid pore entry pressures.

Overall, due to the inconsistent results of this project, the EOL technology has not demonstrated the required performance capabilities to warrant immediate study at future full-scale application.

6.3 REGULATORY ISSUES

Many sites at DoD installations are listed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). These DoD installations are engaged in active Installation Restoration Programs. Remedial Investigations are an integral element of the CERCLA process. A main objective of a Remedial Investigation is to determine the nature and extent of contamination at waste sites so that an effective remedial design can be implemented. 3-D EM resistivity imaging tends to support these efforts by providing information on subsurface site geologic features and contaminant distribution.

Electromagnetic resistivity surveys are relatively non-invasive; however, they do require that at least two instrumentation wells are located and, if necessary, installed within a few hundred feet of the region of interest. In addition, subsurface samples must be taken, using either conventional drilling and sampling techniques or direct push methods. As a result, the prevention of cross contamination through an upper confining layer situated above an uncontaminated aquifer is a primary concern at any site. Steps were taken to mitigate this regulatory concern. The Geoprobe® and Site Characterization and Analysis Penetrometer System (SCAPS) methods consisted of pushing a small diameter probe into the ground, and were a relatively slight intrusion into the subsurface. Both wells were grouted and sealed after the EM survey, and within two weeks after the well installation. These push borings were limited to the upper confining layer, and were immediately grouted upon recovery of samples. These procedures minimized any potential for creating preferential pathways through which DNAPLs could migrate.

In addition, contractors obtained proper clearances and permits for the installation of the borings, and had each potential push location cleared for utilities. The contractors also disposed of investigation-derived wastes (IDW) that were generated during this effort in accordance with Resource Conservation and Recovery Act (RCRA) guidelines. IDW consisted of the wash-down water used to decontaminate the Geoprobe and SCAPS probes and samplers after each use, as well as all borehole and well drill cuttings. These wastes were contained in 55-gallon drums per regulatory requirements. An additional permit was required to temporarily accumulate the IDW at the site.

A final regulatory issue involved the transmission of electromagnetic radiation from the equipment. The magnitude of the electromagnetic field generated by the signal transmitter was less than an EM field generated by the 15-amp (A) power lines in a 10-x-10-foot room, when standing 4 feet from the transmitter. Thus, the magnitude of EM radiation at the site was relatively small. Regulatory and safety issues were avoided by maintaining a 4-foot safety distance from the energized transmitter. Due to these considerations, a special permit to operate the EM technology was not required.

6.4 LESSONS LEARNED

The results from the two sites that hosted demonstrations are at best inconclusive because EOL imaging provided inaccurate and inconsistent predictions or indications of DNAPL presence in areas proven to have significant NAPL and DNAPL contamination. An additional limiting factor is that since the data is remote and is modeled, the location of suspected anomalies is not exact. Demonstrating the EM surveys with these variables in mind will significantly reduce the margin of uncertainty and error associated with the system and the user. When EM site characterization for DNAPL in the field becomes better understood under controlled variables, its ability to readily detect and image subsurface anomalies under varying conditions can be enhanced.

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APPENDIX A

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