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Final Report

TTP AL921102

**An Integrated Geophysics Program
for Non-Intrusive Characterization of
Mixed-Waste Landfill Sites**

September 1993

J. C. Hasbrouck

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Work performed under DOE Contract No. DE-AC04-86ID12584 for the U.S. Department of Energy
Grand Junction Projects Office

Chem-Nuclear Geotech Inc.

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Contents

	Page
Executive Summary	v
Introduction	1
Description of Surveys	4
Overview	4
Quality Assurance	4
Complex Galvanic Resistivity and Spontaneous Potential	6
Ground-Penetrating Radar	6
Surface Time-Domain Electromagnetics	6
Surface-to-Borehole Time-Domain Electromagnetics	7
S-Wave Refraction Seismic	7
P-Wave Reflection Seismic	7
Results and Interpretation	8
Background	8
General	8
Line 20E	9
Line 60E	17
Line 125E	18
Summary and Conclusions	42
Acknowledgments	46
References	47

Figures

Figure 1. Location of MWLID Test Site at Technical Area 3	1
2. Technical Area 3, Chemical Waste Landfill, and Locations of Geophysical Survey Areas	2
3. Geophysical Survey Area A	2
4. Geophysical Survey Area B	3
5. Complex Galvanic Resistivity, Parallel-Dipole Electrode Array ($\alpha = 10$ feet, $n = 1$ to 6), Line 20E	10
6. Complex Galvanic Resistivity, Dipole-Dipole Electrode Array ($\alpha = 10$ feet, $n = 1$ to 6), Line 20E	11
7. Complex Galvanic Resistivity, IP Modeling Parameters	13
8. Complex Galvanic Resistivity, Vertical Dike IP Model ($\alpha = 10$ feet, $n = 1$), Line 20E	13
9. Complex Galvanic Resistivity, Vertical Dike IP Model ($\alpha = 10$ feet, $n = 3$), Line 20E	14

Contents (continued)

	Page
Figure 10. SP, Line 20E	14
11. GPR (80 MHz), Line 20E	16
12. Surface TDEM, 300-Hz Field Data, 10- by 10-Meter Transmitter Loop, Line 20E	17
13. Surface TDEM, 300-Hz Free-Space Response Modeled Data, One Vertical and Two Horizontal Sources, 10- by 10-Meter Transmitter Loop, Line 20E	18
14. Surface TDEM, 300-Hz Free-Space Response Modeled Data, One Vertical and One Horizontal Source, 10- by 10-Meter Transmitter Loop, Line 20E	19
15. S-Wave Refraction Seismic, Files 35 and 36, Line 20E	20
16. S-Wave Refraction Seismic, Expanded Portion with Moveout Removed, Files 35 and 36, Line 20E	21
17. S-Wave Refraction Seismic, Arrival Times with Regional Trend Removed, File 35, Line 20E	22
18. S-Wave Refraction Seismic, Power Spectral Density, Stations 147.5 to 155, File 35, Line 20E	22
19. P-Wave Reflection Seismic, CMP Stacked Section with 0- to 60-Hz Bandpass Filter, Line 20E	23
20. Complex Galvanic Resistivity, Parallel-Dipole Electrode Array ($\alpha = 10$ feet, $n = 1$ to 6), Line 60E	24
21. Complex Galvanic Resistivity, Dipole-Dipole Electrode Array ($\alpha = 10$ feet, $n = 1$ to 6), Line 60E	25
22. SP, Line 60E	26
23. GPR (80 MHz), Line 60E	27
24. Surface TDEM, 300-Hz Field Data, 10- by 10-Meter Transmitter Loop, Line 60E	28
25. Surface TDEM, 300-Hz Field Data, 5- by 5-Meter Transmitter Loop, Line 60E	28
26. Surface TDEM, 300-Hz Free-Space Response Modeled Data, One Vertical Source, 5- by 5-Meter Transmitter Loop, Line 60E	29
27. S-Wave Refraction Seismic, Files 85 and 86, Line 60E	30
28. P-Wave Reflection Seismic, CMP Stacked Section with 0- to 60-Hz Bandpass Filter, Line 60E	31
29. Complex Galvanic Resistivity, Parallel-Dipole Electrode Array ($\alpha = 10$ feet, $n = 1$ to 6), Line 125E	32
30. Complex Galvanic Resistivity, Dipole-Dipole Electrode Array ($\alpha = 10$ feet, $n = 1$ to 6), Line 125E	33
31. SP, Line 125E	34
32. GPR (80 MHz), Line 125E	35
33. Surface TDEM, 300-Hz Field Data, 10- by 10-Meter Transmitter Loop, Line 125E	37

Contents (continued)

	Page
Figure 34. Surface TDEM, 300-Hz Field Data, 5- by 5-Meter Transmitter Loop, Line 125E	37
35. S-Wave Refraction Seismic, Files 306 and 307, Line 125E	38
36. S-Wave Refraction Seismic, Expanded Portion with Moveout Removed, Files 306 and 307, Line 125E	39
37. S-Wave Refraction Seismic, Power Spectral Density, Stations 262.5 to 270, File 306, Line 125E	40
38. P-Wave Reflection Seismic, CMP Stacked Section with 0- to 60-Hz Bandpass Filter, Line 125E	41

Tables

Table ES-1. Geophysical Techniques Applicable to Mixed-Waste Landfill Characterization	vi
1. Approximate Subsurface Data Coverage by Station Number	5
2. Anomaly Location Summary by Station Number	43
3. Geophysical Techniques Applicable to Mixed-Waste Landfill Characterization	45

Executive Summary

This Technical Task conducted for the U.S. Department of Energy Office of Technology Development demonstrates the effectiveness of integrating several surface geophysical techniques to nonintrusively characterize mixed-waste landfill sites. An integrated approach enables an area to be characterized faster and cheaper because repeated access is not necessary and offers data and interpretations not attainable by a single technique.

Field demonstrations using the complex galvanic resistivity, spontaneous potential (SP), ground-penetrating radar (GPR), time-domain electromagnetic (TDEM), shear-wave (*S*-wave) seismic and compressional-wave (*P*-wave) seismic geophysical techniques were conducted at the Mixed-Waste Landfill Integrated Demonstration (MWLID) test site at the Sandia National Laboratories/New Mexico in Albuquerque. Data were acquired in two areas that have both known and unknown attributes. Although data from numerous profiles were analyzed, three lines were chosen as representative of the landfill site: Line 20E that crosses both the known Chromic Acid and Organics Pits, Line 60E that transectes an essentially barren area, and Line 125E located in an area with unknown subsurface conditions.

The locations of the known Chromic Acid and Organics Pits were interpreted at or near their historical boundaries, unknown pits were identified, areas of disturbance possibly related to contaminants were interpreted outside the boundaries of both the known and unknown pits, rudimentary waste types were identified and modeled where appropriate, and anomalies from recent activities were identified and discounted from further analyses. Pit boundaries and basic geometries (horizontal and vertical extent) were identified to less than 3 feet through integrated interpretation of complex

galvanic resistivity, GPR, and *S*-wave seismic data. Indication of metallic debris within the identified pits was accomplished through combined interpretation of all the data sets; the presence of nonmetallic debris was interpreted if an anomaly was indicated in the *S*-wave seismic, *P*-wave seismic, or GPR data but was not evident in the complex galvanic resistivity or TDEM data. All debris were assumed to be within pits, thus further constraining their interpreted geometries. Disturbed areas were interpreted within all the data sets. However, an integrated interpretation was necessary to determine either the source or extent of disturbances. Contaminant migration beyond the historical pit boundaries was suggested from interpretation of the data, but no identification of discrete contaminants or assignment of concentrations was possible.

Three characterization needs were addressed in this Task (pit boundary location, waste volume characterization, and contaminant plume detection). Table ES-1 presents a numerical grade for eight geophysical techniques that are applicable to characterization of mixed-waste landfills. Using the table as a guide, a project manager can select multiple geophysical techniques for faster, cheaper, and better characterization of an area than that possible with a single technique. However, the characterization needs addressed are not unique to mixed-waste landfill sites. A program that integrates numerous geophysical techniques is applicable at many U.S. Department of Energy environmental restoration sites. However, this type of geophysics program must be conceived, conducted, monitored, and interpreted by trained, knowledgeable, experienced geophysicists without intellectual or fiscal bias toward a particular technique.

Table ES-1. Geophysical Techniques Applicable to Mixed-Waste Landfill Characterization^a

Method	Pit Boundary Location	Waste Volume Characterization	Contaminant Plume Detection
Magnetic Gradiometer ^b	4	3	N/A
Complex Galvanic Resistivity ^c	4	3	4
Spontaneous Potential	1	2	2
GPR	3 ^d	3	N/A
Surface TDEM	2 ^e	3 ^f	2 ^g
Surface-to-Borehole TDEM	1	2	2 ^h
S-Wave Seismic	4	2 ⁱ	1
P-Wave Seismic	2 ^j	1	N/A

^aThe methods are graded from 1 to 4 on the basis of least applicable to the identified need "1" or most applicable to the identified need "4"; N/A = not applicable.

^bFrom Naval Research Laboratory and Naval Explosive Ordnance Technology Center report dated April 30, 1992.

^cAt least two types of arrays should be used: parallel-dipole and dipole-dipole.

^dOnly when interpreted in conjunction with other methods.

^e"Small" pits not resolved; "large" pits well resolved.

^f"Small" contents not resolved; "large" contents well resolved.

^gSubtle anomalies overshadowed by anomalies from metallic objects.

^hNear surface not well resolved.

ⁱDifficult to determine depth, therefore difficult to calculate volume.

^jUseful for general determination of presence of pits (i.e., continuous or noncontinuous reflection).

Introduction

Chem-Nuclear Geotech, Inc. (Geotech), operating contractor for the U.S. Department of Energy Grand Junction Projects Office (DOE-GJPO), conducted the Integrated Geophysics Program for Non-Intrusive Characterization of Mixed-Waste Landfill Sites (Technical Task Plan [TTP] AL921102) as a part of the Mixed-Waste Landfill Integrated Demonstration (MWLID). The objective of this task was to demonstrate that an integrated program of surface geophysics can be used to characterize mixed-waste landfill sites effectively and nonintrusively.

To accomplish this objective, field demonstrations were conducted over two previously identified areas of interest (designated Areas A and B) within the MWLID test site at the Technical Area 3, Chemical Waste Landfill, at the

Sandia National Laboratories/New Mexico in Albuquerque (Figures 1 and 2). The demonstration area was completely surrounded by a 6-foot, chain-link fence. Area A (Figure 3) was centered roughly around the Chromic Acid and Organics Pits in the southeast-central portion of the landfill, and Area B (Figure 4) was centered around the "60's Pits" area in the northeast-central portion of the landfill. Pit locations were known in Area A and suspected in Area B. This report describes the geophysical surveys conducted by Geotech and presents the results and interpretation of data from those surveys. Copies of the raw data for all the surveys conducted by Geotech for this TTP are in Volume 2 of the *FY 1992 Year-End Progress Report* (Hasbrouck 1992).

Figure 1. Location of MWLID Test Site at Technical Area 3

Figure 2. Technical Area 3, Chemical Waste Landfill, and Locations of Geophysical Survey Areas

Figure 3. Geophysical Survey Area A

Figure 4. Geophysical Survey Area B

Description of Surveys

Overview

The use of a particular geophysical technique primarily depends on the target of interest, the geology of the survey area, and the possible interference from surrounding cultural objects. Because each technique measures different physical parameters and/or is appropriate for different situations, an integrated approach offers data and interpretations that are not attainable by a single technique. Three needs were identified as major components of mixed-waste landfill characterization: pit boundary location, waste volume characterization, and contaminant plume detection. Geophysical methods applicable to these needs include

- Magnetic Gradiometer
- Complex Galvanic Resistivity
- Spontaneous Potential (SP)
- Ground-Penetrating Radar (GPR)
- Time-Domain Electromagnetic (TDEM)
- Shear-Wave (S-wave) Refraction Seismic
- Compressional-Wave (P-wave) Reflection Seismic

Geotech conducted field demonstrations of each of the techniques listed above except for the magnetic gradiometer surveys. The Naval Research Laboratory and Naval Explosive Ordnance Disposal Technology Center performed magnetic gradiometer surveys in December 1991 (Naval Research Laboratory 1992). These data were reviewed and judged to be of high quality; there was no perceived need to repeat this method. Table 1 presents the approximate subsurface area of data acquisition for each technique. Subsurface areas are approximate because they are relative to each technique's data acquisition parameters and theoretical assumptions.

Surface geophysical data were acquired during two field trips: May 12 through 20, 1992, and May 27 through June 3, 1992. The surface-to-borehole data were acquired during a separate field trip on July 18 and 19, 1992. All data were either acquired or downloaded

onto computer diskettes in the field, transferred to a computer hard disk at the completion of each field day, and backed up on magnetic tape before demobilization. Daily review of all survey data permitted daily decisions on data acquisition activities. Preliminary analysis of previously acquired Navy magnetic data and S-wave refraction seismic data acquired by Geotech on a grid of lines 10 feet apart indicated that efforts should be concentrated along three profiles within each survey area to best meet the objective of the project. Those three profiles traversed both pit and barren areas. Data were acquired along other profiles only with the techniques and field setup that appeared to be producing high-quality interpretable results. All profiles were tied to an existing grid that was referenced to State plane coordinates.

Quality Assurance

Data quality was ensured through specific measures to assess the precision, accuracy, representativeness, completeness, and comparability of the geophysical survey data. Work was controlled by following existing procedures, when practical. When procedures were not practical, the work was controlled by the Work Plan, the TTP, and the task documentation.

Complex galvanic resistivity, SP, TDEM, and seismic data were acquired at data points that were defined as discreet; GPR data were acquired continuously along each survey line. To provide a measure of the precision of the data acquired, at least 10 percent of the profiles of the surface data and 5 percent of the borehole TDEM data are repeated. Geophysical equipment manufacturers do not usually follow a formal instrument calibration or standardization program. Because most geophysical data are relative (anomalies, not absolute values, are sought), a calibration-standardization program is not used. Instead, the instruments are periodically returned to the manufacturer, or authorized representative, for calibration or standardization to their internal company specifications to confirm designed measurement accuracy. If necessary, approximate field standardizations of GPR and seismic data are

Table 1. Approximate Subsurface Data Coverage by Station Number^a

Line-Area	S-Wave Seismic	P-Wave Seismic	R/IP W5	R/IP W10	R/IP DP10	R/IP DP20	R/IP II-DP	GPR	TDEM (5 x 5)	TDEM (10 x 10)	SP
0E-A	65-180	—	—	—	—	—	—	—	—	—	—
10E-A	65-180	—	—	—	—	—	—	—	—	—	—
20E-A	65-180	90-155	65-155	65-155	35-155	0-140	55-155	65-185	—	65-215	65-165
30E-A	65-180	—	—	—	35-155	—	—	65-185	—	—	—
35E-A	—	—	—	—	—	—	—	65-185	—	—	—
40E-A	65-180	90-155	65-155	65-155	35-155	—	55-155	65-185	65-215	65-215	65-165
50E-A	65-180	—	—	—	35-155	—	—	—	—	—	—
60E-A	65-180	90-155	65-155	65-155	35-155	—	55-155	95-185	65-215	65-215	65-165
70E-A	65-180	—	—	—	—	—	—	—	—	—	—
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20N-A	—	—	—	—	—	—	—	0-55	—	—	—
35N-A	—	—	—	—	—	—	—	0-55	—	—	—
85N-A	-5-70	—	—	—	—	—	—	—	—	—	—
95N-A	-5-70	—	—	—	—	—	—	—	—	—	—
105N-A	-5-70	—	—	—	—	—	—	0-100	—	—	—
110N-A	—	—	—	—	—	—	—	0-100	—	—	—
115N-A	-5-70	—	—	—	—	—	—	—	—	—	—
125N-A	-5-70	—	—	—	—	—	—	—	—	—	—
135N-A	-5-70	—	—	—	—	—	—	—	—	—	—
145N-A	-5-70	—	—	—	—	—	—	0-100	—	—	—
155N-A	-5-70	—	—	—	—	—	—	—	—	—	—
165N-A	-5-70	—	—	—	—	—	—	—	—	—	—
185N-A	—	—	—	—	—	—	—	0-100	—	—	—
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125E-B	185-300	210-265	170-290	170-290	140-300	140-280	170-290	185-300	185-330	185-330	185-330
135E-B	185-300	210-265	—	—	140-300	—	170-290	185-300	185-330	185-330	185-330
145E-B	—	—	—	—	140-300	—	—	185-300	—	185-330	—
155E-B	185-300	210-265	170-290	170-290	140-300	140-280	170-290	185-300	185-330	185-330	185-330
185E-B	185-300	210-265	—	—	—	—	—	185-300	—	—	185-330
212E-B	—	—	—	—	—	—	—	125-185	—	—	—
220E-B	—	—	—	—	—	—	—	100-185	—	—	—
247E-B	—	—	—	—	—	—	—	145-165	—	—	—

^aS-wave seismic = shear-wave refraction seismic; P-wave seismic = compressional-wave reflection seismic; R/IP W5 = resistivity/induced polarization (IP), Wenner Array, $a = 5$ feet; R/IP W10 = resistivity/IP, Wenner array, $a = 10$ feet; R/IP DP10 = resistivity/IP, dipole-dipole array, $a = 10$ feet; R/IP DP20 = resistivity/IP, dipole-dipole array, $a = 20$ feet; R/IP II-DP = resistivity/IP, parallel-dipole array, $a = 10$ feet; GPR = ground-penetrating radar; TDEM (5 x 5) = surface time-domain electromagnetic (TDEM), 5- by 5-meter eight-turn transmitter loop; TDEM (10 x 10) = surface TDEM, 10- by 10-meter, one-turn transmitter loop; and SP = spontaneous potential.

made from instructions in the instruments' operator's manuals (e.g., speed of electromagnetic energy for GPR or sound in air for seismic).

Representativeness, completeness, and comparability of the geophysical survey data were

achieved on the basis of the data precision and accuracy previously described. A field surveillance was conducted by the Geotech Quality Assurance Section; data quality was determined to be sufficient to satisfy the objective of the task.

Complex Galvanic Resistivity and Spontaneous Potential

Complex galvanic resistivity and SP data were acquired simultaneously using the same instrumentation; SP data also were acquired with an independent system. Simultaneous complex galvanic resistivity and SP data were acquired using an Androtex TDR-6 multichannel resistivity-IP-SP receiver and a Phoenix IPT1 transmitter. Ten induced polarization (IP) windows were measured on as many as six dipoles simultaneously. All data were stored in the instrument's internal memory in a format compatible with the Geosoft IP Plotting System computer software. Independent SP data were acquired with a digital voltmeter (Omega model HHM57) and recorded in a field notebook.

The simultaneous complex galvanic resistivity and SP data were acquired through the use of electrode arrays: two current electrodes (into which current was injected) and two potential electrodes (from which the resulting electric potential was measured). Different types of electrode arrays were used to minimize the effects of nearby cultural features (e.g., metal fences) and electromagnetic coupling and to maximize the amount of useful data.

Data were acquired with the following electrode array types: (1) Wenner configuration with a spacings* of 5 and 10 feet and at least $3a$ away from the fence; (2) dipole-dipole (axial-dipole) configuration with 10- and 20-foot a spacings and $n = 1$ to 6 and at least na away from the fence; and (3) parallel-dipole (equatorial-dipole) configuration with 10-foot a spacings and $n = 1$ to 6, dipoles perpendicular to the fence and distance na away. Independent SP data were acquired using two potential electrodes—one as a fixed reference and the other roving.

Electromagnetic coupling, primarily to the surrounding metal fence, was significant over portions of the survey areas. Therefore, depth soundings using the Schlumberger-array configuration were not conducted. All data were

processed and displayed through use of Androtex's Data Editor V3.01, GEOSOFT's IP Plotting System V2.0, and QUATTRO PRO computer software.

Ground-Penetrating Radar

A Geophysical Survey Systems Inc. (GSSI) SIR8 impulse radar system that included a transmitter, receiver, recorder, and antenna was used in these surveys. Initially, data were acquired along selected profiles with 80- and 300-megahertz (MHz) antennae. A lower frequency antenna afforded greater depths of investigation with limited resolution compared with a higher frequency antenna that would provide limited depths with greater resolution. Graphic records of the data produced in the field were reviewed, and additional surveys were conducted as necessary. Data were acquired on magnetic tape suitable for additional processing and analysis using the GSSI RADAN 1 V3.0 software package.

Surface Time-Domain Electromagnetics

A Geonics Ltd. EM-47 TDEM system was used in these surveys. The EM-47 system consisted of a wire-loop transmitter, generally configured in a 5- or 10-meter square, a magnetic dipole receiver coil, and associated transmitter and receiver consoles. All data were stored within the system's receiver console and were processed and displayed using Geonics Ltd. GSPX7 V1.0 and Interpex Ltd. TEMIX PLUS V1.0 software. Data were separately acquired at 5-foot intervals using the 5- by 5-meter eight-turn and 10- by 10-meter one-turn transmitter with a 10-meter offset to the receiver coil and a 16-meter offset to the receiver console. To minimize the effects of the metal fence, data were acquired at a distance away from the fence that equaled at least one side of the transmitter loop. These field data acquisition parameters were chosen from previous experience at similar sites and field evaluation of preliminary results.

*For Wenner, dipole-dipole and parallel-dipole electrode arrays, a spacing refers to the distance between the two current or the two potential electrodes, which are equal for these arrays. The current and potential electrode pairs are distance n (generally an integer) times a apart.

Surface-to-Borehole Time-Domain Electromagnetics

The surface-to-borehole TDEM survey was conducted after the surface surveys using a Geonics Ltd. EM-47 TDEM system coupled to a BH-43 downhole receiver system. The EM-47 system consisted of a wire-loop transmitter, generally configured in a 5- or 10-meter square. The BH-43 system comprised one vertically oriented receiver and associated electronics that were capable of deployment down a borehole. All data were stored within the system's receiver and were processed and displayed using the Geonics Ltd. GSPX7 V1.0 software. Data were acquired with the receiver deployed in each of the three boreholes adjacent to and within the Chromic Acid Pit. Initially, data were acquired with the transmitter loop located in a barren area determined on the basis of preliminary analyses of data from the previous surface surveys.

Subsequently, data were acquired with the transmitter loops within the historic boundary of the Chromic Acid Pit. The transmitters were configured separately with 5- by 5-meter eight-turn and 10- by 10-meter one-turn wire loops, both with a minimum 10-meter offset to the receiver console. To minimize the effect of the metal fence, the transmitters were located a nominal distance from the fence equal to at least one side of the transmitter loop.

S-Wave Refraction Seismic

An EG&G Geometrics ES-2401 signal enhancement seismograph coupled to a Geo-Stuff model RS-48/24 roll-along box was used for the surveys. A roll-along box was used to lay out two geophone spread cables, each with 24 takeouts; any contiguous set of 24 channels was selected for data acquisition. Seismic energy was generated by striking a 20-pound (lb) sledgehammer horizontally against a rectangular steel fixture coupled to the ground. The steel fixture had a mass of 90 lb, measured approximately 12 by 20 inches at the base, and was coupled to the ground by eight 8-inch spikes. The relatively large mass of the steel fixture plus the mass of the operator standing on

the fixture provided excellent coupling with the ground. The seismic energy was received with uniquely designed two-spike, 40-hertz (Hz) horizontal geophones (the spikes are located on both ends of the geophone and offer excellent coupling to the ground and reduction of possible spurious vibrations).

Field noise analysis tests ("walkaways") of the S-wave data were conducted initially. A walkaway is conducted by moving the source points to successively larger offsets while keeping the geophones at fixed locations. As a result of the walkaway test analysis, data were acquired with the geophones separated 2.5 feet and oriented transverse to the axis of the survey line and with the source points located 10 feet from each end of the 24-geophone spread. All data were stored on 3.5-inch flexible disks within the seismograph in SEG-2 (Society of Exploration Geophysicists) standard format. The data were converted, processed, and analyzed using GJPO's SHEARVIEW V2.0 software and programs developed within the 386 MATLAB V3.5k set of programs.

P-Wave Reflection Seismic

An EG&G Geometrics ES-2401 signal enhancement seismograph coupled to a Geo-Stuff roll-along box also was used for the P-wave seismic surveys. Seismic energy was generated by striking a 20-lb sledgehammer vertically against a rectangular 6-inch-square aluminum plate and was received by 40-Hz vertical geophones. Standard P-wave walkaway tests were conducted initially. As a result of these tests, data were acquired in the common-midpoint (CMP) configuration with the geophones separated 2.5 feet along the survey line and the source 2.5 feet off-end and inline. For CMP-type of data acquisitions, the source point and the entire line of geophones were moved in tandem along the survey line for each subsequent record, which resulted in a maximum of 12-fold data. All data were stored on 3.5-inch flexible disks within the seismograph in SEG-2 standard format. The data were converted, processed, and analyzed using the Interactive Concepts Incorporated EAVES-DROPPER V2.51 software.

Results and Interpretation

Background

Certain chemicals react with clays to produce substances that have a characteristic response to the complex galvanic resistivity method, as described by King and Olhoeft (1991) and Olhoeft (1986). In addition to possibly identifying broad classes of wastes in the pits, the complex resistivity response will delineate the chemical interaction boundary and, thus, the waste-pit boundaries. An electrical potential, generally termed a spontaneous potential, frequently builds up at the boundaries of waste pits because of differences in the chemical composition and solution pressures of the material on either side of the boundary. A simple map of the voltages of an undisturbed area can be used to define the pit boundaries.

Under favorable transmissivity circumstances, GPR profiles may indicate pit boundaries because of a propagation contrast in the disturbed, compared with undisturbed, soil. A moisture contrast also can occur, which is caused by the higher solution pressure in the pit area and by mechanical factors related to disturbance of the soil. Modern GPR processing techniques calculate velocities and dielectric constants of the area and, thus, provide measurements highly sensitive to water content. Also, GPR measurements may yield information on the volume of wastes within a pit.

The waste materials within the pits (such as metals, metal salts, and other chemicals) have a profound effect on the conductivity of the subsurface area as contrasted with the undisturbed ground. TDEM methods map the conductivity/resistivity contrasts. In addition to delimiting the pit area by the conductivity contrast of the pit material with country rock, the conductivity data will provide insights of the type and quantity of material in the pits. Large volumes of metals and salts will result in much higher conductivities than other forms of waste, such as paper and building materials. Pits containing large amounts of metal salts and acids will be highly conductive. High-conductivity zones that extend beyond the presumed pit limits are an indication of possible migration of contaminants beyond the pit boundaries. An extremely sensitive detector of

conductivity anomalies caused by small conductive sources can be achieved by measuring the TDEM transient voltages in boreholes placed near the pits. A conductive plume that moves beyond the pit boundary toward a borehole would be readily detected with this technique.

Seismic wave transmission differences expected between disturbed and undisturbed material can be detected by *S*-wave refraction and *P*-wave reflection seismic surveys. Variations in the phase, amplitude, frequency, and velocity of horizontally polarized *S*-waves are indicative of changes within the subsurface. The locations of these anomalies can be related to pit boundaries and can be used to determine the volume of waste within a particular pit. The pit image from *P*-waves may not be as obvious as in the *S*-wave method because the undisturbed ground at the pit boundaries may not be an easily recognized reflection event. However, *P*-wave reflection seismic is the most advanced technique used for hydrocarbon exploration and is being used more frequently for shallow-exploration purposes because of the increased availability of instrumentation, data processing, and data interpretation software suitable for the particular problems encountered in the near-surface region.

General

Preliminary data analysis consisted of the processing and the display of each data set. Raw data files were first converted into a format compatible for processing, then processed and displayed using appropriate software. Appendices A through J in Volume 2 of the *FY 1992 Year-End Progress Report* (Hasbrouck 1992) include all the raw and preliminarily processed computer files, a computer file tracking and/or processing summary, and examples of preliminary displays of the data.

The dipole-dipole and parallel-dipole array complex galvanic resistivity data were processed and displayed with GEOSOFT IP Plotting System V2.0 software. A constant color scale was used for all the color plots to permit comparison of results from the different lines.

Selected dipole-dipole IP data sets were compared with models from Elliot (1967). The Cole-Cole parameters Tau (time constant), C (frequency dependence), and M (chargeability) also were calculated using the GEOSOFT software. Those results will not be presented in this report because analyses of resistivity and IP responses only were sufficient to satisfy the project objectives; further analyses using the Cole-Cole parameters will be deferred to a future TTP. The Wenner array complex galvanic resistivity data are not presented in this report (see Hasbrouck 1992 for examples) because relatively high noise levels, probably from near-surface effects, are present. Thus, reliable interpretation of the data was not possible. The SP data acquired using the digital voltmeter presented in this report were processed and displayed using the QUATTRO PRO software package.

GPR data acquired on magnetic tape were processed and displayed with the GSSI RADAN 1 V3.0 computer software package. Overall, the 80-MHz data appeared to offer the best combination of resolution in relation to depth of investigation, and only results from that antenna are presented in this report.

Processing and display of the surface TDEM data were accomplished with Geonics Ltd. GSPX7 V1.0 and Interpex Ltd. TEMIX PLUS V1.0 computer software. Selected free-space models were constructed with the Gapak Systems MULTILoop (1991) computer modeling package. The MULTILoop transmitter and receiver parameters were designed to exactly match the Geonics EM-47 instrumentation used to acquire the field data. The general philosophy of conducting the free-space modeling was to match the general shape of the field and model anomalies with regard to wavelength and relative anomaly amplitude only; modeling the effects of the host material was beyond the scope of this project.

The surface-to-borehole TDEM data were processed and displayed using the Geonics Ltd. GSPX7 V1.0 software. Because of the presence of near-surface noise sources, no further interpretation of those data was conducted beyond that presented in Volume 1 of the FY 1992 *Year-End Progress Report* (Hasbrouck 1992).

Conversion, processing, and display of the S-wave seismic data were accomplished with the GJPO SHEARVIEW V2.0 software and programs developed within the 386 MATLAB V3.5k computer package. Through the use of SHEARVIEW it was possible to import two separate S-wave field data files (acquired 180 apart at the same location) and then to conduct numerous operations on the data for initial inspection of anomalous areas. Subsequently, portions of the data set were identified and output in a format compatible for further analyses within the MATLAB programs. Velocity, magnitude, frequency, and phase seismic-wave attributes typically were analyzed using various programs developed within the MATLAB package.

P-wave reflection seismic data were converted, processed, and displayed with Interactive Concepts Incorporated EAVESDROPPER V2.51 software. Standard CMP processing was conducted with a typical processing sequence as follows:

1. Convert to Kansas Geological Survey format;
2. Edit bad traces, if necessary;
3. Apply first arrival mute;
4. Sort into CMP gathers;
5. Perform CMP stack using velocities determined from previous velocity scans; and
6. Apply bandpass filter.

Extensive data analyses were conducted over each profile, and interpretation of data from three of those profiles (Lines 20E, 60E, and 125E) are presented in this report. These three profiles are chosen as representative of the Chemical Waste Landfill and include areas of both known and unknown attributes. Two of the profiles are within Area A, and one is within Area B: Line 20E crosses known pits, Line 60E transects a known barren area, and Line 125E is within an unknown area (Figures 3 and 4).

Line 20E

Line 20E crosses both the Chromic Acid and Organics Pits. Figures 5 and 6, are interpreted complex galvanic resistivity data from

Figure 5. Complex Galvanic Resistivity, Parallel-Dipole Electrode Array ($a = 10$ feet, $n = 1$ to 6), Line 20E

Figure 6. Complex Galvanic Resistivity, Dipole-Dipole Electrode Array ($a = 10$ feet, $n = 1$ to 6), Line 20E

the parallel-dipole and dipole-dipole arrays, respectively. The responses from the different dipole arrays are dissimilar and are interpreted as indicating different anomaly sources. A near-surface disturbed area is interpreted in the parallel-dipole data as the relatively low-resistivity zone to approximately $n = 3$, which corresponds approximately to a depth of investigation of less than 8 feet (Roy and Apparao 1971). Within that disturbed area, locations of both the Chromic Acid and Organics Pits are interpreted within the IP data; agreement between the historical and interpreted pit boundaries are good (Chromic Acid Pit historical versus interpreted boundaries equals Stations 103 to 118 versus Stations 103 to 123; Organics Pit historical versus interpreted boundaries equals Stations 137 to 154 versus Stations 132 to 148). A slightly increased IP response is present within the Chromic Acid Pit compared with the Organics Pit. This increased response is interpreted as indicating different anomalous sources; however, these different responses cannot be directly attributed to specific chemical compounds.

The disturbed area in the dipole-dipole complex galvanic resistivity data is probably related more to the IP response of the interpreted vertical body than to the source of the parallel-dipole disturbed area anomaly. The dipole-dipole IP response is dominated by what is interpreted as a vertical body from approximately Stations 125 to 135. The body is modeled as a vertical dike using the parameters indicated with Figure 7 (from Elliot 1967). Figures 8 and 9 are modeled versus field data (from Figure 6) for n values of 1 and 3, respectively. For both models, the width (w) of the source is equal to the a spacing (10 feet), the source is vertical with infinite depth and strike, the host and dike resistivities (p_1 or ρ_{01} and p_2 or ρ_{02} , respectively) are equal, and the response is shown in terms of B_2 where (according to Elliot 1967)

$$B_2 = \frac{M_A - M_1}{M_2 - M_1} \quad (1)$$

where

- M_A = measured IP response,
- M_2 = true IP response of the target for a fixed resistivity ratio, and
- M_1 = IP response of the outside media.

Commonly, M_1 can be taken as 0 so

$$B_2 = \frac{M_A}{M_2}. \quad (2)$$

For the purposes of this report, the families of B_2 curves found in Elliot (1967) were compared to the field data until a reasonably good fit was found, as in Figures 8 and 9, and the model parameters were noted. An extension of this analysis would be the determination of M_2 (since B_2 is obtained, M_A is measured, and M_1 can be determined from the field data). The value of M_2 has been used in mining geophysics to yield estimates of sulfide and/or membrane polarization distribution. It is beyond the scope of this project to assign values of M_2 to physical characteristics of the targets typically found at environmental restoration sites, and the modeling was used only to determine the basic geometry (i.e., vertical body versus horizontal plate) and location of an anomalous source.

Per the determined model parameters that fit the field data, the anomaly source exhibits no resistivity contrast with the surrounding media and is approximately 10 feet wide. However, such an interpretation assumes that the electrode spread perfectly straddles the anomaly source. If the electrode spread and source geometry are offset by a factor of d/a approaching 1 (i.e., $d = 10$ feet), then the interpreted anomaly source could be a thin, vertical body (e.g., drill pipe) and still honor the modeling results. Because of the nonuniqueness of the solution, final determination of the anomalous source will depend upon the results of the interpretation of the other data sets (i.e., the interpretation will be integrated).

As indicated in Figure 10, a disturbed area is interpreted from the SP data over an area that roughly approximates the anomalous zone indicated for the dipole-dipole complex galvanic resistivity data and, to a lesser extent, the parallel-dipole data. The interpreted SP disturbed area essentially encompasses the Chromic Acid Pit but does not extend to the Organics Pit. The source of the anomaly in the SP data is interpreted as a combination of a metallic body (i.e., the vertical body in the dipole-dipole complex galvanic resistivity interpretation) and a zone of increased potential possibly related to the IP response indicated in

Figure 7. Complex Galvanic Resistivity, IP Modeling Parameters

Figure 8. Complex Galvanic Resistivity, Vertical Dike IP Model (a = 10 feet, n = 1), Line 20E

Figure 9. Complex Galvanic Resistivity, Vertical Dike IP Model ($a = 10$ feet, $n = 3$), Line 20E

Figure 10. SP, Line 20E

the parallel-dipole complex galvanic resistivity data. It is not possible to state that the combined SP/IP anomaly is directly related to the concentration of the chromic acid within the pit. However, the interpretation does indicate an area of anomalous activity that extends beyond the historical boundary of the Chromic Acid Pit and, thus, suggests a certain amount of contaminant migration has occurred or the original boundary has been altered.

Interpreted 80-MHz GPR data are shown in Figure 11 with two-way time in nanoseconds (ns) along the ordinate and station numbers along the abscissa. When interpreted in conjunction with other techniques (primarily complex galvanic resistivity), some of the point sources appear to be at the edges of area interpreted as pits; specifically, the area from approximately Stations 103 to 119 (which corresponds to the Chromic Acid Pit) and the area from Stations 134 to 154 (which corresponds to the Organics Pit). Without the influence of interpretations from other data sets, it would be difficult to ascribe these areas as pits. In addition, separate, small point sources are located in somewhat more discrete locations and are not interpreted to be associated with the pits. A larger area of disturbance is present from approximately Stations 69 to 82; that area also is interpreted as disturbed from the parallel-dipole complex galvanic resistivity data.

Two significant anomalies are present within the surface TDEM data along Line 20E, as indicated in the 10- by 10-meter transmitter loop data shown in Figure 12. As previously discussed, free-space response modeling was conducted using the MULTILoop computer package to determine the general source of selected anomalies. Figures 13 and 14 present the results of such modeling with horizontal bodies located in two separate areas (from less than Station 50 to just beyond Station 60 and from approximately Stations 110 to 130) and a vertical body from approximately Station 120 to 125 (congruent with one of the horizontal bodies.) The match of anomaly shapes between the field data and the two horizontal/one vertical body model is good (Figures 12 and 13, respectively). As indicated in Figure 14, the majority of the modeled response at the Stations 110 to 130 anomaly is from the vertical

body, while the horizontal body contributes little but is necessary to generate a good match in anomaly shape with the field data. The predominate vertical-body anomaly source is near the edge of the dipole-dipole IP anomaly and is probably caused by the same metallic source. A possible source of the anomalies within both the dipole-dipole IP and TDEM data is 2-inch aluminum drill pipe left in place from previous Geoprobe operations at approximately Line 25, Station 122 (Burford 1993). Such a source is consistent with the modeled responses for both techniques and is further substantiated from the concurrent location of an SP anomaly. The modeled horizontal bodies do not correspond to the locations of either of the known pits and are most likely disturbed areas as indicated within the parallel-dipole resistivity data.

Polarized S-wave data are shown in Figures 15 and 16. Geophone and station numbers are along the ordinates with time along the abscissas. Figure 15 is a copy of the raw data, and Figure 16 is an expanded portion with moveout removed. The indicated interpreted location of the pit (which corresponds to the Organics Pit) was determined from analyses of all the seismic attributes; velocity and magnitude or power anomalies are the most striking and are essentially evident from visual inspection only. However, additional analyses of those attributes confirm the initial inspection and, where necessary, are used to detect more subtle anomalies. Figure 17 indicates the arrival times of the S-waves with the moveout (or regional) removed; a delay of greater than 30 milliseconds (ms), which corresponds to a lower velocity, is evident within the interpreted pit. A significant decrease in power is present beyond the interpreted pit boundary, as shown in Figure 18, and is indicative of the response expected from a barren area.

CMP-processed *P*-wave reflection seismic data in Figure 19 have two-way time in milliseconds along the ordinate; station and CMP numbers are along the abscissa. While coherent seismic events are present along Line 20E, assignment of much relevance to any of the separate events would be tenuous at best.

Figure 11. GPR (80 MHz), Line 20E

Figure 12. Surface TDEM, 300-Hz Field Data, 10- by 10-Meter Transmitter Loop, Line 20E

Line 60E

Line 60E is located within Area A and transects an essentially barren area (Figure 3). Figures 20 and 21 are interpreted complex galvanic resistivity data from the parallel-dipole and dipole-dipole arrays, respectively. Areas of minor near-surface disturbance are present within both data sets. Although the interpreted extents of these areas are different for each array type, the disturbance generally encompasses the area from approximately Stations 100 to 135. A small SP response (Figure 22) also is present within the general area from approximately Stations 100 to 140.

In Figure 23, GPR data also indicate a disturbed area from approximately Stations 118 to 140. This area generally encompasses the disturbed area interpreted from the complex galvanic resistivity and SP data. The response is relatively subtle and includes two small interpreted point sources. The reflector character beyond approximately Station 160 varies considerably from the rest of the line and may be interpreted as indicating the presence

of a relatively large pit. From approximately Stations 165 to 170, a discrete disturbance is present that is interpreted as a body of some sort, probably more horizontal than vertical. An alternative interpretation could be that the side walls of the interpreted pit are shallow and sloping within this area. A vertical body is interpreted to be present from approximately Stations 178 to 180.

Figures 24 and 25 are surface TDEM field data for the 10- by 10-meter and 5- by 5-meter loop transmitters, respectively. The horizontal and vertical scales are different for each plot and were chosen to best display the full amplitude of each four-channel set at a scale for easy visual inspection. Little response is present within the 10- by 10-meter loop data. However, a significant anomaly is present within the 5- by 5-meter loop data, particularly within the later channels. A free-space response model constructed for a 5- by 5-meter loop transmitter (Figure 26) indicates the causative source of the anomaly to be a vertical sheet from approximately Stations 175 to 180, at a depth ranging from approximately 5 to 20 feet.

Figure 13. Surface TDEM, 300-Hz Free-Space Response Modeled Data, One Vertical and Two Horizontal Sources, 10- by 10-Meter Transmitter Loop, Line 20E

This anomalous body corresponds with similar interpreted results from the GPR data.

No significant anomalies are present within the *S*-wave seismic data as shown in Figure 27; computer analyses of the attributes also indicated no anomalies. A coherent reflection event is present at approximately 40 to 60 ms within the *P*-wave seismic data as indicated in Figure 28. A slight perturbation is present from approximately Stations 120 to 140 and may be caused by a zone of decreased velocity. This anomalous zone correlates with indicated results in other data sets (complex galvanic resistivity, SP, GPR) and further substantiates the interpreted location of some sort of area of disturbance.

Line 125E

Line 125E is located in an area of unknown subsurface conditions. Parallel-dipole complex galvanic resistivity data (Figure 29) indicate two areas of near-surface disturbance from approximately Stations 185 to 230 and from Stations 270 to 290; the low resistivity anomaly zones extend to only $n = 2$, which corresponds to a depth of investigation of approximately 5 feet (Roy and Apparao 1971). The dipole-dipole data (Figure 30) also indicate two disturbed areas in generally the same area. From approximately Stations 195 to 225, the disturbed area is interpreted to be shallow (approximately 5 to 8 feet), while from approximately Stations 270 to 315 the disturbance appears to extend much deeper. Within these

Figure 14. Surface TDEM, 300-Hz Free-Space Response Modeled Data, One Vertical and One Horizontal Source, 10- by 10-Meter Transmitter Loop, Line 20E

disturbed areas are interpreted metallic bodies at approximately Stations 210 to 225, 265 to 275, and 300 to 310. The depths to these anomalies are interpreted to be greater than 10 feet. These bodies are interpreted to be metallic because of their relatively large IP response; the negative values are indicative of a highly conductive source. Such large anomalies also will influence the resistivity within the area to such an extent that other disturbances are indistinguishable. Therefore, the presence of a disturbed zone within an area with metallic sources is difficult to determine from this data set and requires the use of other techniques.

SP data shown in Figure 31 are noisy, and meaningful interpretation would be difficult without the use other techniques. A possible

metallic source is indicated from approximately Stations 290 to 305. This anomaly is difficult to discern from the background but can be identified when considered in conjunction with the dipole-dipole resistivity and IP anomalies.

The GPR data shown in Figure 32 indicate numerous small pits within two relatively large disturbed area from approximately Stations 190 to 230 and from Stations 263 to 285. The general locations of the disturbed areas are similar to those indicated within the complex galvanic resistivity and SP data. Discrete debris is interpreted to be within some of the pits, and the pits appear larger farther to the north (pits interpreted to be located approximately from Stations 263 to 271 and from

Figure 15. S-Wave Refraction Seismic, Files 35 and 36, Line 20E

Figure 16. S-Wave Refraction Seismic, Expanded Portion with Moveout Removed,
Files 35 and 36, Line 20E

Figure 17. S-Wave Refraction Seismic, Arrival Times with Regional Trend Removed, File 35, Line 20E

Figure 18. S-Wave Refraction Seismic, Power Spectral Density, Stations 147.5 to 155, File 35, Line 20E

Figure 19. P-Wave Reflection Seismic, CMP Stacked Section with 0- to 60-Hz Bandpass Filter, Line 20E

Stations 275 to 285 are larger). A relatively large debris area is indicated from approximately Stations 280 to 282.

Essentially, two anomalous areas are indicated within the surface TDEM data, as shown in Figures 33 and 34. Considering the results of previous modeling, a vertical body with limited depth extent is interpreted to be located at approximately Station 220. Because the anomaly is more prevalent within the 10- by 10-meter as compared with the 5- by 5-meter data, the body is buried relatively deep (probably greater than 10 feet). This anomaly is within interpreted disturbed areas from other techniques (i.e., complex galvanic resistivity, GPR) and may have the same source as the Stations 214 to 218 GPR anomaly. The more predominate TDEM anomaly located

approximately at Station 265 is interpreted as a relatively large vertical body. This anomaly corresponds to the large dipole-dipole IP anomaly and an S-wave anomaly.

Figures 35 and 36 are copies of raw S-wave seismic data and an expanded portion of the same file with moveout removed, respectively. While all attributes of the seismic data were analyzed, perhaps the most striking is the large change in power between Stations 265 and 267.5. Figure 37 indicates this change to be approximately one order of magnitude. An anomaly at the same location is also evident with the dipole-dipole IP and TDEM data. The P-wave reflection seismic data are shown in Figure 38. Coherent seismic events are present along portions of Line 125E, but assignment of any relevance to them is dubious.

Figure 20. Complex Galvanic Resistivity, Parallel-Dipole Electrode Array ($a = 10$ feet, $n = 1$ to 6), Line 60E

Figure 21. Complex Galvanic Resistivity, Dipole-Dipole Electrode Array ($a = 10$ feet, $n = 1$ to 6), Line 60E

Figure 22. SP, Line 60E

Figure 23. GPR (80 MHz), Line 60E

Figure 24. Surface TDEM, 300-Hz Field Data, 10- by 10-Meter Transmitter Loop, Line 60E

Figure 25. Surface TDEM, 300-Hz Field Data, 5- by 5-Meter Transmitter Loop, Line 60E

Figure 26. Surface TDEM, 300-Hz Free-Space Response Modeled Data, One Vertical Source, 5- by 5-Meter Transmitter Loop, Line 60E

Figure 27. S-Wave Refraction Seismic, Files 85 and 86, Line 60E

Figure 28. P-Wave Reflection Seismic, CMP Stacked Section with 0- to 60-Hz Bandpass Filter, Line 60E

Figure 29. Complex Galvanic Resistivity, Parallel-Dipole Electrode Array ($a = 10$ feet, $n = 1$ to 6), Line 125E

Figure 30. Complex Galvanic Resistivity, Dipole-Dipole Electrode Array ($a = 10$ feet, $n = 1$ to 6), Line 125E

Figure 31. SP, Line 125E

Ground-Penetration

Figure 32.

Figure 33. Surface TDEM, 300-Hz Field Data, 10- by 10-Meter Transmitter Loop, Line 125E

Figure 34. Surface TDEM, 300-Hz Field Data, 5- by 5-Meter Transmitter Loop, Line 125E

Figure 35. S-Wave Refraction Seismic, Files 306 and 307, Line 125E

Figure 36. S-Wave Refraction Seismic, Expanded Portion with Moveout Removed, Files 306 and 307, Line 125E

Figure 37. S-Wave Refraction Seismic, Power Spectral Density, Stations 262.5 to 270, File 306, Line 125E

Figure 38. P-Wave Reflection Seismic, CMP Stacked Section with 0- to 60-Hz Bandpass Filter, Line 125E

Summary and Conclusions

Summaries of the interpreted location and type of anomalous sources are presented in Table 2. In general, anomaly locations determined from the geophysical interpretations are no more accurate than one-half the station spacing for the complex galvanic resistivity (5 feet), SP (2.5 feet), TDEM (2.5 feet), and *S*-wave and *P*-wave seismic techniques (1.25 feet). Because data locations essentially are continuous for the GPR technique, its accuracy of interpretation is generally considered to be one-half the distance between the transmitter and receiver or one-half the size of the transceiver (approximately 2 feet for the 80-MHz transmitter).

The locations of both the Chromic Acid and Organics Pits were interpreted at or near their historical boundaries along Line 20E, areas of disturbance were identified surrounding both pits, rudimentary waste types were interpreted, and anomalies of seeming importance were discounted as originating from recent activity. The pit locations were interpreted from the parallel-dipole complex galvanic resistivity, *S*-wave seismic (Organics Pit only), and GPR data sets. However, the pits could not be identified within the GPR data unless interpreted in conjunction with both the other data sets. An explanation is not available for why only the Organics Pit was indicated in the *S*-wave data. Therefore, only the parallel-dipole complex galvanic resistivity data indicated conclusively the location of both known pits.

Line 20E disturbed areas were interpreted from the parallel-dipole and dipole-dipole complex galvanic resistivity, SP, GPR, and TDEM data. Of these data sets, the TDEM and parallel-dipole data appeared to be most indicative of areas of disturbance, while the other data sets may have been influenced by the presence of other sources. The interpreted disturbed areas in the TDEM data model as horizontal bodies with little depth extent and approximately correspond to the location of the parallel-dipole anomaly. The TDEM responses of these horizontal bodies are relatively small, and without an indication of anomalies from other techniques the responses would be attributed to either noise or an unknown source. However, the presence of

anomalies within both the parallel-dipole complex galvanic resistivity and TDEM data lend credence to the interpretation of the presence of a disturbed area possibly related to the contaminants within the pit. These areas of disturbance extend beyond the historical pit boundaries and may suggest contaminant migration, but assignment of concentrations of contaminants or identification of separate entities is not possible.

Types of waste along Line 20E can be separated into metallic and nonmetallic sources. For example, a response indicated in the *S*-wave seismic data and not in the complex galvanic resistivity or TDEM data was interpreted as resulting from nonmetallic sources. Predominate anomalies in both the dipole-dipole IP and TDEM data were modeled as vertical bodies and were interpreted to be from aluminum drill pipe left in place from previous operations. These anomalies were quite large and could be mistaken for contaminant material if modeling were not conducted. Subtle anomalies that might be present tend to be masked by such large responses and, thus, necessitate the use of other techniques.

No known pits are present along Line 60E. However, geophysical data indicate definitely one (approximately Stations 120 to 140) and perhaps another (approximately Stations 165 to past 185) disturbed area that may be interpreted as pits. The disturbed area between Stations 120 to 140 is subtly indicated within the complex galvanic resistivity, SP, GPR, and *P*-wave seismic data. Two small point sources shown within the GPR data are interpreted as discrete objects within the pit area. This disturbed zone may indicate a minor amount of contaminant migration from either the Chromic Acid or Organics Pits. However, such an interpretation is somewhat speculative because the specific contaminants cannot be identified by these particular geophysical methods. Nevertheless, the presence of concurrent anomalies from four geophysical techniques does signify an area in which further subsurface analyses should be conducted.

An interpreted vertical sheet or body is present from approximately Stations 175 to 180

Table 2. Anomaly Location Summary by Station Number^a

Technique	Disturbed Area	Pit Boundary	Vertical Body/Sheet	Horizontal Plate
Line 20E				
II-dp Resis.	58-149	-	-	-
dp-dp Resis.	93-145	-	-	-
II-dp IP	-	103-123, 132-148	-	-
dp-dp IP	-	-	125-135	-
SP	95-132	-	-	-
GPR	69-82, 146-155(?)	103-119(?), 134-154 (?)	87, 99, 104, 119, 134-136, 146-155	-
TDEM (10 x 10)	111-130	-	120-125	50-60, 110-130
TDEM (5 x 5)	-	-	-	-
S-Wave	-	138-150	-	-
P-Wave	-	-	-	-
Line 60E				
II-dp Resis.	-	-	-	-
dp-dp Resis.	97-137	-	-	-
II-dp IP	105-140	-	-	-
dp-dp IP	-	-	-	-
SP	100-140	-	-	-
GPR	118-140	-	132(?), 140(?), 165-170, 178-180	-
TDEM (10 x 10)	-	-	-	-
TDEM (5 x 5)	-	-	175-180	-
S-Wave	-	-	-	-
P-Wave	120-140	-	-	-
Line 125E				
II-dp Resis.	185-230, 270-290	-	-	-
dp-dp Resis.	195-225, 270-315	-	300-310	-
II-dp IP	-	-	210-225, 265-275, 300-310	-
dp-dp IP	-	-	-	-
SP	-	-	290-305(?)	-
GPR	190-230, 263-285	Within Disturbed Areas	-	-
TDEM (10 x 10)	-	-	220, 265	-
TDEM (5 x 5)	-	-	220, 265	-
S-Wave	-	-	266	-
P-Wave	-	-	-	-

^aII-dp Resis. = parallel-dipole resistivity; dp-dp Resis. = dipole-dipole resistivity; II-dp IP = parallel-dipole induced polarization (IP); dp-dp IP = dipole-dipole IP; SP = spontaneous potential; GPR = ground-penetrating radar; TDEM (10 x 10) = surface time-domain electromagnetic (TDEM), 10- by 10-meter one-turn transmitter loop; TDEM (5 x 5) = surface TDEM, 5- by 5-meter, eight-turn transmitter loop; S-Wave = shear-wave refraction seismic; and P-Wave = compressional-wave reflection seismic

along Line 60E in both the GPR and TDEM data. The presence of this sheet or body in the TDEM data indicates it is metallic in nature. Another possible body is present within the GPR data (approximately Stations 165 to 170) but is not indicated within any of the other data sets. Consequently, the anomaly may be better interpreted as the edge of a disturbed area or pit. However, without confirmation from other techniques, the presence of a pit is questionable.

Numerous small pits are indicated along Line 125E within the GPR data. These pits may be grouped generally into two disturbed areas (approximately from Stations 190 to 230 and from Stations 265 to 285). These areas also are indicated within the parallel-dipole complex galvanic resistivity data, while disturbed areas within the dipole-dipole and SP data may be due more to the presence of metallic bodies that mask the effects of any other contaminants within those data sets.

Through modeling of TDEM data for Line 125E, vertical bodies are interpreted to be located at approximately Stations 220 and 265. At Station 220, corresponding anomalies also are present within both the GPR and dipole-dipole IP data. The source of these anomalies is interpreted to be a relatively large, metallic object. A similar type of object, perhaps even larger, is interpreted to be located at approximately Station 265 with anomalies indicated

within dipole-dipole IP, GPR, TDEM, and S-wave seismic data.

While GPR data appear to offer the most definitive interpretation along Line 125E, the identification of disturbed areas with results from other techniques (particularly parallel-dipole complex galvanic resistivity) indicates that the contaminant zones are not discrete but extend over a large area. The size and type of waste objects are determined from a combined interpretation of the data sets that is not possible with only GPR data.

The identified needs for mixed-waste landfill characterization are pit boundary location, waste-volume characterization, and contaminant plume detection. These needs are not unique to mixed-waste landfills and exist at many DOE environmental restoration sites. Table 3 is a subjective graded indication of the applicability of the geophysical techniques demonstrated at the MWLID test site to these needs. The numerical grading ranges from "1" for least applicable to "4" for most applicable. Footnotes provide additional clarification of the assigned numerical grade. This table represents a summary of the results of this Technical Task and can be used as a guide to select the combination of techniques that are most applicable to a specific need. However, final selection of a geophysics program should be made in consultation with and monitored by an experienced, unbiased geophysicist.

Table 3. Geophysical Techniques Applicable to Mixed-Waste Landfill Characterization^a

Method	Pit Boundary Location	Waste Volume Characterization	Contaminant Plume Detection
Magnetic Gradiometer ^b	4	3	N/A
Complex Galvanic Resistivity ^c	4	3	4
Spontaneous Potential	1	2	2
GPR	3 ^d	3	N/A
Surface TDEM	2 ^e	3 ^f	2 ^g
Surface-to-Borehole TDEM	1	2	2 ^h
S-Wave Seismic	4	2 ⁱ	1
P-Wave Seismic	2 ^j	1	N/A

^aThe methods are graded from 1 to 4 on the basis of least applicable to the identified need "1" or most applicable to the identified need "4"; N/A = not applicable.

^bFrom Naval Research Laboratory and Naval Explosive Ordnance Technology Center report dated April 30, 1992.

^cAt least two types of arrays should be used: parallel-dipole and dipole-dipole.

^dOnly when interpreted in conjunction with other methods.

^e"Small" pits not resolved; "large" pits well resolved.

^f"Small" contents not resolved; "large" contents well resolved.

^gSubtle anomalies overshadowed by anomalies from metallic objects.

^hNear surface not well resolved.

ⁱDifficult to determine depth, therefore difficult to calculate volume.

^jUseful for general determination of presence of pits (i.e., continuous or noncontinuous reflection).

Acknowledgments

The author, Geotech Geophysics Projects Section, and K. L. Antwine and J. E. Trevino, Geotech Field Assessments Section, acquired the complex galvanic resistivity, SP, surface TDEM, and *S*-wave and *P*-wave seismic data. Messrs. Antwine and Trevino's untiring efforts in the acquisition of high-quality data are gratefully acknowledged. J. W. Allen, Geophysics Projects, with the assistance of J. E. Trevino, acquired the GPR data. The author, with the assistance of T. D. Burford, Sandia National Laboratories/New Mexico (SNL/NM), acquired the surface-to-borehole TDEM data.

The author processed and displayed all data, with the exception of the GPR and surface-to-borehole TDEM data. J. W. Allen, Geophysics Projects, processed and displayed the GPR data. H. D. Mac Lean, Geophysics Projects, displayed the surface-to-borehole TDEM data.

The successful completion of the field data acquisition portion of this task was made possible with the much appreciated assistance of T. D. Burford, R. F. Helgesen, and J. C. Stormont of SNL/NM.

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