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Calibration, Installation Techniques, and Initial Measurements for Vertical Resistivity Probes Used in Hydrogeologic Investigations

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CALIBRATION, INSTALLATION TECHNIQUES, AND INITIAL MEASUREMENTS FOR VERTICAL RESISTIVITY PROBES USED IN HYDROGEOLOGIC INVESTIGATIONS

by

Jeffrey Mark Groncki

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Jeffrey Mark Groncki
CALIBRATION, INSTALLATION TECHNIQUES, AND INITIAL MEASUREMENTS FOR VERTICAL RESISTIVITY PROBES USED IN HYDROGEOLOGIC INVESTIGATIONS

Jeffrey Mark Groncki, M.S.
Western Michigan University, 1999

Vertical Resistivity Probes (VRPs) are being increasingly used in a variety of applications where detailed vertical resistivity information in both the vadose and saturated zones is needed. All the different possible array types and spacings must be calibrated for the effect of the 2" (outer diameter) insulating PVC cylinder on which the electrodes are mounted. Apparent resistivities must be corrected by calibration factors. Varying the installation parameters greatly influences the measured apparent resistivity because of the disturbed annulus and the composition of the backfill materials. Bentonite slurry is necessary for the installations to keep the electrodes in good contact with the formation. However, leaches ions into the formation with the passage of time loses ions to the formation by diffusion or leaching, causing resistivities to increase. The equilibration time for this annular filling is thus important to document, if repeat readings of resistivity are to be interpreted properly. Properly calibrating for array geometry, and correcting for temporal changes in the bentonite-based annular space filling, allow for very useful resistivity or conductivity information to be extracted from these probes.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS.................................................................................. ii

LIST OF TABLES.......................................................................................... vi

LIST OF FIGURES......................................................................................... vii

CHAPTER

I. INTRODUCTION....................................................................................... 1

   Problem................................................................................................. 1

   Objective.............................................................................................. 2

II. THEORY.................................................................................................. 3

   Electrical Methods............................................................................... 3

   Direct Current Electrical Resistivity.................................................. 4

   Resistivity Well Logging....................................................................... 8

   Induced Polarization............................................................................ 9

   Electrode Arrays.................................................................................. 15

      Wenner Array.................................................................................. 15

      Pole-dipole Array.......................................................................... 16

      Pole-pole Array............................................................................. 17

III. LITERATURE REVIEW........................................................................... 19

   Vertical Resistivity Probes................................................................. 19

   Stratigraphic Response....................................................................... 21
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV.</td>
<td>VERTICAL RESISTIVITY PROBE DESIGN</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Overview</td>
<td>23</td>
</tr>
<tr>
<td>V.</td>
<td>PROBE CALIBRATION</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Methodology</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Wenner Array Calibration</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Pole-dipole Array Calibration</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Pole-pole Array Calibration</td>
<td>35</td>
</tr>
<tr>
<td>VI.</td>
<td>FIELD TESTING</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Purpose</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Asylum Lake Test Site</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Geology</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Installation Types</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Comparison of Installation Types</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Temporal Changes</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Comparison of Each Array</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>Wurtsmith Air Force Base</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Geology</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Background Information</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Installation Types</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>Comparison of Each Array</td>
<td>73</td>
</tr>
</tbody>
</table>
Table of Contents—continued

CHAPTER

Temporal Changes ........................................................................ 84
Comparison of Background Data Versus Plume Data .......... 85
Lakeside Refinery ..................................................................... 92
Geology .................................................................................... 92
Background Information .............................................................. 94
Installation Types ...................................................................... 94
Results of Initial Investigation ..................................................... 96

VII. CONCLUSIONS AND RECOMMENDATIONS .......................... 102

Installation Techniques and Temporal Variations .................. 102
Electrode Array Comparison ...................................................... 103
Asylum Lake Test Site ............................................................... 103
Wurtsmith Air Force Base ......................................................... 105
Lakeside Refinery ................................................................. 106
Recommendations .................................................................... 107

APPENDIX

A. Vertical Resistivity Probe Installation Reports ................. 110

BIBLIOGRAPHY ...................................................................... 121
LIST OF TABLES

1. Calibration Factors for Various Electrode Arrays and Electrode Spacings ................................................. 29
LIST OF FIGURES

1. Frequency Domain Waveform Used for Acquisition of DC Resistivity Data. Square Wave (On +, On -) Cycle With Equal Pulse Widths. ................................................................. 5

2. Time Domain Symmetrical Waveform. (On +, Off, On -, Off) Cycle With Equal Injection Times of 1000ms. ........................................................................................................... 10

3. Illustration of Voltage Increase During Current Transmission and Relaxation Phenomena Observed When Current is Suddenly Shut Off for Polarizable Medium. ................................................................. 11

4. Typical Time Integration Windows for Determining Chargeability in the Time Domain. ................................................................. 13

5. Geometric Arrangement of Electrodes for Wenner Array .................................................................................................................. 16

6. Geometric Arrangement of Electrodes for Pole-dipole Array ........................................................................................................... 17

7. Geometric Arrangement of Electrodes for Pole-pole Array .................................................................................................................. 17

8. Results of 2 cm and 4 cm Wenner Array Floating Tray Water Tank Baseline Experiment ................................................................. 27

9. Results of 2 Inch Wenner Array Probe Calibration Measurements in Water Tank .................................................................................... 30

10. Results of 4 Inch Wenner Array Probe Calibration Measurements in Water Tank .................................................................................. 31

11. Results of 2 Inch Pole-dipole Array Probe Calibration Measurements in Water Tank .................................................................................. 33
List of Figures—Continued

12. Results of 4 Inch Pole-dipole Array Probe Calibration Measurements in Water Tank ................................................................. 34

13. Results of 2 Inch Pole-pole Array Probe Calibration Measurements in Water Tank ................................................................. 36

14. Results of 4 Inch Pole-pole Array Probe Calibration Measurements in Water Tank ................................................................. 37

15. Results of 2 Inch Wenner Array Probe Measurements in Asylum Lake for Cross Calibration of 4 Inch and 6 Inch Pole-pole Arrays. Values Normalized to 20.0 Degrees Celsius ................................................................. 39

16. Results of 4 Inch Pole-pole Array Calibration Measurements in Asylum Lake Normalized to 20.0 Degrees Celsius ................................................................. 40

17. Results of 6 Inch Pole-pole Array Calibration Measurements in Asylum Lake Normalized to 20.0 Degrees Celsius ................................................................. 41

18. Map of Locations of Vertical Resistivity Probes at Asylum Lake Site ........................................................................... 44

19. Results of 2 Inch Wenner Array at Asylum Lake on July 12, 1999 ........................................................................... 50

20. Results of 4 Inch Wenner Array at Asylum Lake on July 27, 1999 ........................................................................... 51

21. Results of 2 Inch Pole-dipole Array at Asylum Lake on July 27, 1999 ........................................................................... 52

22. Results of 4 Inch Pole-dipole Array at Asylum Lake on July 27, 1999 ........................................................................... 53

23. Data Extracted From 2 Inch Wenner Array Profiles at 6 Specific Elevations to Demonstrate the Temporal Changes in Resistivity at ALVRP1 ........................................................................... 57
List of Figures—Continued

24. Average Apparent Resistivities From Each 2 Inch
   Wenner Profile to Demonstrate the Temporal Changes
   in Resistivity........................................................................................................... 59

25. Profiles of 2 Inch Wenner Array and 4 Inch Wenner
   Array From ALVRP1 on 9/4/1999........................................................................ 60

26. Profiles of 2 Inch Pole-dipole Array and 4 Inch Pole-
   dipole Array From ALVRP1 on 9/4/1999................................................................ 62

27. Profiles of 2, 4, and 6 Inch Pole-pole Arrays From
   ALVRP1 on 8/14/1999.......................................................................................... 63

28. Profiles of 4 Inch Wenner Array and 4 Inch Pole-
   dipole Array From ALVRP1 on 9/4/1999................................................................ 65

29. Profiles of 4 Inch Wenner Array and 4 Inch Pole-
   dipole Array From ALVRP1.................................................................................... 67

30. Profiles of 4 Inch Pole-dipole Array and 4 Inch Pole-
   pole Array From ALVRP1.................................................................................... 68

31. Induced Polarization Profile Along ALVRP1 Using 4-
    Inch Pole-pole Array on 8/14/1999...................................................................... 69

32. Base Map of Former Wurtsmith Air Force Base Study
    Site.............................................................................................................................. 72

33. Profiles of 2 Inch Wenner Array and 4 Inch Wenner
    Array From VRP2 at Wurtsmith Air Force Base on
    8/23/99.................................................................................................................. 75

34. Profiles of 2 Inch Pole-dipole Array and 4 Inch Pole-
    dipole Array From VRP2 at Wurtsmith Air Force Base
    on 8/24/99.............................................................................................................. 76

35. Profiles of 4 Inch Wenner Array and 4 Inch Pole-
    dipole Array From VRP2 at Wurtsmith Air Force Base
    on 8/23/99 and 8/24/99, Respectively.................................................................. 78
List of Figures—Continued

36. Profiles of 2, 4, and 6 Inch Pole-pole Arrays From VRP2 at Wurtsmith Air Force Base on 8/23/99 .......................................................... 79

37. Induced Polarization Profiles of the 4 Inch and 6 Inch Pole-pole Array From VRP2 at Wurtsmith Air Force Base on 8/23/99 ................................. 80

38. Profiles Comparing 2 Inch Pole-pole Array and 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base on 8/23/99 ................................. 82


40. Profiles of 4 Inch Pole-dipole Array From VRP1 at Wurtsmith Air Force Base Demonstrating the Stability of the System in the Background Region ......................... 86

41. Profiles of 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base Demonstrating the Stability of the System in the OT-16b Plume ........................................ 87

42. Profiles of 4 Inch Pole-dipole Array From VRP3 at Wurtsmith Air Force Base Demonstrating the Stability of the System in FT-02 Plume ........................................ 88

43. Comparison of 4 Inch Pole-dipole Results From VRP1 and VRP2 at Wurtsmith Air Force Base ......................................................... 90

44. Comparison of 4 Inch Pole-dipole Results From VRP1 and VRP3 at Wurtsmith Air Force Base ......................................................... 91

45. Location of Vertical Resistivity Probes at Lakeside Refinery Site ......................................................... 93

46. Results of 4 Inch Pole-dipole Array and 4 inch Wenner Array From VRP1 at Lakeside Refinery on 9/26/99 ......................................................... 97

47. Results of 4 Inch Pole-dipole Array and 4 inch Wenner Array From VRP2 at Lakeside Refinery on 9/26/99 ......................................................... 98
List of Figures—Continued

48. Results of 4 Inch Wenner Array From VRP1 and VRP2 at Lakeside Refinery on 9/26/99 .......................................................... 100

49. Results of 4 Inch Pole-dipole Array From VRP1 and VRP2 at Lakeside Refinery on 9/26/99 ......................................................... 101
CHAPTER I

INTRODUCTION

Problem

Monitoring wells are commonly used to obtain information about subsurface fluids at depths of interest. Although this proves to be effective, it can be very expensive if samples are taken frequently and at many different depths. Because typical monitoring well screen lengths of 3 and 5 feet produce a composite sample across the range of the screen, events and processes on a smaller scale are not readily discernable. Even multilevel wells with screens of 0.5 feet can miss many features because there is usually a vertical gap between sampling screens or ports. What is needed for certain hydrogeological problems is the capability to measure subsurface properties with vertical resolution of inches. Also needed is the ability to repeat these measurements at short time intervals to monitor temporal changes or transient events. Something is also needed that can show exactly what depths to sample because the depths at which the multilevel wells are placed are arbitrary.

Vertical resistivity probes have been built recently by geophysicists for use in hydrogeologic investigations. They can be used to trace infiltration events, trace inorganic contamination, and to monitor light non-aqueous phase liquids (LNAPL). By repeating these measurements at different times, one can also observe changes and vertical movements of these anomalous zones.
Before any system can be used effectively, a few considerations must be made. First, the system must be calibrated. The vertical resistivity probe can be used to collect data using numerous geometric electrode configurations. A calibration factor must be calculated for each geometric array to account for the presence of the infinitely resistive PVC cylinder to which electrodes are mounted. Next, each array must be field tested to determine which is most effective in providing the desired subsurface information. Along with field-testing the arrays, it must be noted that variations in installation parameters could drastically affect the effectiveness of each probe.

Objective

This project consists of four main objectives designed to make the use of vertical resistivity probes more effective: (1) to determine the calibration factors to be used for the different geometric arrays in order to correct for the insulating cylinder to which the electrodes are mounted, (2) to evaluate the variations in installation parameters, (3) to examine the transient changes due to leaching of the slurry used in installations that require bentonite slurry, and (4) to evaluate the different electrode arrays as to their effectiveness in delineating stratigraphic boundaries and other boundaries of interest.
CHAPTER II

THEORY

Electrical Methods

Historically, resistivity methods have been used primarily for geothermal, mining, coal, groundwater, and engineering applications (Ward, 1990). Recently, resistivity has undergone rapid development in applications in the petroleum industry as well as groundwater applications.

Each electrical resistivity method measures the electric potentials generated by applying a current into the ground using a battery, generator, or similar source. In surficial investigations, four electrodes are generally used. Two of the electrodes are used to applying the current and two are used to measure the potential. It is necessary to use two electrodes of each type in order to complete a circuit so the potential gradient and current can be measured in the presence of variable contact resistances.

Upon measuring the voltage, current, and geometrical arrangement of the electrodes, the resistivity can be calculated. This calculation is based on a uniform half space. Since nature never provides a completely homogeneous media, the measurement obtained from the resistivity meter is not the true resistivity of the ground; rather, it is the equivalent resistivity of a uniform half space. Therefore, it is more accurate to refer to measured field resistivities as apparent resistivities.
When dealing with buried electrodes, as in this experiment, the uniform half space assumption does not satisfy the conditions. Rather, it is appropriate to consider a uniform whole space. This does not complicate the calculation for apparent resistivity, but does change it by a factor of two (Telford, et al, 1990).

For each of the electrical methods tested, vertical resistivity profiling was the mode of operation. Resistivity profiling involves simply moving an array (both transmitting and receiving electrodes) with a fixed geometry along a line. This is used to detect anomalies along the line that may be the result of various factors that will be discussed later.

By changing the electrode geometry, the depth of investigation can be altered, hence altering the resolution of the data. In some situations, resolution of very slight features may be needed, while in others a broader trend may be of more interest. Consideration of the resolution needed should dictate the use of specific electrode arrangements with an appropriate spacing.

**Direct Current Resistivity**

In the direct current (DC) resistivity method, current is injected into the ground between two electrodes and the voltage is measured between two other electrodes (Ward 1990). To avoid electrode polarization effects, the polarity of the direct current is switched at very low frequency. The geometry of the electrodes, voltage, and current are then used to calculate the apparent resistivity of the earth circuit.
The square wave is usually the input waveform used in DC resistivity. Figure 1 illustrates the wave as it cycles through positive and negative pulses at a fixed frequency. The instrumentation used in this study required a time \( t \) to be input for determining the frequency to be used. A series of fixed preset times, ranging from 500ms to 2000ms could be used or programmable times could be used for the Syscal R2 Resistivity and IP Meter. Since the reciprocal of time equals frequency, selecting a pulse time allowed for accurate control of the frequency.

\[ \text{Intensity} \]

\[ +I \]

\[ \text{ON}^+ \quad \text{ON}^+ \quad \text{ON}^+ \quad \text{ON}^+ \quad \text{ON}^+ \]

\[ t \quad t \quad t \quad t \quad t \quad t \quad t \quad t \quad t \quad t \]

\[ -I \]

\[ \text{ON}^- \quad \text{ON}^- \quad \text{ON}^- \quad \text{ON}^- \quad \text{ON}^- \]

\[ t = \text{pulse time} \]

Figure 1. Frequency Domain Waveform Used for Acquisition of DC Resistivity Data. Square Wave (On +, On -) Cycle With Equal Pulse Widths.

When collecting DC resistivity data many different types of electrodes can be used. In this experiment, stainless steel was used for the electrodes on the probe and aluminum electrodes were used for remote surface electrodes when needed.

Understanding the cause of resistivity variations in the vadose zone sediments is an important step toward interpreting the data. Since most sedimentary facies are
very poor conductors, having resistivities in the range $10^3$ to $10^{10}$ Ω·m, some other property of the sediments must be governing the resistivity response (Telford, 1990).

The porosity and degree of cementation of the sediments control the size and number of available pore spaces that are present in the sediment. Since some of the pore spaces contain water the resistivity response is affected by it. Resistivity increases with decreasing water content and decreases with increasing water content.

In 1942, Archie demonstrated this relationship by developing empirical equations relating water content to resistivity. This development was crucial for the use of resistivity methods because the interstitial water is often the controlling factor of resistivity (Telford, 1990).

Resistivities in porous rocks differ with the volume and arrangement of the pores. The amount and resistivity of water or other fluids contained in the pores has an even greater effect on resistivities. Archie's (1942) empirical formulae state:

$$ F = a/\phi^m $$

$$ F = \rho/\rho_w $$

where $F$ is a formation resistivity factor, $\phi$ is the porosity of the formation, $m$ is a dimensionless cementation factor, $a$ is a dimensionless pore geometry coefficient, $\rho_o$ is the total wet resistivity of the formation, and $\rho_w$ is the resistivity of the pore fluid resistivity (Kwader, 1985; Heigold et al., 1979). The values of $a$ and $m$ have been commonly assigned values of 1.0 and 1.3 for unconsolidated surficial sediments (Wyllie and Gregory, 1953; Frolich, 1969).
By obtaining values for background water conductivities from a nearby well, the probe measurements can be used to calculate the conductivity of the pore waters in the contaminated region. Some basic assumptions must be made to make this calculation. First, two resistivity probes must be installed at the site, one in the contaminated region and one in a background area. Next, the subsurface sediments must be assumed to be identical at the locations of each probe. Archie's equations can then be simplified for the two probes such that:

\[
\frac{\rho_{o1}}{\sigma_{w1}} = \frac{\rho_{o2}}{\sigma_{w2}}
\]

where \( \rho_{o1} \) is the bulk wet resistivity measured with the resistivity probe installed in the background region, \( \sigma_{w1} \) is the background conductivity of water measured in a nearby existing well \( \rho_{o2} \) is the bulk wet resistivity measured with the resistivity probe installed in the contaminated region, \( \sigma_{w2} \) is the conductivity of the pore fluids.

Since different sediments have different porosities and subsequent water content, resistivity is affected by changes in the sediment type. This is an important relationship when dealing with vadose zone resistivities.

Another important concept relates ion content within the pore fluids. As ionic concentration increases in the pore waters, resistivity decreases because electrolytic conduction is enhanced. This relationship is extremely important to the geophysical model that will be presented in a later chapter that relates contaminant degradation to the mobilization of ions in solution, resulting in lower measured apparent resistivities.
Resistivity Well Logging

The vertical resistivity probes used in this study provide apparent resistivity values as a function of depth. This is very similar to geophysical well logging that has historically been used for many applications, but mostly in petroleum wells. Borehole techniques involving electrical methods have a long history. Since the late 1920's scientists have been experimenting with resistivity logging for mineral and petroleum exploration (Telford, 1990).

Although the vertical resistivity probes used in this study are permanent or semi-permanent, they provide the same type of information as traditional borehole resistivity methods.

There are some variables that must be accounted for in resistivity well logging methods. First, the mud used for drilling and installation affects the measured resistivity near the borehole. As the pilot hole is drilled, a mud or slurry is circulated or poured down hole to keep the hydrostatic pressure in the formations from collapsing the hole. When the probe is inserted into the pilot hole, the mud remains in the hole. This results in apparent resistivities that are a combination of the formation (including pore spaces), water content, interstitial fluid concentrations, and mud or slurry. The drilling mud tends to penetrate some sediment types more than others. For example, when clay layers are encountered, the slurry wall will remain about the same size as the auger or bit used to drill the hole, leaving only a thin layer of mud. Conversely, sands tend to "flow" when water content is high because of its high permeability, resulting in the mixing of the sand in the slurry around the pilot
hole creating an invaded zone (Telford, 1990). Because the mud moves into the formation further when permeability is high, the mud or slurry will have a larger effect on resistivities within the invaded zone than within the clay zones.

A low resistivity zone may also be encountered when hydrocarbon-bearing units are encountered. Hydrocarbons are displaced further beyond formation water in the invaded zone resulting in a high proportion of conductive formation water in a ring around the borehole (Telford, et al, 1990). The same principle can be applied to free product floating on the water table in environmental studies.

Another problem with resistivity logging is the nature of the resistivity anomaly that is generated as an interface is traversed. The anomalies observed along a profile where interfaces are crossed are not necessarily located precisely at the interface. Some electrode arrays can create artifacts of as many as 2 peaks and 2 troughs when crossing a single boundary. Also, high resistivity beds tend to appear thinner than their actual thickness and low resistivity beds appear to be thicker (Kumar, 1973a, b).

Induced Polarization

Induced polarization (IP) is an electrical method that is more complicated than the previously mentioned DC resistivity. IP is an extension of the DC resistivity method, which provides information about the chargeability or polarizability of the subsurface materials. This property of chargeability has been primarily used in base-

This method employs a symmetrical input waveform (Figure 2). It is similar to the square wave used in DC resistivity except it has an off time after each pulse that in this case is equal to the injection time. It cycles through an ON+, OFF, ON-, OFF sequence. This waveform is termed the "time domain" waveform, to distinguish it from another technique for measuring IP which used 2 or more frequencies of square wave, and is called the "frequency domain." The Off time of this waveform does not necessarily have to equal the On time, however, the system used in this study is restricted to equal On and Off times.

Intensity

\[ t = \text{pulse time} \]

Figure 2. Time Domain Symmetrical Current Waveform. (On+, Off, On-, Off) Cycle With Equal Injection Times of 1000ms.
Although the input waveform is very symmetrical and demonstrates uniform current throughout, the output waveform may look much different in the presence of polarizable material. In order to maintain a constant current throughout the pulse, the voltage must be increased with time.

As the current is injected into the subsurface, the voltage builds rapidly at first and then slowly climbs to a maximum. Figure 3 demonstrates this behavior and denotes the peak voltage as $V_{\text{max}}$. At the end of the current injection time a relaxation

![Diagram of voltage increase during current transmission and relaxation phenomena](image)

**Explanation.** $t_d =$ Delay time before the induced polarization effect can be measured

$\square =$ Window for measuring relaxation phenomena. Can vary from 500ms to 2000ms.

Note: Pulse time is less than Off time in this illustration.

**Figure 3.** Illustration of Voltage Increase During Current Transmission and Relaxation Phenomena Observed When the Current is Suddenly Shut Off for Polarizable Medium.
phenomena can be observed. When the voltage is suddenly shut off (OFF time on Figure 2), rather than observing an instantaneous drop of voltage across the potential electrodes, a gradual decrease is observed. The delay time ($t_d$) on Figure 3 is the time where electromagnetic and other switching transients can cause erratic or spiked potentials. The shaded region is the time in which the relaxation voltage is normally measured. This relaxation time can be on the order of milliseconds or even minutes (Telford, et al, 1990).

Figure 4 more closely examines the shut off time. With an initial delay time of 160ms (times vary depending on the instrumentation), and three subsequent periods ($t_1$, $t_2$, and $t_3$). Each of the three periods denotes a time integration window during which the relaxation voltage is integrated. In some systems longer pulse times and off times can allow for more integration windows.

In each of the integration windows the voltage is measured and normalized by the peak voltage attained at the end of the charging cycle ($V_{\text{max}}$ on Figure 4). This is necessary because the measured voltage is proportional to the peak voltage.

The induced polarization phenomena can be attributed to two main sources or mechanisms. Membrane polarization is the most common of the two causes. Variations in the mobility of ions in solution can result in charge separation in the subsurface when a current is applied. Since most rocks and minerals have a net negative charge at the interface between the surface and pore fluids, positive ions are
Explanation. 

\[ t_d = \text{delay time of 160ms} \]
\[ t_1 = \text{first integration window of 120ms} \]
\[ t_2 = \text{second integration window of 220ms} \]
\[ t_3 = \text{third integration window of 420ms} \]
\[ V_{\text{max}} = \text{primary voltage to which the induced polarization values are referred} \]

Figure 4. Typical Time Integration Windows for Determining Chargeability in the Time Domain.

Attracted toward these interfaces and negative ions repelled. If the pores are small enough, as in areas rich in clay, application of a voltage will cause positive and negative ions to be forced to opposite sides of the pore. This will impede the flow of current. The ions will return to their natural positions after a finite time when the current is shut off (Sumner, 1979). Clay mineral content greatly affects the degree of polarization of the subsurface. This effect is generally more pronounced when the clay content makes up about 2-20% of the soil matrix.

The other main cause for the energizing of the subsurface is electrode polarization. This is different from membrane polarization, and involves the presence of metal mineral grains and can lead to much greater polarization. When a current is
applied to the ground, the electron flow in the pores will be electrolytic. When metallic-lustered minerals are present, electron exchange will take place between the electrolytic solution and one side of the mineral grain and current will be transferred through the grain electronically. Upon reaching the opposite side of the metal, electrons will again be exchanged between the metal and the electrolytic solution. Since the metal grain conducts current at a much faster rate than the pore waters and the chemical reactions take time, a buildup of ions develops while the current is applied. When the current is shut off, the residual voltage decays as the ions return to their original state (Telford, et al, 1990).

"Nonpolarizing" electrodes are generally used for the receiver electrodes in induced polarization studies. This limits the electrochemical reactions that would normally take place at the soil-electrode interface if a metal electrode were used. Typically, nonpolarizing electrodes consist of a metal electrode submersed in a saturated solution of its own salt, with a porous (electrolytic) connection to the earth.

Although studies about the use of stainless steel electrodes for induced polarization have not yet been published, there are ways to evaluate the quality of the induced polarization data. If the IP value has only small fluctuations around the zero value in clean sands, then it can be assumed that electrochemical reactions between the electrode and the ground are minimal and the measuring system is reliable and no spurious values are being caused by the stainless steel electrodes. Another means of assessing this system is to check the repeatability of a series of measurements at some later time.
Electrode Arrays

Measured resistance (V/I) is dependent on the electrode arrangement and spacing. Commonly, a geometric factor, K, is applied to the measured resistance to obtain the resistivity. This factor accounts for the sampling volume and includes another variable, a, which is the spacing between adjacent electrodes. Since this study involves buried electrodes mounted on an insulating cylinder, the equation used in surficial studies must be altered to account for a "whole space" rather than the "half space" used in surficial studies and a calibration factor accounting for the presence of the insulating cylinder must also be determined for each array and spacing. The calibration factor is usually included in the calculation of factor K as a multiplier. More discussion on derivation of the calibration factor will follow in Chapter V.

Wenner Array

The Wenner array is commonly referred to as a nested array because the current electrodes surround the potential electrodes. Figure 5 displays the layout for this array. Each electrode is equidistant from the electrode adjacent to it. The A and B electrodes are used to inject the current and the electrodes denoted M and N are used to measure the potential. M and N are separated by a distance a.

This array has a geometry such that K is equal to two times \( \pi \) times the electrode spacing, a, for measurements made on the surface of a uniform half space (Ward, 1990). A slight adaptation must be made to this formula to adjust for a uniform whole space, which is the case for the underground vertical resistivity probe.
The resulting factor, $K$, is four times the electrode spacing, $a$, times a calibration factor used to correct for the insulating cylinder on which the electrodes are mounted.

**Pole-dipole Array**

The pole-dipole array is commonly referred to as the three-array because one of the current electrodes is placed at a distance at least ten times the electrode spacing, $a$. Figure 6 illustrates the general layout for this array.

The pole-dipole array does not normally require the A, M, N electrodes to be equidistant from one another. The electrode can be at multiples of the $a$ spacing away from the MN dipole. Because the data included in this study was collected using constant electrode spacings, the geometry is much simpler as is the resulting resistivity calculation.

In surficial studies, the geometric factor, $K$, is generally expressed as four times $\pi$ times the electrode spacing, $a$ (Ward 1990). Again this equation must be multiplied by a factor of two for the buried electrode case. The calibration factor must then be applied to this to account for the insulating cylinder. The resulting
The pole-pole array is a variation of the previously mentioned pole-dipole array. This array is different because one of the potential electrodes is also placed at a distance greater than ten times the electrode spacing in the opposite direction of the far current electrode. The conventional layout for this array is depicted on Figure 7.

Explanation.  
A,B = Current Electrodes,  
M,N = Potential Electrodes  
$\alpha$ = Spacing of Electrodes  
$\infty$ = a Distance Greater Than Ten Times the Electrode Spacing ($\alpha$)
The geometric factor, $K$, for this array is fundamentally the same as that of the Wenner array. However, the calibration factors are different for each of the arrays. Due to the far current and potential electrodes, the calibration factor will differ greatly from that of the Wenner array.
CHAPTER III

LITERATURE REVIEW

Vertical Resistivity Probes

Vertical resistivity probes have been experimented with in attempts to detect LNAPL contamination. Schneider and Greenhouse (1992) developed an in situ resistivity probe. These probes were used to monitor an infiltration event of perchloroethelyne (PCE). The probes were designed such that they were not detectable by other geophysical methods that were also being used to monitor the event. This required a removable inner probe that could be used to make contact with the electrodes and be removed prior to the use of other instruments (Schneider and Greenhouse, 1992). This type of probe greatly influenced the design of the probes used in this experiment.

Shoop and others (1996) also developed a vertical resistivity probe for detection of free phase hydrocarbons. These probes were permanently installed and used three wraps of 14-gauge copper wire to make contact with the formation. Unlike the probes used by Schneider and Greenhouse (1992), these probes had a hard-wired design. Each individual electrode was permanently attached to a lead wire that was run to the surface and used to activate specific electrode pairs (Shoop et al 1996). However, they used only a two-electrode measuring system and hence
measured primarily the sum of the two contact resistances. Their results were not in units of resistivity, and must be regarded as flawed from a geophysical standpoint.

Vertical resistivity probes have also been experimented with at Western Michigan University (WMU). The probes used in the following studies (more completely described in Chapter IV) measure the resistivity as a function of depth. A study by Kirt Elliott examined probe measurements and array configurations in a controlled laboratory tank experiment involving kerosene contamination (Elliott, 1998). This experiment was flawed because the tank system failed to provide a contaminant environment similar to field sites and the resistivity probes used were not calibrated for each of the electrode arrays used.

The early field installations of these probes by Marty Harmless and Dr. William Sauck involved the use of bentonite slurry. Early results have shown a drift in resistivity with respect to time. The change has been attributed to the leaching of ions from the bentonite creating a temporal variation in resistivity that mimics a standard diffusion curve.

Initially, bentonite has a high ionic concentration, with large amounts of Na⁺ and SO₄, as well as HCO₃⁻, Cl⁻, K⁺, and Mg²⁺. Each of these ions are readily soluble in water. In 1999, Wassenaar and Hendry determined that pore water chemistries could be contaminated by contact with bentonite seal materials. Samples taken from piezometers yielded high concentrations of each of the ions present in the bentonite, which demonstrated the mobility of the ions from the bentonite into solution.
Wassenaar, et al., 1999). Keller and others (1991) also examined water-soluble extract analyses on bentonite samples and showed similar results.

The mobility and leaching of the ions out of the bentonite into the formation causes an increase in resistivity of the bentonite slurry (used in vertical resistivity probe installation) with respect to time, resulting in a higher measured apparent resistivity with time (Keller, et al, 1991).

Stratigraphic Response

Stratigraphic boundaries could cause misleading responses when attempting to analyze the geoelectric effects of contaminants or infiltration events. Therefore, it is important to understand the origin of each anomaly. There have been many surficial resistivity studies that analyze the effect that a vertical dike has as an electrode array traverses it (Kumar 1973a, b). In many ways, the anomalies encountered in the vertical dike situation can be translated to work with the vertical resistivity probes.

If the stratification is generally subhorizontal, the geoelectric response encountered as the vertical profile traverses a stratified layer should be similar to results observed in the vertical dike situation in surficial studies with horizontal profiling.

The response of horizontal resistivity profiling over a vertical dike has been documented many times in recent literature. Telford and others (1990) examined the observed resistivity response with the dipole-dipole, half-Schlumberger, Wenner, and half-Wenner array types as the spread traverses a vertical dike. The Wenner array
yielded an anomaly that is larger than the dike and that has artifacts on either side of the profile. The other array types tested were not used in this experiment and therefore will not be discussed here.

Kumar (1973a, b) also investigated the resistivity response over a vertical dike. First various electrode spacings and dike widths were experimented with and the resulting resistivity contrasts were analyzed. The Wenner array showed a large anomaly associated with the dike with artifacts on either side of the anomaly and some within the anomalous feature (Kumar, 1973a). The pole-pole array yielded results that showed fewer artifacts than the Wenner array (Kumar, 1973b). Although the vertical dike scenario provides information about the response expected with the vertical resistivity probes, slurry or other backfill used in installation of the probes complicates the geometry by adding another layer analogous to a surface soil layer.

Kirt Elliott (1998) attempted to find an alternate method of determining contaminant thickness and monitor contaminant movement with vertical resistivity probes in a laboratory setting. The resistivity response as the electrodes cross an interface is also discussed.

With respect to vertical resistivity probes, a stratigraphic boundary should yield a different response with each array type and spacing. Therefore, it is necessary to test various arrays in order to determine the relative effectiveness of each array relative to the needed resolution of the boundary or of the thin layer.
CHAPTER IV

VERTICAL RESISTIVITY PROBE DESIGN

Overview

Two types of vertical resistivity probes have been designed for use in this investigation. Each probe, regardless of type, uses a series of stainless steel electrodes mounted on a polyvinyl chloride (PVC) pipe. The electrodes were simply screws that were threaded through the wall of standard schedule 40 pipe used for well casings. Screws were mounted exactly two inches apart along the probe with only the rounded screw head exposed outside the PVC pipe. The probes were completely sealed to prevent leakage and were installed as dry wells. The installation techniques will be discussed later because many types were experimented with.

The first type of probe, designed primarily by Dr. William A. Sauck of Western Michigan University, simply used ½ inch long screws so that a secondary instrument (slider or contacter) could be inserted into the inside of the probe from the surface to make contact with the threaded end of each screw (electrode), which extends into the inside of the probe. The secondary instrument could be easily removed so other geophysical methods (such as electromagnetic induction) could be used nearby without having a large anomaly generated by the wires to the probe contacts.
The prototype slider contained only four contacts at a fixed spacing equal to the electrode spacing and was used in an earlier study of a single VRP installation at the Asylum Lake Test Site (Harmless, pers. comm.). This greatly limited any experimentation with other geometrical arrays and electrode spacings. More recently Werkema (pers. comm.) has developed a slider that can make contact with sixteen consecutive electrodes simultaneously. This offers much more flexibility with respect to array types and electrode spacing. The contacts on this slider can be plugged into a switch box to select the electrodes that are to be used.

The other type of probe used in this study is very similar to the above-mentioned with one exception. Prior to the development of a multi-contact slider having more than 4 contacts, there was no way to utilize different electrode arrays and spacings. Therefore, a hard-wired probe was developed. Each electrode is sequentially wired into a fifty-pin communication plug. Another short wire bundle with a matching plug is then brought into the field and connected between the vertical resistivity probe and a switch box to control the active electrodes. This allows for simple data collection from the surface. This can also allow tomographic measurements to be made if another VRP is located in the vicinity.

Although both types of probes were used, there was fundamentally no difference in the time needed to make the desired measurements. Each probe offered the ability to make accurate and rapid resistivity and induced polarization measurements.
CHAPTER V

PROBE CALIBRATION

Methodology

In order to correct field measurements, the vertical resistivity probes must be calibrated to account for the insulating PVC cylinder to which the electrodes are mounted. This calibration also allows for accurate comparison between each of the different arrays and electrode spacings.

First a water tank (3.56 feet by 4.90 feet by 2.50 feet) of wood and fiberglass construction was drained and cleaned to extract any foreign materials that may have fallen into it over time. Then the tank was refilled with tap water and covered to prevent evaporation. Three days were allowed for the water to chemically equilibrate and for it to reach a uniform temperature. The water in the tank was 21.5°C for each of the calibration tests.

Next a floating tray with a row of small diameter electrodes (≈1mm) was set in the tank and resistivity measurements were made. Since the water was at a uniform temperature and concentration, it was treated as a uniform half space. Resistivity data were collected using 0.7874 inch (2 cm) and 1.5748 inch (4 cm) electrode spacings for the Wenner array. The resistivities were calculated using the following formula:
\[ \rho = (V/I) K \]

where K equals the geometric factor derived for each array. In surficial profiling, the geometric factor, K, for the Wenner array is equal to \(2\pi a\).

The floating tray measurements were repeated three times for both electrode spacings at 24 different positions. This was done to ensure that enough data were obtained for statistically meaningful averages to be calculated. The data were then examined to remove any outlier readings and averaged to obtain the true resistivity of the water.

A total of sixty-nine data points were gathered with an average resistivity of 16.779 Ohm-meters (\(\Omega\cdot m\)). The minimum and maximum resistivities observed were 16.170 and 17.447, respectively. A standard deviation of 0.331 \(\Omega\cdot m\) was also calculated to provide some quality assurance to the data. Figure 8 displays the data obtained in this baseline measurement using 0.7874 inch (2 cm) and 1.5748 inch (4 cm) electrode spacings.

Next, part of a probe was put into the tank and resistivity data were gathered for each of the tested arrays and electrode spacings. The vertical resistivity probes are much longer than the tank and therefore had to be inserted at an angle to optimize the number of measurable submersed electrodes.

The walls and bottom of the tank and the top of the water affected some of the data collected because the normal divergence of the current lines was impeded as the measuring electrodes approached the edge, bottom, and top and there was no way to
Figure 8. Results of 2 cm and 4 cm Wenner Array Floating Tray Water Tank Baseline Measurements.
analytically adjust the geometric factor, $K$, to account for this. This effect can be seen on the profiles as an apparent increase in the resistivity of the water at both ends of the profile.

With each array and spacing, the data were plotted and examined to eliminate readings affected by the tank walls and water surface. The unaffected data points were used to obtain the calibration factor for that array and spacing, using the following expression:

$$\rho_{\text{meas}} F = \rho_{\text{true}}$$

where $\rho_{\text{meas}}$ is the measured resistivity from each array and spacing, $\rho_{\text{true}}$ is the actual resistivity of the water in the tank, and $F$ is a multiplicative calibration factor. Each spacing and array type has its own calibration factor ($F$). This must be included in the calculation for resistivity to obtain correct resistivities.

Table 1 displays the calibration factors calculated as a result of each of the electrode array and spacing experiments. The following discussion details the data and the manner in which it was collected and treated.

**Wenner Array Calibration**

The Wenner array calibration was completed with both 2 inch and 4 inch electrode spacings. A total of 52 resistivity data points were collected for the 2 inch test and 48 data points were obtained for the 4 inch test.

The results of the 2 inch Wenner array calibration experiment are displayed on
Table 1

Calibration Factors for Various Electrode Arrays and Electrode Spacings

<table>
<thead>
<tr>
<th>Geometric Array</th>
<th>Electrode Spacing (inches)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Wenner</td>
<td></td>
<td>0.7343</td>
<td>0.8323</td>
<td>N/A</td>
</tr>
<tr>
<td>Pole-dipole</td>
<td></td>
<td>0.7459</td>
<td>0.9268</td>
<td>N/A</td>
</tr>
<tr>
<td>Pole-pole</td>
<td></td>
<td>0.9038</td>
<td>0.9116</td>
<td>0.9521</td>
</tr>
</tbody>
</table>

Figure 9. The gray horizontal bars on Figure 9 depict the upper and lower lateral limits of the data used to determine the calibration factor. The points used were determined by accepting data one standard deviation from the minimum value. These 44 data points were used to determine the calibration factor, F. An average apparent resistivity of 22.8521 $\Omega \cdot m$ was determined as well as a multiplicative (calibration) factor to adjust this value to the measured true resistivity of the water. The calibration factor, F, of 0.7343 was calculated. Earlier Harmless and Sauck (pers. comm.) determined calibration values for the 2 inch Wenner array to be 0.7220.

When experimenting with the 4 inch electrode spacing (Figure 10) it was obvious that the edges of the tank affected the resistivities much more than the 2 inch spacing. Again, the gray horizontal bars indicate the limits of usable calibration data. Only 18 data points were not affected by the edges of the tank. When larger electrode
Figure 9. Results of 2 Inch Wenner Array Probe Calibration Measurements in Water Tank.
Figure 10. Results of 4 Inch Wenner Array Probe Calibration Measurements in Water Tank.
spacings are used, a larger volume of the subsurface, or water in this case, is sampled. This effect will be of great importance in later discussion about the effectiveness of each electrode array and spacing. The resulting average apparent resistivity for the 4 inch Wenner array was 20.1639 Ω·m with a subsequent calibration factor of 0.8323.

Pole-dipole Array Calibration

Similar to the Wenner array, both 2 and 4 inch electrode spacings for the pole-dipole array were calibrated. In order to simulate a far current electrode, a metal screen was inserted into the tank along a far side. Only three of the electrodes on the probe were active at one time, two potential and one current. The screen was used to complete the circuit for the current in a manner that would imitate the current paths of an electrode spaced approximately two tank lengths away (via theory of images).

Figures 11 and 12 show profiles of the data collected using the 2 inch and 4 inch electrode arrays, respectively. A total of 46 data points were used to obtain the observed apparent resistivity for the 2 inch pole-dipole array and 28 measurements for the 4 inch array. Only data less than one standard deviation from the minimum was used in the calibration calculations. On both Figures 11 and 12, the gray bars show the limits of the data used for the calculation. The 2 inch array data yielded an average resistivity of 22.4953 Ω·m and a calibration factor of 0.7459, while the 4 inch array gave a resistivity of 18.5593 and a calibration factor of 0.9268.
Figure 11. Results of 2 Inch Pole-dipole Array Probe Calibration Measurements in Water Tank.
Figure 12. Results of 4 Inch Pole-dipole Array Probe Calibration Measurements in Water Tank.
Pole-pole Array Calibration

Unlike the other electrode arrays, calibration factors for three different electrode spacings were determined for this array. 2, 4, and 6 inch electrode spacings were calibrated for the pole-pole array.

First the 2 inch array was tested in the water tank. A total of 56 data points were measured, 40 of which were used to determine the calibration factor because they were less than one standard deviation from the minimum. Figure 13 displays the results of the 2 inch test. The data yielded an average resistivity of $18.8038 \ \Omega \cdot m$ and a calibration factor of 0.9038.

Upon examining the data from the 4 inch array, it appeared that the water tank was too small for accurate calibration. The current lines were being constrained by the edges of the tank, resulting in a higher current density and a measured resistivity that was less than the true resistivity at the center of the profile (Figure 14). Since the probe is constructed from insulating material, it is impossible to have a calibration factor greater than one.

Therefore, to avoid problems of limited tank dimensions for the larger "a" spacings, a calibration procedure similar to those above were performed, except that it was on a lake (Asylum Lake). Temperature readings were taken as a function of depth using the YSI Model 3000 Temperature, Level, and Conductivity Meter in order to correct for any changes in measured resistivities due to changes in temperature. Measured resistivities were adjusted $+2\%$ for each decrease of one degree Celsius. The data points were then adjusted to a normalized temperature of
Figure 13. Results of 2 Inch Pole-pole Probe Calibration Measurements in Water Tank.
Figure 14. Results of 4 Inch Pole-pole Array Probe Calibration Measurements in Water Tank.
20.0°C. The temperature correction ultimately was not necessary since the temperature only varied one degree Celsius.

The 20 foot long probe was weighted at the tip, and anchored in more than 20 feet of water with the upper 3 feet protruding above the surface. Probe measurements were made using the 2 inch Wenner array so that the resistivity of the water could be determined. This cross calibration technique was necessary because the floating tray data for the lake were questionable because of large vertical gradients in temperature in the upper twelve inches of the lake and the physically large temperature probe which precluded valid readings in the upper 2 inches of water. The results of the 2 inch Wenner array are shown graphically on Figure 15. The true resistivity of the lake water was determined to be 11.9207 Ω·m.

Next, the vertical resistivity probe was measured using the 4 inch and 6 inch pole-pole array. To simulate two far electrodes, two copper electrodes were placed at a distance greater than ten times the electrode spacing off opposite ends of the boat.

Figure 16 displays the results of the 4 inch pole-pole data normalized to a temperature of 20.0°C. The gray bars delineate the data points that were used in the calibration calculation. A total of 47 data points were used to calculate an average measured apparent resistivity of 13.0760 Ω·m and a subsequent calibration factor of 0.9116.

A profile of the 6 inch calibration data is depicted on Figure 17. 48 measured resistivities were averaged to determine the average apparent resistivity of the lake water. The average, 12.5917 Ω·m, was then compared to the true resistivity of the
Figure 15. Results of 2 Inch Wenner Array Probe Measurements in Asylum Lake for Cross Calibration of 4 Inch and 6 Inch Pole-pole Arrays. Values Normalized to 20.0 Degrees Celsius.
Figure 16. Results of 4 Inch Pole-pole Array Calibration Measurements in Asylum Lake Normalized to 20.0 Degrees Celsius.
Figure 17. Results of 6 Inch Pole-pole Array Calibration Measurements in Asylum Lake Normalized to 20.0 Degrees Celsius.
water in order to determine the effect of the probe on the measurements. This resulted in a calibration factor of 0.9521.
CHAPTER VI

FIELD TESTING

Purpose

The purpose of this aspect of the study was to test the effects of the installation parameters on vertical resistivity probe measurements. Four different installations were tested for probes in close proximity at the Asylum Lake Test Site in Kalamazoo, MI. After evaluating the installations and comparing the results, the temporal changes in resistivity were evaluated for the probes installed with bentonite slurry. Then the effectiveness of each electrode was examined using the probes at the Asylum Lake Test Site and at the former Wurtsmith Air Force Base.

Asylum Lake Test Site

Geology

The Asylum Lake Test Site is approximately located at 42°16' North latitude and 85°38'30" West longitude. It borders the western edge of the Kalamazoo city limits. There are three separate well fields and a geophysical test site within the Asylum Lake property. Figure 18 displays the location of the vertical resistivity probes in Well Field #3.
Figure 18. Map of Locations of Vertical Resistivity Probes at Asylum Lake Test Site.
Hand auger information from one of the probe installations has revealed a fairly detailed stratigraphic sequence of the subsurface. The upper six feet consists of brown silty clay. A layer of well-graded brown sand with traces of gravel approximately six feet thick underlies the uppermost layer. The third layer extends beneath the water table and is primarily comprised of well-graded fine to medium grained brown sand.

Water level measurements in neighboring wells indicate that the water table lies about 20 feet below the surface. Results from the vertical resistivity probes, discussed in the following sections, yield similar depths based on the location of typical saturated zone resistivities of about 70-90 \( \Omega \cdot m \).

**Installation Types**

Four vertical resistivity probes were installed at this site on the corners of a four foot square (Figure 18). The installations tested at this site were chosen as a function of availability of equipment, cost, and ease of installation.

The first installation, completed on April 27, 1996, used a very effective method. To create a pilot hole a Geoprobe™ point was attached to drilling rods and pounded into the ground by repeatedly dropping a large weight on it using the WMU drill rig. The annulus of the hole was kept filled with a slurry made up of water and high yield bentonite to keep hydrostatic pressure from collapsing sediments into the hole. The Geoprobe™ point was repeatedly pulled up and hammered back down in order to get some slurry ahead of the point and into the walls of the boring. This
increased ability to extend the pilot hole below the saturated zone. When the pilot hole reached a sufficient depth without collapsing, the probe point and attached drill rod were removed from the hole and a vertical resistivity probe was inserted. The probe was pushed through the slurry with the bentonite and water slurry filling the annular space outside the probe. This VRP was given the name ALVRP1. Figure 18 displays the location of this probe. The final installation depth of ALVRP1 is 22.75 feet with electrodes spaced from top to bottom in one-inch intervals.

The next probe, ALVRP2, was installed four feet north of ALVRP1 (Figure 18) on 4/24/99. This installation was labor intensive, mostly due to the manner in which the pilot hole was created. A hand auger with a diameter slightly larger than the probe was used to create the pilot hole. Similar to the previously mentioned installation, bentonite slurry was used to keep the hole open. Approximately five gallons of slurry was used for the installation of this probe. The slurry consisted of high yield bentonite and water.

This installation method is, by far, the least expensive since it only requires a hand auger and a few hours of manual labor. This less technological approach has benefits such as low cost, offering the ability to access normally unattainable sites, and a very small annulus of disturbed sediments immediately around the probe.

One problem with this method is preventing the sediments from collapsing beneath the water table. Typically, it takes more time to penetrate a few feet beneath the water table than it takes to penetrate the entire vadose zone with this method because of the collapsing of the sediments below the saturated zone. Another
drawback is the limitation of attainable depth beneath the saturated zone. It is extremely difficult to keep an open hole more than three or four feet beneath the water table with this method. Therefore the probe is limited to the vadose zone and the upper few feet of the saturated zone.

The final installation depth of ALVRP2 was 22 feet deep (approximately 4 feet below the saturated zone). Electrodes are spaced every two inches along the bottom twenty feet of this probe.

The other two probes installed at this site had very similar installations, only differing in the backfill materials. ALVRP3 and ALVRP4 were installed exactly four feet west of ALVRP2 and ALVRP1, respectively (Figure 18). Pilot holes for these probes were created using a drill rig owned by Western Michigan University. A 3.5-inch inner diameter hollow stem auger was used to drill each pilot hole. A knockout plug was inserted into the bottom of the auger to prevent sediments from filling up the auger during the drilling. Then when the appropriate depth was reached, the plug was knocked out and the probe was inserted.

ALVRP3 was installed and a clean, uniform, fine grained sand was backfilled into the auger to fill the annulus. The sand was used in the hope that it would eliminate many of the stratigraphic boundaries that interfere with the measurements of the fluid properties. Ideally, the sand would offer the opportunity to limit the anomalies to those caused by chemical changes in the aquifer. This could prove to be very effective when using these VRP's to monitor contaminated sites.
During the installation of ALVRP3 the backfill material caused the probe to become sand locked in the auger. This resulted in the loss of a few feet of the hole. Ideally, the bottom of the probe would have been 25 feet below ground level. As a result of the installation problem, the probe only extends 23 feet below grade.

ALVRP4 was similar to ALVRP3 except the backfill sediments were cuttings from the initial drilling of the pilot hole. This method was experimented with to observe the resistivity anomalies associated with stratigraphy and water content without the influence of bentonite or other foreign materials that might channel the current or distort current flow.

The hydrostatic pressure beneath the water table was allowed to naturally collapse the sediments around the probe while the annulus in the vadose zone was backfilled with cuttings. A final installation depth of 25 feet was obtained for this probe.

As well as having similar installation parameters, both ALVRP3 and ALVRP4 possess a hard wired design. The bottom twenty feet of these probes have electrodes spaced evenly every two inches with each electrode wired into a multi-contact plug at the surface. This design does not affect the measured resistivities.

Reports detailing each installation at this site are included in Appendix A.

Comparison of Installation Types

Upon completion of several profiles on each probe with each of the four different electrode arrays, a qualitative evaluation of each installation was made. It
was clearly apparent what types of installations were most effective when the results from each array and spacing were plotted against the profile of the same array on the other probes (Figures 19, 20, 21, 22).

The lowest five data points on Figure 19 from AL VRP2 represent some water that has leaked into the probe. Also, the higher resistivities associated with AL VRP3 beneath the water table were likely a result of the sand annulus around the probe.

It was obvious that the probe installed with the sand annulus (VRP3) caused problems with measurements above the water table. Since the annulus was clean uniform sand, it lacked sufficient moisture in the vadose zone for accurate measurements to be made. The extremely high contact resistance in the unsaturated zone impeded the flow of current into the subsurface such that vadose zone potentials could not be measured. The capillarity of the sand annulus provided enough moisture to attain measurable resistivities to approximately three feet above the saturated zone.

The probe installed with the hollow stem auger and backfilled with cuttings (VRP4) provided some useful resistivity data in the vadose zone because of the naturally occurring silt and clay in the area. The silt and clay particles allowed some moisture to be held in the lower vadose zone, but none in the upper parts. This moisture made it possible to generate measurable potentials. Although this installation provided much more useful data than the VRP3 installation, there were some problems. First of all, in the vadose zone, there were still some problems with the contact resistance as the electrode array approached the uppermost sand unit.
Figure 19. Results of 2 Inch Wenner Array at Asylum Lake on July 12, 1999.
Figure 20. Results of 4 Inch Wenner Array at Asylum Lake on July 27, 1999.
Figure 21. Results of 2 Inch Pole-dipole Survey at Asylum Lake on July 27, 1999.
Figure 22: Results of 4 Inch Pole-dipole Survey at Asylum Lake on July 27, 1999.
This unit is very resistive naturally and contact resistance problems occur, the compounded effect is an immeasurable potential caused by lack of enough current to produce measurable potentials. The other problem with this type of installation is that the sedimentary strata were greatly disturbed by the auger flights during creation of the pilot hole. Although some of the arrays may penetrate this disturbed zone, many of the naturally occurring stratigraphic boundaries are not observed. This can be good or bad, depending upon the intended use of the vertical resistivity probe.

The other two installations (AL VRP1 and AL VRP2) utilized bentonite slurry and had a very limited disturbed zone. These had benefits that greatly outweighed the drawbacks when compared to the previously mentioned installations (AL VRP3 and AL VRP4).

The bentonite slurry allowed for good coupling with the surrounding subsurface materials. A thin annulus of bentonite slurry allowed for more measurable resistivities along the profile as compared to the other two installations.

The relatively small-disturbed annulus encountered during installation of AL VRP1 and AL VRP2 allowed for accurate measurements of the naturally occurring stratigraphic boundaries in the surrounding sediments.

Upon comparing the results from AL VRP1 with AL VRP2, it is apparent that AL VRP1 provided a number of more useful readings than AL VRP2. This variation is the result of the amount of slurry used during the installations. For AL VRP1 a slurry annulus was used over the entire length of the probe, while for AL VRP2 only enough slurry was used to prevent the hole from caving in beneath the water table.
The slurry annulus for AL VRP2 is not continuous along the entire length of the probe, but it is continuous over the section of the probe containing electrodes. The lesser amount of slurry used in this installation has created problems with the contact resistance toward the top of the probe. This can be observed by referring to Figures 19, 20, 21, and 22. The useable data set for ALVRP2 is smaller than the data set for ALVRP1.

Therefore, the installation of ALVRP1 was much more successful for acquisition of the resistivity data. Although the bentonite causes a temporal variation (increase) in the resistivity profiles as ions leach into the subsurface, it keeps the electrodes in good contact with the surrounding formation.

**Temporal Changes**

The analysis of the different installation techniques has shown that the bentonite slurry installations yield the best contact with the formation. The only drawbacks to the use of the slurry are the settling, the potential cracking, and the leaching of ions into the subsurface. Each of these can cause considerable problems when attempting to measure temporal variations of the subsurface volume being studied. As the slurry in the vadose zone is contacted by formation pore waters and infiltrating surface waters it loses ions to the surrounding area resulting in an increase in the apparent resistivity of the annular volume. Although a notable change is not obvious over short periods (weeks) of time, the cumulative effect for a long period of one year or more.
The 2-inch Wenner array on VRP1 was chosen to evaluate the temporal change in resistivity because it provides the longest time series of data. A total of ten profiles were measured between April of 1996 until September of 1999.

To evaluate the temporal variation effectively, resistivity data at a series of points were extracted from each data set from equal elevations and plotted against the others with respect to time. Figure 23 displays the time variation of the apparent resistivities at six different depths along the profile for each ALVRP1. This shows the general trend of increasing resistivity as a function of time. The three deepest points (-222, -230, -260 inches) reside in the saturated zone. Therefore, the variations in the resistivity with time at these points can be assumed to be solely a result of leaching ions and not climatic infiltration events. The trend for these points is similar to a diffusion curve where most of the leaching occurs in the early times. The data from -194 inches lies slightly above the saturated zone. The data from this depth has a similar trend as the points from beneath the saturated zone. Capillary action is likely keeping the sediments at this depth uniformly wet and the variations can again be attributed to leaching of the ions from the slurry with exception of the last two data points that could be the result of infiltration events. The two uppermost depths on Figure 23 (-102, -122 inches) are from the vadose zone. The rise in the resistivity of data from -102 inches could represent the drying out of the formation after a rain event. While the deeper point, at -122 inches shows a drop in resistivity on August 3 and then another rise at the end of the survey period. This could represent an
Figure 23. Data Extracted From 2 Inch Wenner Array Profiles at 6 Specific Elevations to Demonstrate the Temporal Changes in Resistivity at ALVRP1.
infiltration and drying out cycle within the sand unit due to unusually dry conditions in the summer of 1999.

The temporal variations can also be noted on Figure 24. This is a graph of the average apparent resistivity for each entire 2-inch Wenner array profile at ALVRP1 with respect to time. Because the bentonite in the vadose zone dried out with time, there is a large increase in the resistivities with respect to time. The data presented in this graph is dominated by very high vadose zone resistivities and does not necessarily reflect the changes due to ion leaching. However, the large variations are likely due to the drying out of the vadose zone. As the adjacent bentonite dries, it may even crack or pull away from the probe, resulting in poor electrode contact and high apparent resistivities.

An overall drying out of the vadose zone in the area could cause variations in vadose zone resistivities.

Comparison of Each Array

Since ALVRP1 provided the best contact with the formation and hence more complete data set, resistivity profiles from this probe will be used to evaluate each electrode array. The geometrical arrangements, as discussed in chapter five, control the depth of investigation into the formation.

Since several arrays were experimented with using multiple electrode spacings, the effectiveness of the electrode spacings was determined. The Wenner array was tested with an AB/3 spacing of 2-inches and 4-inches. Figure 25 displays
Figure 24. Average Apparent Resistivities From Each 2 Inch Wenner Profile to Demonstrate the Temporal Changes in Resistivity.
Figure 25. Profiles of 2 Inch Wenner Array and 4 Inch Wenner Array From ALVRP1 on 9/4/1999.
profiles of the results from each of these spacings on September 4, 1999. Although upon initial observation there doesn't seem to be much difference, on closer examination it becomes apparent that the 4-inch electrode array yields a much smoother curve. The smoothness of the profile allows for much easier observation of the stratigraphic boundaries. The 4-inch electrode spacing gives higher resistivities than the 2-inch array because the effect of the bentonite on the apparent resistivity is less with respect to the sampled volume of the subsurface. Although the apparent resistivities are higher the slight vertical changes in resistivity can still be observed. Therefore, the 4-inch electrode spacing seems to provide better results than the 2-inch spacing for locating stratigraphic boundaries and lessening the contribution of the bentonite annulus.

Next, the pole-dipole array was evaluated for both 2 inch and 4 inch electrode spacings. The results (Figure 26) are very similar to the Wenner array results. Again, an increase in the electrode spacing provides a smoother curve without losing the necessary detail along the profile. For this reason, the 4 inch pole-dipole array was determined to be more effective than the 2 inch array for the delineating stratigraphic features and the water table.

2, 4, and 6 inch electrode spacings were then compared for the pole-pole array. Figure 27 displays profiles of the apparent resistivity for each electrode spacing. It is quite interesting how the profiles using this array seem to be identical in areas that are conductive and then stray from the others in zones of resistive material. In the resistive zones, the apparent resistivities increase as a function of the electrode
Figure 27. Profiles of 2, 4, and 6 Inch Pole-pole Arrays From ALVRP1 on 8/14/1999.
spacing. This different behavior of the apparent resistivities in conductive sediments and resistive sediments is likely to be the result of the bentonite annulus. In depth intervals that are conductive the bentonite will have a limited effect on the resistivity, while in resistive zones it will have a larger effect due to current channeling along the more conductive bentonite and invasion of the bentonite further into the formation (mixing of the bentonite with sand). The 2 inch array would not function as well as the other two array spacings because the bentonite greatly decreases the apparent resistivity of resistive zones, in effect suppressing the resistivity anomaly. In contrast, the 6-inch array has such a large sampling volume that it can also suppress some thin anomalous zones. The 4-inch electrode spacing for the pole-pole array offers the best compromise of characteristics of the other two spacings without the drawbacks.

Next, the most effective spacings for each array type were compared to the others in order to attempt to determine the best electrode array and spacing for this type of work. Figure 28 presents the profiles of the 4-inch Wenner array and the 4-inch pole-dipole array. Typically the Wenner array response shows a strong contact effect as an interface is traversed. The pole-dipole array does not present such extreme artifacts at interfaces in this manner, rather as a single change in resistivity. The pole-dipole array seems to offer slightly better results than the Wenner array because it tracks the apparent resistivity change across the interfaces on each profile without generating any artifacts.
Next, the 4-inch Wenner array and 4-inch pole-dipole array were compared to the 4-inch pole-pole array (Figures 29 and 30, respectively). On both of the profiles, the pole-pole array offers a much smoother curve. As well as yielding a smoother curve, the pole-pole array provides nearly equivalent detail in the stratigraphic sequence of the vadose zone. An example of this smoothing can be observed by comparing the measured apparent resistivities at a depth of 190 inches on Figure 29 and a depth of 208 inches on Figure 30. It should be noted that the pole-pole data used to compile Figures 29 and 30 was measured on August 14, 1999 and the Wenner and pole-dipole data was recorded on September 4, 1999. The differences in the upper portion of the vadose zone are likely due to changes in water content following a rain event, not the electrode array. The pole-pole array also offers the ability to measure the induced polarization phenomena. Figure 31 shows the IP profile along ALVRP1. These data were not collected using non-polarizing electrodes and the composite IP values determined from all three IP windows are plotted. Rather, the stainless steel screws in the probe and two remote aluminum electrodes were used. Since the IP effect seems to trend about the zero value, it can be inferred that the collection of IP data using these types of electrodes is valid and can provide useful information. The large single point excursions are probably spurious points, however. Although the IP response along this profile does not seem to provide any additional information, it may provide important information in locating contamination or emphasizing changes in clay content at other sites.
Figure 29. Profiles of 4 Inch Wenner Array and 4 Inch Pole-pole Array From ALVRP1.
Figure 30. Profiles of 4 inch Pole-dipole Array and 4 Inch Pole-pole Array From ALVRPI.
Figure 31. Induced Polarization Profile Along ALVRP1 Using 4 Inch Pole-pole Array on 8/14/1999.
Wurtsmith Air Force Base

Geology

The former Wurtsmith Air Force Base (WAFB), decommissioned in 1993, is located in Oscoda, Michigan, in Iosco County in the northeastern part of Michigan's lower peninsula at approximately 44°28' North latitude and 38°22' West longitude.

The base is located on a 5-mile wide sandy plain that is part of the Oscoda Lake plain (USGS, 1990). This plain extends from Lake Huron on the east to 80-foot high bluffs (remnants of Pleistocene deltaic deposits) west of the base (USGS, 1990). The surficial geologic unit is a uniform fine to medium grained sand unit of probable aeolian origin. This sand unit extends far below the zone of investigation of the vertical resistivity probes to approximately 65 feet. Depending on the topography, the depth to the water table varies from 14 feet to 18.5 feet.

Background Information

The site of investigation was formerly used to train fire fighters on the base. Typical training exercises involved the combustion of several thousand gallons of jet (JP-4) and other hydrocarbon fuels. The fires would then be extinguished as part of the training exercise. Some of the unburned fuel would percolate into the subsurface and contaminate groundwater (Bermejo et al, 1997). This was the source one of the contaminant plumes (FT-02) investigated in this project. The source of the other plume (OT-16b) was likely a maintenance building that no longer exists. It is
believed that this building had a dirt floor and used oil and solvents were simply
drained on the ground. Both of these well developed plumes are displayed on Figure
32 as shaded regions.

Installation Types

Three vertical resistivity probes were installed on this site in December of
1997. One probe is located in an uncontaminated zone between the two contaminant
plumes, while each of the other probes are installed in each plume. Figure 32
displays a map of the site, including the location of the vertical resistivity probes and
the lateral boundaries of each contaminant plume.

The pilot holes for each of the installations at this site were created using the
same procedure that was used for ALVRP1 at the Asylum Lake Test Site. VRP1 was
installed using fine granulated bentonite for the slurry, VRP2 used both powdered
bentonite and fine granulated bentonite for the slurry, and VRP3 used only powdered
bentonite for the slurry mixture. The probes installed with the granulated bentonite
slurry also had a small amount of polymer added to the slurry to prevent clumping of
the bentonite.

Each vertical resistivity probe installed on this site extends 25 feet below surface
elevation and has stainless steel electrodes equally spaced every one inch over the
entire length of the probe. Unfortunately, due to changes in the topography, VRP3
does not penetrate as deeply into the saturated zone as the other two probes.
Figure 32. Base Map of Former Wurtsmith Air Force Base Study Site.
To account for this change in topography, the elevation scale for graphs of data from VRP3 have been shifted when compared to VRP1.

Installation reports detailing each specific installation at this site are included in Appendix A.

Comparison of Each Array

Before attempting to interpret the resistivity profiles an understanding of the resistivity response in the presence of contamination must be obtained. In 1997, Bermejo and others observed a high conductivity zone associated with a LNAPL contaminant plume. The measured conductivities were 2.5 to 3.3 times background levels. The geoelectric signature of the contaminated zone appeared to contradict the previous models, which showed a high resistivity zone associated with the hydrocarbon.

Another study by Sauck and others (1998) documented a similar geoelectric response. The contaminated area was more conductive than the background areas. This demonstrated that the previous resistive model was inadequate for use in field investigations over mature contaminant plumes.

Comparisons between different electrode arrays were made by using profiles of data from VRP2. VRP2 was chosen because it is located in a contaminated zone and it penetrates the water table deep enough to get background water resistivities below the anomalously conductive plume. Prior to this phase of the research, the ability for each electrode array to detect stratigraphic changes was tested at the
Asylum Lake Test Site. Next it was necessary to determine which array was most effective in detecting the anomalous conductive zone associated with contaminant degradation. The effectiveness of each array is governed by the depth of penetration into the subsurface and the resolution that it provides along the profile.

First the various spacings for each array were evaluated to determine which spacing yields the best resolution of the conductive zone attributed to the degradation of hydrocarbons. The profiles of the 2-inch and 4-inch Wenner array from VRP2 are displayed on Figure 33. Water table depth on these profiles is 160-inches below grade. Both array spacings also detect an anomalous conductive zone that can be attributed to the degradation of the contaminants present. This zone extends from depths of 160 to 260 inches below grade. As the profile extends deeper into the aquifer, resistivities gradually shift back to the background levels. Above the water table, it appeared the 2 inch array had too much resolution and was detecting very small-scale stratigraphic boundaries along the profile or irregularities in the thickness of the bentonite annulus. This was obscuring the larger anomalies that are of interest. For this reason, the 4 inch array was determined to be more appropriate for this type of investigation.

Next, the 2 inch and 4 inch pole-dipole arrays were compared. Figure 34 displays the profiles of the pole-dipole data. The profiles again showed the presence of the anomalous conductive zone at the top of the aquifer and resistivities beneath the conductive zone increasing with depth until background resistivities were obtained. The 4 inch spacing also showed the necessary resolution along the profile
Figure 33. Profiles of 2 Inch Wenner Array and 4 Inch Wenner Array From VRP2 at Wurtsmith Air Force Base on 8/23/99.
Figure 34. Profiles of 2 Inch Pole-dipole Array and 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base on 8/24/99.
while the 2 inch spacing was biased to significantly lower the apparent resistivity by the bentonite annulus and was dominated by changes in the annular thickness. Again, the 4-inch electrode spacing provided better results.

Figure 35 displays the apparent resistivity profiles along VRP2 from the 4-inch Wenner array and the 4-inch pole-dipole array. The profiles are almost identical along the majority of the profile. The only notable difference is in the magnitude of the response at the upper interface of the anomalous conductive zone. The zone is defined much better on the pole-dipole profile. Therefore, the 4-inch pole-dipole array provided better results than the Wenner array.

2, 4, and 6 inch spacings were then analyzed using the pole-pole array. Figure 36 displays the measured apparent resistivities along the profile. Regardless of the spacing, this array seems to smooth out most of the stratigraphic boundaries and the anomalous conductive zone. Although each of the spacings experimented with detected the conductive zone, the boundaries of this zone are smoothed out. The progressive increase of apparent resistivity with electrode spacing is a clear indicator of the large influence of the bentonite annulus at smaller spacings.

Induced polarization measurements were made simultaneously with the pole-pole resistivity measurements. A non-polarizing electrode was used for the remote potential electrode in order to attempt to limit the electrode polarization effects. Figure 37 shows the results of the IP survey. The data is plotted on this figure is a composite value from all three of the integration windows. Other than a few erratic data points the IP effect did not stray from the zero point below 80 inches, implying
Figure 35. Profiles of 4 Inch Wenner Array and 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base on 8/23/99 and 8/24/99, Respectively.
Figure 36. Profiles of 2, 4, and 6 Inch Pole-pole Arrays From VRP2 at Wurtsmith Air Force Base on 8/23/99.
Figure 37. Induced Polarization Profiles of the 4 Inch and 6 Inch Pole-pole Array From VRP2 at Wurtsmith Air Force Base on 8/23/99.
that valid IP measurements were made. At this site the IP method did not seem to show any notable response from the contaminated zone other than a small step to more negative at 148 inches on the 6 inch pole-pole profile which "decayed" back to zero over the next 8 inches up the profile. The 1-3% increase in the upper 80 inches is noteworthy and may be due to a few percent increase of clay in the sands. However, there is no granulometry data available from nearby sample borings to confirm this.

The anomalous points at the bottom of the profile are due to water that slowly leaked into the probe. Overall, the combined results from the pole-pole array provided enough resolution to delineate the conductive zone, but the large sampling volume of the pole-pole arrays provided some "smoothing" of the interfaces and decreased resolution of small stratigraphic features.

To further demonstrate the effectiveness of the 4 inch pole-dipole array and the diminished vertical resolution with the pole-pole arrays, profiles were constructed comparing the 4 inch pole-dipole array to the 2 inch and 4 inch pole-pole arrays (Figures 38 and 39, respectively). Installation reports included in Appendix A indicate that the vertical resistivity probes at Wurtsmith Air Force Base required 2-3 times more bentonite slurry than those at the Asylum Lake Test Site, hence the annulus effects of the bentonite should be greater at WAFB. Therefore, the pole-pole arrays are more effective because they sample a larger volume of the formation or deeper into the formation.
Figure 38. Profiles Comparing 2 Inch Pole-pole Array and 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base on 8/23/99.
Figure 39. Profiles of 4 Inch Pole-pole Array and 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base on 8/23/99.
The low apparent resistivity anomaly at approximately 164 inches on the pole-dipole profile (Figures 38, 39) could be due to invasion of the bentonite into the sands at the water table, a wash out, or hole enlargement at and below the water table. Either of these would increase the amount of bentonite in the annulus or surrounding formation, hence increasing the bentonite effect. Therefore, the pole-dipole array is just showing more sensitivity to the bentonite than the 2, 4, and 6 inch pole-pole arrays.

Temporal Changes

The 4-inch pole-dipole array was chosen to evaluate the post-installation temporal changes in the resistivity for each vertical resistivity probe at this site. Due to the distance from Kalamazoo there is not a good time series of data from the probes immediately after installation and the data that are available used the 2 inch Wenner array. Since the use of the Wenner array was judged less effective for delineating the desired features, it was not used for this aspect of the project. Although, to date, only two data sets are available using the pole-dipole array, the temporal stability of the system may still be demonstrated. The data shown here from probes installed at WAFB were collected after a considerable delay after installation (at least 1.5 years). Because there is not a sufficient amount of data present to evaluate the post-installation temporal changes in resistivity caused by the bentonite, only the more recent stability of the system can be demonstrated.
Figures 40, 41, and 42 display resistivity profiles from two different dates for VRP1, VRP2, and VRP3, respectively. The vertical resistivity profiles for each of the probes were nearly identical over the entire length of the probe. This temporal consistency in the resistivities implies that the system has stabilized.

Comparison of Background Data Versus Plume Data

Since there are two distinctly different contaminant plumes that were monitored with the vertical resistivity probes, they will be compared to background measurements separately. VRP1 was installed between the two plumes in a clean environment (Figure 32). For each of the following profiles the 4-inch pole-dipole array was used to make comparisons because it showed the best vertical resolution of stratigraphic changes.

Stratigraphic features along each resistivity profile were used to normalize the depths so that the profiles could be successfully compared. Because VRP1 and VRP2 were installed at nearly the same elevation, no adjustment was necessary. However, VRP1 and VRP3 were installed at different elevations due to local topography. Therefore, an adjustment or shift of the depths was applied to the data from VRP1 based on a key stratigraphic feature beneath the water table to that of VRP3. The feature beneath the water table was chosen for this adjustment to eliminate any variances in the stratigraphic response due to water content. The selected characteristic present on both profiles lies beneath the saturated zone at a depth of 251-265 inches on the profiles of VRP3 and at a depth of 181-195 inches on VRP1.
Figure 40. Profiles of 4 Inch Pole-dipole Array From VRP1 at Wurtsmith Air Force Base Demonstrating the Stability of the System in the Background Region.
Profiles of 4 Inch Pole-dipole Array From VRP2 at Wurtsmith Air Force Base Demonstrating the Stability of the System in the OT-16b Plume.
Figure 42. Profiles of 4 Inch Pole-dipole Array From VRP3 at Wurtsmith Air Force Base Demonstrating the Stability of the System in FT-02 Plume.
Therefore, the depths for VRP1 were increased by 30 inches to allow for comparison between the probes. It should be noted that only depths for VRP1 were adjusted for this comparison; all other resistivity profiles from VRP1 show true depth below ground surface versus apparent resistivity.

First, resistivities from VRP1 were compared to VRP2. Figure 43 displays the resistivity profiles of data obtained using the 4 inch pole-dipole array. The profiles show very comparable results in the vadose zone. Beneath the water table, at depths greater than 163 inches, the profile from VRP2 shows a conductive zone with resistivities gradually increasing toward the bottom of the profile. The profile of VRP1 shows a gradual increase in resistivity above this depth (163 inches), indicating a decrease in water content in the vadose zone. Beneath this depth VRP1 shows relatively consistent background resistivities. VRP2 demonstrates a completely different response. The profile shows a conductive zone above the top of saturated zone interface. This zone on VRP2 is likely the result of a larger bentonite annulus around the probe caused by the penetration of bentonite farther into the formation.

Next, results from VRP1 and VRP3 were compared. Figure 44 displays the resistivity profiles generated using data collected with the 4 inch pole-dipole array. The depths from VRP1 were adjusted to compensate for differences in topographic elevation using the previously discussed methodology. This comparison shows fairly consistent vadose zone apparent resistivities. This comparison shows a much smaller magnitude anomaly associated with the conductive zone. The lesser magnitude of this anomaly is likely due to the location of the probe relative to the source area.
Figure 43. Comparison of 4 Inch Pole-dipole Results From VRP1 and VRP2 at Wurtsmith Air Force Base.
Figure 44. Comparison of 4 Inch Pole-dipole Results From VRP1 and VRP3 at Wurtsmith Air Force Base.
VRP3 is located much further down gradient from the free/residual product source zone and this is probably beyond the zone of primary leachate generation, and is instead in an area of diffusion of the leachate plume.

Lakeside Refinery

Geology

Lakeside Refinery, no longer active, is located in Section 25, T.2.S., R.11.W., Kalamazoo Township, Kalamazoo County, Michigan. The study area is bounded on the south by Davis Creek and to the west by railroad tracks and a swampy zone that feeds into Davis Creek (Figure 45).

The topography of this area is very undulating. Between the VRP's and the recovery wells that are installed at this site the surface elevation decreased 17 feet toward the west. The depth to saturated sediments is typically less than 2 feet in the western low lying area. The depth to water table on the terrace where the vertical resistivity probes are located is between 17-20 feet. Ground water flow is generally from the east toward the west where it discharges into the swampy area near the railroad tracks and flows into Davis Creek.

A series of glacial outwash channels appear to make up the upper 17 feet of sediment on the terrace (Johannes, personal communication). Beneath the channel forms is a clean fine to medium grained sand. This sand unit is the only sediment layer above the water table in the lowlands on the western part of the site.
Figure 45. Location of Vertical Resistivity Probes at Lakeside Refinery Site.
**Background Information**

Lakeside Refinery was a privately owned 50 acre facility that operated from 1940 to 1986. Various grades of refined petroleum hydrocarbons were produced during the years of operation.

Since closure of the refinery, the Environmental Protection Agency (EPA) removed all surficial facilities and tanks in 1996 and 1997. After this, the Michigan Department of Environmental Quality (MDEQ) became involved at the site with soil and ground water clean up. More recently, pilot scale recovery experiments were installed to begin remediating two contamination plumes emanating from the former tank farm east of Davis Creek. One of the recovery systems is located directly down gradient from two vertical resistivity probes.

**Installation Types**

There are three vertical resistivity probes installed at this site. Two of the probes are located in a contaminated region and the other is located in an area believed to be clean for use in obtaining background resistivities. Sampling from wells MW51s and MW51d (Figure 45) yielded no free product. Although there is no free product entering the well, there may be a substantial dissolved plume flowing through the area (Johannes, personal communication).

The first probe, VRP1 was installed in May of 1999. This installation used a combination of methods that were used at the Asylum Lake Test Site. A pilot hole was created in the vadose zone using a hollow stem auger and a mini-drill rig. Then a
Geoprobe™ point was pounded into the ground to complete the hole beneath the water table. The hole was held open by using bentonite slurry. To attempt to keep the bentonite from cracking and pulling away from the probe some solids were mixed in with the bentonite. 36 ounces of silica flour was used for this purpose. The completed depth of the probe was 25 feet. This probe is located on a terrace 12 feet northeast of MW51-s.

The next two probes, installed in a contaminated zone on 8/26/99, used another new installation technique. First a pilot hole was created using a 2.25 inch ID hollow stem auger. When a sufficient depth was attained, a high solids slurry was poured into the auger. The slurry used for these installations was composed of powdered bentonite, clean fine to medium grained sand, and distilled water. The sand was used to attempt to prevent shrinking and cracking of the bentonite. Distilled water was used to attempt to minimize the ions in the bentonite so that equilibration time would be decreased.

VRP2 is located 135.5 feet north of VRP1. VRP3 was installed five feet north of VRP2 to allow for the possibility of tomographic measurements. This could provide a two-dimensional model of the contaminated region as a function of depth. All vertical resistivity profiles are plotted relative to ground level.

Appendix A contains detailed reports of each specific installation.
Results of Initial Investigation

Because only initial data sets are available from the probes installed at this site the interpretation of the results is limited. Using the results from the Asylum Lake Test Site and Wurtsmith Air Force Base, two arrays were chosen for use on the probes at this site. The 4 inch Wenner array and the 4 inch pole-dipole array were used to collect resistivity data along VRP1 and VRP2.

Figure 46 displays the resistivity profiles collected using both arrays on VRP1. This probe was installed to monitor background resistivities. The top of the saturated zone appears to reside at a depth of approximately 170 inches. The very conductive zone, about 15 Ohm-m, located from depths of 235 to 270 inches is likely due to a change in stratigraphy from sand to clay.

On VRP2 the top of the saturated zone appears to be at a depth of about 165 inches below grade. The conductive upper portion directly beneath the top of the saturated zone (ranging from a depth of 165 to 240 inches) of the profile of VRP2 (Figure 47) is likely due to stratigraphy or it may be an anomalous conductive zone associated with the degradation of the contaminants. However, lacking lithologic data and in the absence of water conductivity values, this zone could have either a lithologic or water conductivity origin. Beneath the conductive zone resistivities appear to steadily increase until background levels are reached.

The observed resistivities along VRP2 indicate relatively conductive measurements associated with the saturated zone compared to VRP1. This may be attributed to the much thicker bentonite annulus created during installation of VRP2;
Figure 46. Results of 4 Inch Pole-dipole Array and 4 Inch Wenner Array From VRP1 at Lakeside Refinery on 9/26/99.
Figure 47. Results of 4 Inch Pole-dipole Array and 4 Inch Wenner Array From VRP2 at Lakeside Refinery on 9/25/99.
hence there is a greater influence of the bentonite on the measured apparent resistivities.

When comparing the data from VRP1 with data from VRP2 (Figures 48, 49), the complexity of the geology at this site became apparent. Glacial outwash channels and other heterogeneities throughout this area have made it very difficult to correlate stratigraphic boundaries at this site. Elevations of these probes have not yet been surveyed and the geology varies so much that the elevations could not be accurately adjusted by using stratigraphic boundaries. The following profiles, however, are referenced to ground elevation at each probe and the difference in surface elevation for each probe is less than 2 feet. The increase in resistivity (below 260 inches) on the profile of VRP1 on Figures 48 and 49 can be attributed to a stratigraphic boundary. Since this boundary is not present on the VRP2 profiles, it is likely a glacial outwash channel.
Figure 48. Results of 4 Inch Wenner Array From VRP1 and VRP2 at Lakeside Refinery 9/25/99.
Figure 49. Results of 4 Inch Pole-dipole Array From VRP1 and VRP2 at Lakeside Refinery on 9/25/99.
CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Installation Techniques and Temporal Variations

The installations of ALVRP1 and ALVRP2 provided the best resistivity data. Although the other two installations did not provide good data, they provided good information that can be used for future installations and investigations. First, the results from ALVRP3 demonstrated that a clean sand backfill did not retain enough moisture in the vadose zone to provide the electrodes with good contact with the formation. ALVRP4 showed that the natural sediment backfill provided much better data than the sand backfill used in ALVRP3 because of the naturally occurring silt and clay, but the contact resistances encountered were still too high to obtain quality data.

Upon examining the results of each installation, it became apparent that the electrodes needed an appreciable amount of fine grained silts and clays in the annulus to make electrical contact with the formation. Results from ALVRP1 and ALVRP2 demonstrated this. Since the bentonite dried out in the vadose zone, resulting in shrinking, cracking, and possibly pulling away from the probe, a combination two or more of the tested installations may provide better results. Additives, such as sand or naturally occurring sediments extracted during drilling, may be added to the standard
bentonite slurry. This could offer the best features of both installations. The bentonite would provide good contact with the subsurface and the sand or other additive would increase the solids content could provide added support to the bentonite and prevent it from pulling away from the probe and cracking.

Also, the pole-pole data from ALVRP1 demonstrated the noteworthy influence of the bentonite annulus. Therefore, future installations should be very cautious in regards to the choice of installation (i.e. hollow stem auger, or Geoprobe™ point technique). The smaller the annular space, the less effect the bentonite will have on the measurements.

Electrode Array Comparison

Asylum Lake Test Site

The array comparison allowed for evaluation of the resolution of each array and spacing tested. A total of seven arrays and spacings were evaluated. Profiles from the 2 inch spacings for the Wenner array and pole-dipole array were very erratic because most of the current was being channeled through the slurry annulus, rather than diverging into the formation. Minor changes in stratigraphy, differences in thickness of the annular material, and artifacts of the Wenner array caused the apparent resistivities to be quite variable at these small spacings. Each of the spacings tested with the pole-pole array (2, 4, and 6 inches) seemed to suppress some of the small-scale stratigraphic features or fluid conductivity changes that the probes were designed to detect, but they did provide good information on the effects of the
annular material by sampling progressively deeper into the formation. Hence, the largest pole-pole array spacing gives the best indication of the true bulk resistivity of the formation. The sampling volume for this array was large enough that small anomalous zones were averaged out so they were virtually undetectable on the resistivity profile. The 4 inch arrays for the Wenner and pole-dipole array seemed to show the desired resolution. The 4 inch spacing was large enough to suppress very small changes in apparent resistivity due to changes in thickness of the annular slurry, but small enough to show a strong response at important interfaces.

The transient effects of the bentonite slurry used for installation of the probes appeared to reach equilibrium with the aquifer after a residence period of 1.5 years for the Geoprobe™ type of installation. A simple diffusion curve approximately represented the curve of resistivity as a function of time, supporting the hypothesis that the governing factor for the changes in resistivity with time was the leaching of ions from the bentonite annulus. Most of the leaching from the bentonite occurred initially and gradually reaches an asymptote where equilibrium prevailed.

In an attempt to decrease the post-installation time necessary for the bentonite resistivity to stabilize, the slurry can be mixed with distilled water. This results in an initial condition of the bentonite slurry that contains fewer ions and thus should decrease the stabilization time.
Probes installed in two separate well-developed contaminant plumes and one probe installed in a background area were measured applying each of the electrode arrays which were tested earlier at the Asylum Lake Test Site. Each array was evaluated for its resolution for detection of an anomalous conductive zone associated with the degradation of the contaminants.

Similar to the results from the Asylum Lake Test Site, the data obtained using the smaller electrode spacings (2 inch) was greatly affected by the annular materials. The magnitude of the effect was much larger at this site because much more bentonite was used during the installation.

The 4 inch Wenner array and the 4 inch pole-dipole array were very effective in delineating the conductive zone extending approximately 5 feet beneath the top of the saturated zone. The pole-pole array was also effective in delineating this zone because it penetrated deeper into the formation; therefore the bentonite had less effect on measurements. Although the pole-dipole array and Wenner array successfully delineated the key stratigraphic interfaces and the anomalous conductive zone, the large amount of bentonite used for the installation of the probes at this site had a large effect on the data. The smoother profile of the pole-pole array resulting from its large sampling volume proved to be successful in delineating the stratigraphy and the conductive zone. The pole-pole array profiles appeared to be less affected by the low resistivity bentonite annulus.
The excellent repeatability of data sets separated by 5 weeks from each probe at this site provided information that indicated that the ionic concentrations in the bentonite annulus surrounding the probes has stabilized with the formation.

Comparison between the probes in plumes compared to the background probe showed a significantly lower resistivity in the plumes than in background aquifer material. It was noted that the probe nearer to the source of contamination showed a higher magnitude decrease in resistivity in the conductive zone, compared to the probe farther from the source.

Induced polarization data obtained at this site was not effective in detecting any of the contamination directly, or indirectly. However, it did provide some information about possible clay content in a few zones along the profiles.

Lakeside Refinery

Both profiles from Lakeside Refinery show a conductive zone beneath the water table. Since only initial measurements have been made at this site, it remains unclear if a conductive zone is a result of conductive groundwater or if it is a finer grained stratigraphic unit. This site is more heterogeneous than the other two sites studied through the course of this project making it an excellent candidate for future investigations.
Recommendations

Throughout this study many observations and difficulties were encountered that can be prevented by making some alterations to the current probe design. Two types of probes were used, a hard wired version and a "slider" version that requires a secondary instrument. Each type offers its own benefits. Water slowly leaking into the probes was a problem with either model of probes. Repeated monitoring of a probe of this type may loosen the seal around the stainless steel screws because of pressures from the secondary instrument inserted into the probe to make contact with the electrodes. Even after most of the water is removed from the leaking probe, the wetted surface along the inside of the probe could cause unreliable potentials to be measured. The insertion of some type of flexible sealant or bushing could decrease the probability of the probes leaking.

When experimenting with different installation types, the physical size of the probes became a controlling factor. The outer diameter of the probes (greater than 2 inches) eliminated the possibility of installing the probes with other technologies. For example, had the outer diameter of the probes been slightly smaller (less than 1½ inches) they could have been installed using Geoprobe™ technology.

Geoprobe now has larger diameter rods, which have a 2.125 inch outer diameter. This method was used very effectively at another site in Michigan (Sauck, pers. comm.). By probing down to depth with an expendable 2.5 inch point, the point could be knocked loose and slurry could be poured down the rods as they are being
withdrawn to keep the pilot hole open. The probe can then be inserted into the slurry filled hole.

The thickness of the slurry annulus used to complete the installations of the resistivity probes is a controlling factor for determining what electrode array should be used. The effectiveness of each array tested on the probes installed with bentonite at the Asylum Lake Test Site and those at WAFB demonstrates the effects of varying quantities of the slurry. Future installations should therefore create a pilot hole for installation that disturbs only a very small zone around the probe in order to limit the quantity of slurry used.

The composition of the slurry used for installation also influences the effectiveness of each array. Other studies have shown ions from the bentonite are leached ions into the surrounding formation, and this was verified by this research by the observed increase in resistivity with time. By mixing the slurry with distilled water, the ions become more mobile, thus minimizing the ions in the bentonite so that equilibration time would be decreased. Resistivity measurements from high in the vadose zone were very difficult to obtain because of high contact resistances due to the drying and subsequent shrinking of the bentonite clay. By increasing the solids content in the slurry, the shrinking and cracking of the slurry may be decreased or eliminated.

Very high contact resistances in the upper portions of the vadose zone made it very difficult to discern some of the stratigraphic boundaries. Data from this zone were not necessary for the contamination studies presented here. However
resistivities from 5-7 feet above the water table are necessary to accurately establish the position of the saturated zone and transitional zone as they seasonally fluctuate. Although resistivity measurements from the upper vadose zone were not very useful for monitoring in this study, they could provide very good information about infiltration events.

Active remediation of Lakeside Refinery is planned for the next few years, which could make it an interesting site to monitor with the vertical resistivity probes to analyze the effects of the remedial activity. I recommend more monitoring of the probes at this site as well as exploring the possibility of completing some tomographic measurements on VRP2 and VRP3.
Appendix A

Vertical Resistivity Probe Installation Reports
Site: Wurtsmith Air Force Base, Oscoda, MI

Location: 10' NW of P-120, just east of FT-02 plume

Probe Name/I.D.: VRP-1

Date of Installation: 12/09/97

Pilot Hole Rig, Tool Type: Small HSA rig; with cat-head, a-rods, geoprobe point

Rig Operators: Jerry Katone and two helpers

Person responsible for installation: W.A. Sauck

Slurry:

Volume mixed: 4 x 5-gallon pails

Type: Powdered Bentonite

Additives:

Completion Type:

Stick-up Height: 3' Threaded PVC

Below Grade Completion: N/A

Probe:

Material: Schedule 40 PVC Pipe

Diameter: 1.5 inch ID

Length: 25 feet

Electrode Type: Stainless steel screws

Electrode Interval: 1 inch

Depth of Top Electrode: 2"
Site: **Wurtsmith Air Force Base, Oscoda, MI**

Location: In OT-16b Plume, 10' E of T116

Probe Name/I.D.: **VRP-2**

Date of Installation: 12/10/97

Pilot Hole Rig, Tool Type: Small HSA rig; with cat-head, a-rods, geoprobe point

Rig Operators: Jerry Katone and two helpers

Person responsible for installation: W.A. Sauck

Slurry:

- Volume mixed: 4 x 5-gallon pails
- Type: Enviroplug; fine granulated bentonite
- Additives: 2 tbsp. Polymer/5-gallon pail

Completion Type:

- Stick-up Height: 3' Threaded PVC
- Below Grade Completion: N/A

Probe:

- Material: Schedule 40 PVC Pipe
- Diameter: 1.5 inch ID
- Length: 25 feet
- Electrode Type: Stainless steel screws
- Electrode Interval: 1 inch
- Depth of Top Electrode: 2"
Site: Wurtsmith Air Force Base, Oscoda, MI

Location: In FT-02 Plume, 13' WSW of M-123, 10' S of well cluster FTMW-5

Probe Name/I.D.: VRP-3

Date of Installation: 12/10/97

Pilot Hole Rig, Tool Type: Small HSA rig; with cat-head, a-rods, geoprobe point

Rig Operators: Jerry Katone and two helpers

Person responsible for installation: W.A. Sauck

Slurry:

- Volume mixed: 4 x 5-gallon pails
- Type: Enviroplug; fine granulated bentonite
- Additives: 2 tbsp. Polymer/5-gallon pail

Completion Type:

- Stick-up Height: 3' Threaded PVC
- Below Grade Completion: N/A

Probe:

- Material: Schedule 40 PVC Pipe
- Diameter: 1.5 inch ID
- Length: 25 feet
- Electrode Type: Stainless steel screws
- Electrode Interval: 1 inch

Depth of Top Electrode: 4"
Site: Asylum Lake Test Site, Well Field #3, Kalamazoo, MI

Location: 10' W of Monitoring Well AL-32

Probe Name/I.D.: ALVRP-1

Date of Installation: 04/27/96

Pilot Hole Rig, Tool Type: WMU Hydradril, a-rod, geoprobe point,

Rig Operators: R. Laton, M. Dalman, M. Harmless

Person responsible for installation: W.A. Sauck

Slurry:

Volume mixed: 5-gallons

Type: Powdered bentonite, water

Additives: N/A

Completion Type:

Stick-up Height: N/A

Below Grade Completion: X

Probe:

Material: Schedule 40 PVC Pipe

Diameter: 1.5 inch ID

Length: 22.75 feet

Electrode Type: Stainless steel screws

Electrode Interval: 2 inches

Depth of Top Electrode: 6"
Site: Asylum Lake Test Site, Well Field #3, Kalamazoo, MI

Location: W of Monitoring Well AL-32, 4' N of ALVRP1

Probe Name/I.D.: ALVRP-2

Date of Installation: 04/24/99

Pilot Hole Rig, Tool Type: Hand Auger

Rig Operators: J. Groncki

Person responsible for installation: J. Groncki

Slurry:

Volume mixed: 5-gallons

Type: Powdered bentonite, water

Additives: N/A

Completion Type:

Stick-up Height: N/A

Below Grade Completion: X

Probe:

Material: Schedule 40 PVC Pipe

Diameter: 1.5 inch ID

Length: 22 feet

Electrode Type: Stainless steel screws

Electrode Interval: 2 inches

Depth of Bottom Electrode: 262"
Site:  **Asylum Lake Test Site, Well Field #3, Kalamazoo, MI**

Location:  W of Monitoring Well AL-32, 4' W of ALVRP2

Probe Name/I.D.:  **ALVRP-3**

Date of Installation:  04/24/99

Pilot Hole Rig, Tool Type:  WMU Hydradril, 3.5" ID HSA

Rig Operators:  J. Groncki, M. Dalman, D. Werkema, A. Hudak

Person responsible for installation:  J. Groncki

Slurry/Backfill:

  - Volume mixed: none, backfilled with sand
  - Type: clean fine to medium grained sand
  - Additives: N/A

Completion Type:

  - Stick-up Height: N/A
  - Below Grade Completion: X

Probe:

  - Material: Schedule 40 PVC Pipe
  - Diameter: 1.5 inch ID
  - Length: 23 feet
  - Electrode Type: Stainless steel screws
  - Electrode Interval: 2 inches
  - Depth of Bottom Electrode: 274"
Site: **Asylum Lake Test Site, Well Field #3, Kalamazoo, MI**

Location: W of Monitoring Well AL-32, 4' W of ALVRP1, 4' S of ALVRP3

Probe Name/I.D.: **ALVRP-4**

Date of Installation: 04/24/99

Pilot Hole Rig, Tool Type: WMU Hydradril, 3.5" ID HSA

Rig Operators: J. Groncki, M. Dalman, D. Werkema, A. Hudak

Person responsible for installation: J. Groncki

Slurry/Backfill:

- Volume mixed: none, backfilled with drill cuttings
- Type: drill cuttings
- Additives: N/A

Completion Type:

- Stick-up Height: N/A
- Below Grade Completion: X

Probe:

- Material: Schedule 40 PVC Pipe
- Diameter: 1.5 inch ID
- Length: 25 feet
- Electrode Type: Stainless steel screws
- Electrode Interval: 2 inches
- Depth of Bottom Electrode: 298"
Site: Lakeside Refinery, Kalamazoo, MI

Location: 13' E of MW-51s, 18' NE of MW-51d

Probe Name/I.D.: LSRVRP1 or VRP1

Date of Installation: 05/20/99

Pilot Hole Rig, Tool Type: Minute Man portable drill rig, 2.25 inch ID HSA

Rig Operators: J. Groncki, Trisha Peters, Paul Massoth, Jeff Spruit

Person responsible for installation: J. Groncki

Slurry/Backfill:

Volume mixed: 20 pounds of bentonite

Type: powdered bentonite

Additives: 36 ounces of silica flour

Completion Type:

Stick-up Height: 3'

Below Grade Completion: N/A

Probe:

Material: Schedule 40 PVC Pipe

Diameter: 1.5 inch ID

Length: 28 feet

Electrode Type: Stainless steel screws

Electrode Interval: 2 inches

Depth of Bottom Electrode: 298"
Site: **Lakeside Refinery, Kalamazoo, MI**

Location: 135.5' N of LSRVRP1, up gradient from recovery trench

Probe Name/I.D.: **LSRVRP2 or VRP2**

Date of Installation: 08/26/99

Pilot Hole Rig, Tool Type: West Michigan Drillers Drill Rig

Rig Operators: Doug Klitz and Jim Moyer

Person responsible for installation: J. Groncki

Slurry/Backfill:

- Volume mixed: 1/4 50- pound bag, 7.5 gallons distilled water
- Type: powdered bentonite
- Additives: 20 pounds of clean fine to medium grained sand

Completion Type:

- Stick-up Height: 2'
- Below Grade Completion: N/A

Probe:

- Material: Schedule 40 PVC Pipe
- Diameter: 1.5 inch ID
- Length: 34 feet
- Electrode Type: Stainless steel screws
- Electrode Interval: 2 inches
- Depth of Bottom Electrode: 386"
Site: **Lakeside Refinery, Kalamazoo, MI**

Location: 5' N of LSRVRP2

Probe Name/I.D.: **LSRVRP3 or VRP3**

Date of Installation: 08/26/99

Pilot Hole Rig, Tool Type: West Michigan Drillers Drill Rig

Rig Operators: Doug Klitz and Jim Moyer

Person responsible for installation: J. Groncki

Slurry/Backfill:

- Volume mixed: 1/4 50-pound bag, 7.5 gallons distilled water
- Type: powdered bentonite
- Additives: 20 pounds of clean fine to medium grained sand

Completion Type:

- Stick-up Height: 2'
- Below Grade Completion: N/A

Probe:

- Material: Schedule 40 PVC Pipe
- Diameter: 1.5 inch ID
- Length: 35 feet
- Electrode Type: Stainless steel screws
- Electrode Interval: 2 inches

Depth of Bottom Electrode: 398"
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121


