IN-SITU PERMEABILITY MEASUREMENTS WITH DIRECT PUSH TECHNIQUES: PHASE II TOPICAL REPORT

March 1999

William Lowry (Principal Investigator)
Neva Mason, Veraun Chipman, Ken Kisiel, Jerry Stockton

Science and Engineering Associates, Inc.
3205 Richard Lane, Suite A
Santa Fe, New Mexico 87505
(505) 424-6955

SEASF-TR-98-207

Submitted to:
Karen Cohen
DOE Federal Energy Technology Center
FETC Contract No. DE-AC21-96MC33124

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

TABLE OF CONTENTS

DISCLAIMER	ii
LIST OF FIGURES	v
LIST OF TABLES.....	vii
EXECUTIVE SUMMARY	1
1. INTRODUCTION	2
2. OBJECTIVE.....	5
3. DESIGN.....	6
3.1 General Design	6
3.2 Measurement Probe Design.....	7
3.3 Data Acquisition and Control System	8
3.4 Data Acquisition and Analysis Software.....	13
3.5 Data Analysis.....	22
3.6 Transducer Calibration Software.....	24
3.7 Regression Formation of Calibration Curves	29
3.8 Cone Permeameter TM Measurement Procedures	30
3.9 Quality Assurance.....	35
3.10 System Operating Parameters.....	36
3.11 Technology Limitations.....	37
4. LABORATORY TEST OF PROTOTYPE SYSTEM	38
4.1 Objectives	38
4.2 Procedures.....	38
4.3 Lab Tests of Soil Samples	40
4.4 Test Cell Results	43
4.5 Discussion.....	44
5. ANALYSIS OF NON-IDEAL EFFECTS.....	46
5.1 Purpose and Methodology	46
5.2 Analytical Permeability Equations	47
5.3 Numerical Modeling.....	47
5.4 Model Assumptions	49
5.5 Modeling Results	50
5.6 Data Reduction and Analysis.....	68
5.7 Conclusions and Recommendations	69
6. FIELD TEST RESULTS	70
6.1 Test Objectives	70
6.2 Cone Penetrometer Truck	70
6.3 Site Characteristics	70
6.3 Testing Chronology	74

6.4 Saturated Zone Hydraulic Conductivity Measurements.....	75
6.5 Unsaturated Zone Gas Permeability Measurements.....	78
6.6 Comparison with other Measurement Data	83
6.7 Integration with Other Tools	83
7. COST EFFECTIVENESS OF THE CONE PERMEAMETER™ MEASUREMENT SYSTEM.....	88
7.1 Baseline Technologies Comparison	88
7.2 Laboratory Analysis.....	88
7.3 Field Testing	89
7.4 Cost Comparison	89
8. PROPOSED PHASE III ACTIVITIES	92
9. SUMMARY AND RECOMMENDATIONS	93
10. ACKNOWLEDGMENTS	95
11. APPENDIX: PERMEABILITY MEASUREMENT MODEL	96
12. REFERENCES	102

LIST OF FIGURES

Figure 1. Cone Permeameter™ system schematic.	6
Figure 2. Prototype Cone Permeameter™ rod section design.....	7
Figure 3. Cone Permeameter™ rod section and data acquisition/control system.	8
Figure 4. Cone Permeameter™ measurement system electrical schematic.	10
Figure 5. Pump package electrical schematic.....	11
Figure 6. Pump package plumbing schematic.	12
Figure 7. Data-acquisition hardware configuration.	13
Figure 8. Data-acquisition code flow schematic.....	14
Figure 9. <i>RawData</i> sheet.....	16
Figure 10. Data-acquisition process diagram.	19
Figure 11. Process-flow diagram for the <i>SaveRecord</i> subroutine.	21
Figure 12. <i>History Plots</i> sheet.	23
Figure 13. The <i>CalibrationData</i> sheet of <i>CalibrateTransducers.xls</i> contains the controls for the calibration data acquisition.	27
Figure 14. Calibration software process diagram.	28
Figure 15. The <i>ProcessData</i> sheet displays results of a five-point calibration.	29
Figure 16. Calibration chamber.	31
Figure 17. Cone Permeameter™ system setup.....	33
Figure 18. Soil test cell used for laboratory evaluation of the prototype permeameter rod section.....	38
Figure 19. Locations of lab test cell samples obtained during filling.....	39
Figure 20. Pressure profile measured by the prototype Cone Permeameter™ during a typical air permeability measurement in the test cell.	44
Figure 21. Cone Permeameter™ rod with pressure sensors at discrete locations above the injection zone.	47
Figure 22. Cone Permeameter™ pushes were simulated by progressively changing the material properties of the mesh layers (note that the figure is not drawn to scale and represents only a portion of the 10 meter by 10 meter mesh).	49
Figure 23. Air injection test, homogeneous, isotropic baseline case.....	55
Figure 24. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 1.....	56
Figure 25. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 2.....	57
Figure 26. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 3.....	58
Figure 27. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 4.....	59

Figure 28. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 5.....	60
Figure 29. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 6.....	61
Figure 30. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 1.....	62
Figure 31. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 2.....	63
Figure 32. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 3.....	64
Figure 33. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 4.....	65
Figure 34. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 5.....	66
Figure 35. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 6.....	67
Figure 36. Cone penetrometer truck in position for SRS Area M measurements.	71
Figure 37. Cone Permeameter™ rod prior to initial push during SRS demonstration.	71
Figure 38. Location of coal pile runoff basin and well DCB-25 (Phifer, Sappington, Pemberton, and Nichols 1996).	72
Figure 39. Core sample descriptions of DCB-25 (Rust Environmental & Infrastructure 1996).	73
Figure 40. General stratigraphy of the M area.	73
Figure 41. Depth vs. hydraulic conductivity of D area coal runoff basin (near DCB-25).	77
Figure 42. Area M (between MHV-10 and MHV-11) using the injection zone/flow equation.	80
Figure 43. The permeability vs. depth profiles of the 321 M area.	82
Figure 44. Comparison of Cone Permeameter™ saturated hydraulic conductivity measurements with minimum and maximum values obtained in previous borehole flowmeter measurements.	84
Figure 45. CPT cone and Cone Permeameter™ measurements taken near DCB - 25.	85
Figure 46. CPT cone and Cone Permeameter™ measurements taken between MHV-10 and MHV-11.	86
Figure A1. Schematic of spherical flow geometry resulting from fluid injection.	97
Figure A2. Conceptual flow field of penetrometer permeability measurement configuration.	98

LIST OF TABLES

Table 1. Typical permeability values for various media (one Darcy equals $9.87 \times 10^{-13} \text{ m}^2$).....	2
Table 2. Process data unit conversions.	22
Table 3. Cone Permeameter™ measurement system measurement limits.....	37
Table 4. Air permeability laboratory test results.	41
Table 5. Saturated hydraulic conductivity laboratory test results.....	42
Table 6. Cone Permeameter™ measurements compared to laboratory air permeability measurements of the soil samples.	43
Table 7. Summary of Cone Permeameter™ water measurements and falling head permeability measurements of the soil samples.	43
Table 8. Summary of the Cone Permeameter™ numerical simulations.	48
Table 9. Air injection simulations, heterogeneous, isotropic cases.....	51
Table 10. Air injection simulations, heterogeneous, anisotropic cases.	52
Table 11. Air injection simulations, heterogeneous, isotropic, compacted annulus cases.....	53
Table 12. Air injection simulations, heterogeneous, anisotropic, compacted annulus cases.	54
Table 13. Results of the saturated hydraulic conductivity tests performed near well DCB-25 with the Cone Permeameter™ measurement system.....	76
Table 14. Results of the unsaturated zone air permeability measurements performed in the M area, between SEAMIST boreholes MHV-10 and MHV-11.	79
Table 15. Results of the unsaturated zone air permeability measurements performed in the 321 M area.	81
Table 16. Cost comparison of Cone Permeameter™ measurements compared with conventional techniques.	91
Table A1. Parameters and units.....	98

EXECUTIVE SUMMARY

The Cone PermeameterTM measurement system provides quantitative soil gas permeability and saturated hydraulic conductivity measurements with direct push measurement techniques. In the initial phase of this development effort, the Cone PermeameterTM measurement model was derived and demonstrated in a large-scale laboratory test cell. Numerical analysis evaluated the measurement geometry and guided the design of the subsequent prototype development phase. Both the laboratory and numerical experiments showed that the basic premise of the measurement was credible and the method was capable of measurements within 20% of laboratory-derived results on unconsolidated media.

The objective of the second phase of the contract effort was to design and fabricate a prototype measurement system and then apply this prototype system in field demonstrations at a DOE site. The integrated system was to be capable of both hydraulic conductivity measurements in the saturated zone and air permeability measurements in the unsaturated zone. The major accomplishments of the Phase II effort include:

- An integrated system was designed and fabricated, including an instrumented penetrometer rod section, real-time data acquisition system, and flow control system capable of easy transport to sites and use with a range of cone penetrometer trucks.
- The prototype system was tested in a large laboratory test cell to evaluate its operation and confirm its performance in lower permeability media than was possible in the Phase I tests.
- Additional numerical analyses were performed to evaluate the effects of layering and anisotropic permeability on the measurement approach.

The resulting field system is capable of several decades of measurement resolution based on present instrument ranges, which can be tailored to suit specific site requirements: saturated hydraulic conductivity in soils ranging from $3\text{e-}6$ to 0.1 cm/sec , and air permeability from $1\text{e-}5$ to 4.5 Darcies.

The prototype system was then fielded at the DOE Savannah River Site for tests both above and below the water table. Three test areas were selected: the D Area Coal Pile Runoff Basin, the 321 M Area, and the M Area Integrated Demonstration Site. Initial tests conducted at the Coal Pile Runoff Basin were highly successful, completing 38 measurements to a maximum depth of 57 ft. with typical times of 8 to 10 minutes per measurement location. The results agreed well with prior testing in the same area that was accomplished using four screened wells and a borehole flowmeter survey. Air permeability measurements at the 321 M Area and the M Area Integrated Demonstration Site were complicated by repeated plugging of the pressure ports by clay and regions of clay with no apparent air permeability. Measurements at these two sites were completed to a depth of 46 ft., with 8 out of 34 measurements yielding good results using the standard Cone PermeameterTM model.

With some modification of the pressure port design to minimize plugging, the Cone PermeameterTM system is capable of rapid, high-resolution permeability measurements, in a wide range of media, at implementation costs significantly lower than standard techniques.

1. INTRODUCTION

The permeability of soil to fluid flow defines the magnitude of soil gas and groundwater flow under imposed pressure gradients. Pressure gradients exist due to natural effects such as hydraulic gradients (in the case of groundwater) and barometrically imposed gradients (in the case of soil gas). Unnatural gradients are imposed by soil vapor extraction, air sparging, active venting, pump-and-treat, and other remediation processes requiring the active movement of fluids through the soil. The design of these processes requires knowledge of the flow characteristics of the soil. The most variable of the soil's flow characteristics is its permeability, which can vary by several orders of magnitude in a given geologic and hydrologic setting. Knowledge of *soil gas permeability* is needed to design soil vapor extraction systems and predict the general movement of gas in soil. *Saturated hydraulic conductivity*, or the soil's permeability to liquid flow, is required to predict movement of groundwater in saturated soils. The variability of permeability is illustrated by the range of values for different media in the table below. It is not uncommon for permeabilities to vary by several orders of magnitude at a given site.

Table 1. Typical permeability values for various media
(one Darcy equals $9.87 \times 10^{-13} \text{ m}^2$).

Media	Sat. Hydraulic Conductivity (cm/s)	Permeability (Darcy)
Clay	4.6e-7	4.8e-4
Sand	4.7e-2	49
Gravel	4.7	4900
Gravel/Sand Mixture	0.47	490
Sandstone	4.7	4900
Limestone/Shale	4.7e-5	4.9e-2
Granite	4.6e-7	4.8e-4

In-situ permeability measurements are typically conducted in open or screened holes formed by conventional drilling techniques. In saturated conditions they are obtained with borehole flowmeter, drawdown, or isolated packer measurements. Soil gas permeability measurements are obtained either with total borehole flow or isolated packer measurements in uncased or screened wells. Obtaining permeability data in conventionally drilled boreholes can be expensive, primarily due to the cost of borehole formation.

If it is possible to gain access with direct push techniques like cone penetrometers, sonic emplacements, or smaller manual or truck mounted equipment (such as Geoprobos), significant savings can be realized. Benefits of direct push measurement techniques include reduced time, increased safety, minimal secondary waste generation,

and integration with the other measurements obtained during the process (such as the geophysical data obtained during instrumented cone penetrometer emplacements).

Direct push emplacements pose challenges for permeability determinations. Typically the rods are relatively small, restricting the size of instrument hardware that can be used for the measurement. In cone penetrometer (CPT) applications, for example, the rod outside diameter may be 2" and the inside diameter only 0.75". The major issue, however, is the reduction in permeability adjacent to the rod surface due to the compaction of the soil caused by the rod emplacement. This alteration of the soil flow characteristics can be significant and would result in artificially low permeability data with conventional techniques. A method called the pore pressure dissipation technique has been used with cone penetrometers to obtain hydraulic conductivity in saturated soils, and actually capitalizes on the compaction to obtain permeability data. This method uses the pore pressure instrumentation in the cone penetrometer tip to sense the buildup and decay of pore pressure due to the emplacement of the rod and the resulting compaction of the soil adjacent to the rod. The approach requires some understanding of soil type to infer permeability, but its major limitation is that if the soil permeability is too high the pore pressure will increase only slightly and decay too quickly to measure. Consequently, this technique is typically applied in soils with permeability below 10^{-4} Darcies (10^{-7} cm/s hydraulic conductivity) in water saturated conditions.

The Cone PermeameterTM incorporates multiple pressure measurements along the axis of a cone penetrometer rod with a well-defined and measured injection zone and flow rate. The permeability value is obtained by applying a one dimensional, spherical, steady state Darcy flow model to the measured injection rate and pressure profile (see the appendix for the derivation of the flow model). A fundamental premise of the measurement is that, as the distance from the injection point is increased, the resulting pressure distribution will become spherical (near to the injection point the pressure field is distorted by a combination of the cylindrical injection zone and the compacted soil near the rod surface). A second feature of the measurement geometry is that, as the radial distance from the source increases, the isobars intersect the cone rod in an almost perpendicular fashion, minimizing any azimuthal gradient that exists across the compacted annulus. By sensing the pressure gradient along the rod at a distance from the injection point, this method essentially ignores the near field effects.

The benefits of the Cone PermeameterTM method include:

- Small volumes of injected fluid due to small region of influence
- Rapid measurements (3-10 minutes per station)
- Minimizes impact of compacted soil due to penetrometer emplacement
- Integrated with CPT geophysical measurements
- All the benefits of cone penetrometer emplacements
 - Minimal secondary waste
 - Rapid mobilization and setup
 - Low unit measurement cost
 - Mature technology

In the first phase of this development effort, Science and Engineering Associates evaluated the viability of the proposed measurement technique. Numerical modeling and laboratory tests demonstrated that the basic premise of the system's operation was credible. The pressure fields resulting from injection at a well-defined section of the penetrometer rod were spherical, and they could be measured in such a fashion that the near field compaction resulting from the penetrometer emplacement could be avoided. The Phase I results are documents in Lowry, et al. 1996.

In Phase II, an engineering prototype of the measurement rod section and the accompanying data/control system were designed and fabricated. The integrated system was evaluated in a laboratory test cell under both air and water flow conditions. The phase culminated in a field demonstration at the Savannah River Site (SRS), where air and water measurements were obtained at three sites. These field demonstrations showed that the Cone PermeameterTM could obtain measurements rapidly, providing a high degree of vertical resolution in the permeability distribution. Limits of the system's operation, particularly with respect to air permeability measurements in clay media, were identified. Design changes are recommended to improve the system's performance in the more difficult media.

This topical report documents the Phase II development and demonstration effort.

2. OBJECTIVE

In this phase of the Cone PermeameterTM development effort, an engineering prototype of the measurement system was developed and demonstrated at a DOE site. The effort consisted of four discrete tasks:

- *Field prototype system development:* Designed, fabricated, and evaluated in a laboratory test cell a prototype cone penetrometer rod section capable of injecting fluid at a discrete location and measuring the pressure response at multiple radial distances from the injection zone. Designed, fabricated, and tested the data acquisition and control system that supports the instrumented rod, archived the sensor output, and analyzed the data in real time to resolve air permeability and saturated hydraulic conductivity.
- *Field demonstration:* Performed field measurements of soil gas permeability in the unsaturated zone, and saturated hydraulic conductivity below the water table, at a DOE site.
- *Performance assessment:* Evaluated the overall performance of this measurement system to determine its anticipated usage cost, areas of applicability, impact on other CPT measurement operations, and general utility.
- *Final report:* Summarized the Phase II prototype development and demonstration effort, including the system's potential applicability to other sites and other direct push techniques.

In addition to the objectives stated in the contract statement of work, SEA addressed two issues identified in peer review of the Phase I effort. Additional modeling was performed to more completely assess the effects of soil heterogeneity and anisotropy on the measurement technique. Additional laboratory tests of the permeameter probe were performed in a relatively low permeability soil (compared to the initial lab tests that were conducted in soil of moderately high permeability sand).

3. DESIGN

3.1 General Design

For cone penetrometer applications the Cone PermeameterTM system incorporates an instrumented penetrometer rod section in communication with a control and data acquisition system located in the CPT truck. The field system schematic is depicted in figure 1. The Cone PermeameterTM rod incorporates a proven fluid injection design and highly accurate pressure sensing elements embedded in the rod. The design allows the permeameter measurements to be conducted simultaneously with standard CPT cone measurements (pore pressure, tip and sleeve pressure), which results in real time, complementary data sets of soil type and hydrologic properties. The data system provides detailed analyses of pressure profiles and process histories for real time display.

The current system is capable of standalone operation, and can be operated independently of the CPT truck data acquisition and control system. It includes air and water pumps for fluid injection, fluid flow meters and control valves, and a computer controlled data acquisition system for real time acquisition of the data and analysis/display. Standard CPT truck operations include data acquisition systems with sufficient precision to support the Cone PermeameterTM measurements. Consequently, these functions could be performed by the CPT truck's system, eliminating the need for the independent data system used in these measurements.

Figure 1. Cone PermeameterTM system schematic.

3.2 Measurement Probe Design

The penetrometer rod section, designed and fabricated by Applied Research Associates, Inc., allows air or water injection through a screened region at the bottom of the probe. The radial pressure profile is measured with multiple pressure measurement ports distributed above the extraction zone. These points are filtered penetrations into the probe that allow pressure communication to sensors embedded in the rod. The permeameter is fabricated in a standard 2" diameter rod, with five pressure ports ranging from 0.05 m to 0.8 m from the injection zone (see figure 2). The pressure sensors are sapphire diaphragm, temperature compensated four wire bridge sensors with a range of 0-100 psia (6.89e5 Pa). They were chosen because of their low hysteresis and small form factor that allowed straightforward integration in the rod section.

The probe is connected to an above-ground system that provides pressurized fluid (air or water) and collects/analyzes sensor output (see figure 3).

Figure 2. Prototype Cone Permeameter™ rod section design.

Figure 3. Cone Permeameter™ rod section and data acquisition/control system.

3.3 Data Acquisition and Control System

The Cone Permeameter™ instrumented probe is supported by an integrated control and data system located in the penetrometer truck. This is a standalone, portable system designed to allow real-time flow control and data analysis during permeameter measurements. The physical requirements of this system are as follows:

- Portability (must be easily transported by one person)
- Transportability (must be easily transported by air, rental car, etc.)
- Self-contained

Operationally, the system must provide the following:

- Steady, controllable air and water flow at 60 and 200 psi respectively, at 5 to 10 liters per minute
- Data acquisition and signal conditioning
- Local user data display
- Computer data collection and real-time analysis

The measurement system consists of an uphole and downhole package. The uphole package consists of an instrument package and a pump package. The electronics are located in the instrument package while the pumps and plumbing controls are located in the pump package. Both the instrument package and pump package are integrated into a double-wall plastic case which, when opened, separates the uphole package into the

pump and instrument compartments. The outside dimensions of the case are 21" x 21" x 16". The total weight of the package is approximately 60 pounds.

The instrument package houses all power supplies, a/d (analog to digital) modules, ground fault protection, fuses, power switches, and outlets. No plumbing is routed through the instrument package. This design avoids potential for moisture damage to the electronic devices and reduces the risk of electrical shock to the operator. The instrument package cover plate accommodates all connectors, switches, electrical outlets, and fuses, while leaving an open surface for a system laptop computer and optional printer. The electrical schematic is shown in figure 4.

The primary components of the instrument package are the a/d modules, manufactured by American Advantech (called Adam Modules). The specific units used in this application are the models 4520, 4018, and 4017. The 4520 is the communication module that allows the computer RS232 serial port to send and receive data to and from the other Adam modules. The 4017 is an analog input module that is configured to receive 0-5 VDC inputs from the instrument package. The 4018 is similar to the 4017 but can be configured to receive inputs of 0-50mVDC. The Adam modules are located inside the instrument package for protection.

The Adam modules are powered by a 24 VDC supply. This supply also provides power for the air and water flowmeters (located in the pump package), and the 5 VDC converter, which provides excitation voltage for the downhole temperature and pressure sensors. The 24 VDC and 5 VDC supplies are both fused with panel mount in-line fuses for easy replacement. The power supplies are also located inside the instrument package.

The instrument package also contains 120 VAC, which is used to supply power to the computer, printer, air, and water pumps (located in pump package). The computer and optional printer are plugged into a 120 VAC ground fault interrupt (GFI) outlet. The 120 VAC is also fused with a panel mount fuse. The 120 VAC supply to the pump package is switched by an “on-off-on” toggle with one “on” position powering the air pump and the other powering the water pump. This configuration is to avoid an accidental powering of both pumps simultaneously. A “main” illuminated rocker switch provides power to the entire system and is located in the back corner of the instrument package to further decrease the potential for an inadvertent power-up or power-down.

The serial cable extends through a hole at the back of the instrument package cover plate. This cable is hardwired to the 4520 Adam module and strain relieved, leaving only one connection to the computer. Three multiconductor connectors are located on the instrument package cover plate. These connectors accept the power cable from the pump package, the data cable from the pump package, and the power/data cable from the downhole package. For details of the pump package wiring, see figure 5.

NOTES:

1. Both cables are hardwired at instrument package
2. All DC grounds are common
3. Flowmeters and pressure transducer are assumed to be same voltage input

TABLE OF CONDUCTORS:

PUMP PACKAGE POWER CABLE

conductor 1 = air pump power
 conductor 2 = 110 Vac common
 conductor 3 = water pump power

PUMP PACKAGE DATA CABLE

conductor 1 = water flow meter Vout
 conductor 2 = air flow meter Vout
 conductor 3 = DC ground
 conductor 4 = 12 Vdc
 conductor 5 = Uphole line pressure Vout

Figure 5. Pump package electrical schematic.

The pump package contains all pumps, flowmeters, required valves, pressure sensors, filters and piping. Flow rates are set directly at the pump package with the flowmeters and pressure gauges mounted locally at the package. All connections from the pump package to the instrument package are hardwired at the pump package and connected to the instrument package through a set of multiconductor cables and connectors. For a detailed plumbing flow diagram, see figure 6.

TABLE OF SYMBOLS:

Hose connector		Check valve
Pressure transducer		Filter
Pump		Flowmeter
Relief valve		Pressure Gauge

Figure 6. Pump package plumbing schematic.

This package contains all the elements necessary to provide the required airflow (0-10 slpm) and water flow (0-5 lpm) to the downhole package. The primary components are one diaphragm air pump and one rotary vane water pump. The maximum output of the air pump is 60 psig. This pressure is necessary due to the anticipated high-pressure drop of the tubing connecting the pump package to the downhole package. The maximum output of the water pump is 200 psig. This pressure is also necessary to meet the flow requirements at the downhole package.

The output of the pumps is controlled locally by a flow control valve. To read the flow of both air and water, a differential pressure flowmeter is installed on the intake side

of each pump. These flowmeters display standard liters per minute (slpm) on a three-digit LCD display, as well as providing a proportional voltage output to the a/d system. To protect the flowmeters and components downstream, a replaceable filter is installed at the intake of each flowmeter. The outputs of each pump join together and are common at the manifold pressure gauge and pressure transducer. Each individual pump circuit is protected from excessive pressures from the other pump by a check valve installed in the pump circuit. To further protect the pump circuits they are equipped with pressure relief valves. In the event of a system over-pressurization any excess water or air would be vented.

3.4 Data Acquisition and Analysis Software

The data acquisition and analysis software works in conjunction with the in-situ permeability instrument package. The initial data-acquisition process takes place in three Adam modules, which are components of the instrument package. The Adam-4017 and Adam-4018 continuously collect voltage data from various instruments, while the Adam-4520 module, a communication device, allows the RS485 serial port to communicate with the other two Adam modules. Using ASCII format commands, Visual Basic for Applications and WinWedge 32™, Excel 97 communicates directly with the Adam modules. The communication consists of sending out an ASCII command, receiving a string of data in the WinWedge program, and finally placing that string directly into an Excel spreadsheet (see figure 7 for the hardware setup).

Figure 7. Data-acquisition hardware configuration.

There are three major steps in the data-acquisition process. These include a downhole zeroing of the pressure transducers, a data-retrieval run, and a save-data-to-file procedure (see figure 8). The zeroing process (used only during air measurements) brings in raw voltages from the five pressure transducers prior to running the air pumps, and determines a downhole “zero” voltage for each transducer. This process digitally equalizes the pressure in the five measurement locations under no-flow conditions,

increasing the sensitivity of the pressure difference calculations. During the data-acquisition phase, raw voltages, measured from each of the eight instruments, are imported through WinWedge into an Excel 97 workbook. A complete record, which includes a time stamp, an elapsed time, an air or water flow voltage, five probe pressure voltages, an uphole line pressure voltage, a downhole temperature voltage, and a power supply, is brought in approximately once every five seconds. Data retrieval continues until the user terminates the process by clicking a stop button. The save-data-to-file procedure saves the last calculated permeability record to another Excel workbook. It also saves the run by writing all run descriptions and imported raw data to a user-defined text file.

Figure 8. Data-acquisition code flow schematic.

Once the data-acquisition phase is in progress, the data analysis work is automatically set in motion. The data-analysis work uses various Excel 97 functions. Four additional sheets in the workbook utilize the raw voltage data to perform data-analysis calculations. The first sheet simply converts the raw voltages into appropriate engineering units. The second sheet contains plots of “converted data vs. time,” that serve as a “quick look” diagnostics of the working instruments. The third sheet uses the converted voltages to solve for a permeability value; whereas the final worksheet uses the permeability values solved for in the third sheet, and the Darcy spherical model to produce a theoretical pressure profile at the five port locations on the probe.

3.4.1 Data-Acquisition Code: Three files and one executive routine are required in order to run the in-situ permeability data-acquisition code. These files include InSituPermeability.xls, PermResults.xls, WinWedge.exe, and PermSetup.SW3. InSituPermeability.xls is an Excel workbook that contains the user interface for the program, the acquired raw data, the processed data, and the permeability calculations. The PermResults.xls Excel workbook stores a record of permeability data for each new data-acquisition run. WinWedge.exe is the executable routine for the WinWedge 32TM Pro Software v3.0. This software provides a way of connecting the Adam Modules, RS232 and RS485 devices, to a computer through a serial communication port and allows data to be read or written to or from the device directly from within a Windows application. The last required file, PermSetup.SW3, is a WinWedge 32TM file setup specifically for the in-situ permeability hardware.

The data-acquisition code is written in Visual Basic for Applications for Excel 97 and is stored in the Excel Visual Basic Editor. It contains 10 subroutines, which are housed in Module 1 and 6 small private subroutines, which are stored in the *RawData* sheet code. Data-acquisition controls, which consist of four buttons and a site information form, are located in the *RawData* sheet of the InSituPermeability.xls. The user can control all aspects of the program while the *RawData* sheet is active. Figure 9 displays the *RawData* sheet.

Figure 9. *RawData* sheet.

3.4.2 Zero Transducers. Zeroing the pressure transducers downhole is the first step of an air permeability data acquisition. Zeroing measurements are taken once the cone penetrometer is in place and before the air pump has been turned on. This process determines an equilibrated pressure downhole or a “zero pressure.” A “zero pressure” is found when the difference between the current pressure and previous pressure is less than the *ZeroTolerance* and has remained less than the *ZeroTolerance* for a predetermined period of time. The “zero pressures” are necessary to determine a true differential pressure measurement in the permeability calculation phase.

Zeroing the transducers for water permeability measurement would be useful but is not a critical step towards resolving an accurate permeability measurement. Pressure differences under water flow conditions are inherently greater, and the zeroing process is not necessary to achieve adequate measurement resolution.

To run the zeroing code, click the *Zero Transducers* button. This action calls subroutine *ZeroTransducers_Click*, which immediately calls the *OpenWedge* subroutine and passes the variable *ZeroDataIn*, which equals true. Subroutine *OpenWedge* assigns the variable *ZeroData* equal to *ZeroDataIn*. Since the same subroutines are used during a zeroing measurement and a data-acquisition run, the *ZeroData* variable tells the subroutine which process is being carried out - if *ZeroData* equals true it's a calibration and if *ZeroData* equals false then it's a data-acquisition run.

OpenWedge recognizes that a “zeroing function” is in process, so it asks the user to input a zeroing tolerance. This value is then assigned to the variable *ZeroTolerance*. Next WinWedge and the associated file, PermSetup.SW3, are opened (when the program cannot be found, a message box displays that WinWedge.exe cannot be found and the subroutine ends). Once WinWedge opens, focus is set back on Excel and a

SetLinkOnData function is set up between the WinWedge and Cell (3,3) in the *RawData* sheet. When WinWedge receives new data, Cell (3,3)'s value changes, which causes subroutine *GetField* to be called. Next *OpenWedge* initializes other variables that will be used later in the code. *FieldIndex* is set to 1; *AirTestType* is true when an air test is being run and false when a water test is being run; *RowPt* and *ColPt* are set to 42 and 2; the eleven *Prompt\$* variables are equal to the eleven ASCII commands sent to the Adam Modules; and *StartTime* is set to the present time. The last line of the subroutine calls *Prompt\$(1)*, which asks an Adam Module 4018 for the first voltage from channel 0. When the Adam Module sends its response to WinWedge, the value of Cell (3,3) changes and the subroutine *GetField* is called.

First, *GetField* uses a two-second wait to correct an internal timing problem between WinWedge and Excel. Next it checks the value of *FieldIndex*. When *FieldIndex* equals 1 it calls subroutines *PlaceDateTime* and *PlaceElapsedTime*. *PlaceDateTime* places the current date and time into Cell (*RowPt*, *ColPt*) in *RawData*. First *PlaceElapsedTime* increments the *Count1* variable, which is used to count the number of complete records placed into the *RawData* spreadsheet. Then it calculates the time elapsed since the *StartTime* variable was initialized, places the value of *ElapsedTime* into the Cell (*RowPt*, *ColPt*+1) in *RawData*, and updates the record count display on the *RawData* sheet.

Get Field calls *PlaceZeroData* and passes the value of *FieldIndex*. *PlaceZeroData* initiates a link with WinWedge, assigns the value of the response to *MyVariantArray*, and then closes the link. Since *MyVariantArray* is a variant array data type, the value is reassigned to the string variable, *MyString\$*. *PlaceZeroData* then places *MyString\$* into Cell(*RowPt*,*ColPt*+*FieldIndex*+1). If *FieldIndex* is equal to 1, 2, 3, 4, 5, 6, or 7, the value of *MyString\$* is assigned to *Voltage 1, 2, 3, 4, 5, 6, or 7*. Once back into subroutine *GetField*, *FieldIndex* is incremented by one. Next, *FieldIndex* is compared with the number of existing fields. If *FieldIndex* is greater than the number of fields then *FieldIndex* is set to one, and if *ZeroData* is true then subroutine *VoltageCheck* is called. If *FieldIndex* is less than the number of fields then the next *Prompt\$()* command is sent to one of the Adam Modules. When the value of Cell (3,3) receives the response from the Adam Module, then *GetField* is called, which begins the process again.

When the *voltagecheck* subroutine is called, this is an indication that one new row of data has come in to the spreadsheet. *VoltageCheck* determines the difference between the *Voltage 1, 2, 3, 4, or 5* and the *LastVoltage 1, 2, 3, 4, or 5* and determines whether the differences is greater than the *ZeroTolerance*. If at least one of the voltage differences greater than the *ZeroTolerance*, then the *LastVoltage1, 2, 3, 4, or 5* is equal to *Voltage 1, 2, 3, 4, or 5* and the sequence goes back to the end of the *GetField* subroutine. If all the voltage differences are less than or equal to the *ZeroTolerance*, then *Voltages 1, 2, 3, 4, and 5* are placed in the *Process Data* sheet and a message box displays "Process Complete!"

3.4.3 Start Acquisition: The data-acquisition code uses the same logic as the calibration code, but the user is given the decision when to stop the acquisition (see figure 10). Before hitting the *Start* button, the user must fill out the site information form. If this form is not completed, the acquisition will not begin.

To run the data-acquisition code, click the *Start* button. This action calls subroutine *Start_Click*, which calls the *OpenWedge* subroutine and passes the variable *ZeroDataIn*, which equals false. Subroutine *OpenWedge* assigns the variable *ZeroData* equal to *ZeroDataIn*. Since it reads in a false value for *ZeroData*, *OpenWedge* recognizes that a data-acquisition run is in progress. Next *WinWedge* and the associated file, *PermSetup.SW3*, are opened (when the program cannot be found, a message box displays that *WinWedge.exe* cannot be found and the subroutine ends). Once *WinWedge* opens, focus is set back on Excel and a *SetLinkOnData* function is set up between the *WinWedge* and Cell (3,3) in the *RawData* sheet. Next *OpenWedge* initializes variables that are needed later in other subroutines. *FieldIndex* is set to 1, *AirTestType* is true when an air test is being run and false when a water test is being run, *RowPt* and *ColPt* are set to 42 and 2, the eleven *Prompt\$* variables are equal to the eleven ASCII commands sent to the Adam Modules, and *StartTime* is set to the present time. The last line of the subroutine calls *Prompt\$(1)*, which asks an Adam Module 4018 for the first voltage from channel 0. When the Adam Module sends its response to *WinWedge*, the value of Cell (3,3) changes and the subroutine *GetField* is called.

First, *GetField* uses a two-second wait to correct an internal timing problem between *WinWedge* and Excel. Next, it checks the value of *FieldIndex*. When *FieldIndex* equals 1 it calls subroutines *PlaceDateTime* and *PlaceElapsedTime*. *PlaceDateTime* places the current date and time into *Cell(RowPt, ColPt)* in *RawData*. First *PlaceElapsedTime* increments the *Count1* variable, which is used to count the number of complete records placed into the *RawData* spreadsheet. Then it calculates the time elapsed since the *StartTime* variable was initialized; places the value of *ElapsedTime* into the *Cell(RowPt, ColPt+1)* in *RawData*; and updates the record count display on the *RawData* sheet.

GetField calls *PlaceData* and passes the value of *FieldIndex*. *PlaceData* initiates a link with *WinWedge*, assigns the value of the response to *MyVariantArray*, and then closes the link. Since *MyVariantArray* is a variant array data type, the value is reassigned to the string variable, *MyString\$*. *PlaceData* then places *MyString\$* into *Cell(RowPt, ColPt+FieldIndex+1)*. The next two conditional statements check the value of both *FieldIndex* and *AirTestType*, and use these values to determine the appropriate flow voltage. The *AirTestType* variable is linked to the site information form, therefore its value is true if an air test is being run and false if a water test is being run. If *FieldIndex* is equal to one and *AirTestType* is equal to true, then *MyString\$* is compared to *LastFlowString*. If these values are not equal, subroutine *DisplayFlow* is called. This subroutine places the value of *MyString\$*, which contains the airflow voltage, in the flow position of *Run Updates* on sheet *RawData*. *LastFlowString* is then set equal to the value of *MyString\$*. If *FieldIndex* and *AirTestType* weren't equal to one or true, respectively, then they are compared to the values of the other conditional statement. If *FieldIndex* equal two and *AirTestType* equals false, then *MyString\$* is compared to *LastFlowString*. If these values are not equal, Subroutine *DisplayFlow* is called. Again this subroutine places the value of *MyString\$* in the flow position of *Run Updates* on sheet *RawData*, but this time *MyString\$* contains the water flow voltage.

Figure 10. Data-acquisition process diagram.

Once back into subroutine *GetField*, *FieldIndex* is incremented by one and is then compared with the number of existing fields. If *FieldIndex* is greater than the number of fields then *FieldIndex* is set to one, and *RowPt* is incremented by one. The last line sends the next *Prompt\$()* command to one of the Adam Modules. When the value of Cell (3,3) receives the response from the Adam Module, then *GetField* is called, which begins the process again. These subroutines will continue to loop until the user clicks the *Stop* button on the *RawData* sheet.

3.4.4 Stop Acquisition: To stop the data acquisition, click the *Stop* button. This action calls subroutine *StopAcquisition_Click*, which calls the *CloseWedge* subroutine. *CloseWedge* clears the contents of Cell (3,3), that removes the DDE link with WinWedge. Next it shuts down the *SetLinkOnData* function by assigning an empty string to the subroutine call, and asks Excel to ignore errors. Finally, *CloseWedge* shuts down the WinWedge program. This sequence of events may generate a VBA error message box. If this message box appears the *no* button should be clicked.

3.4.5 Save Data-Acquisition Run: The save data code performs two types of saves for each data-acquisition run. First it saves the last row of data from the *Permeability Calculation* sheet to the Permeability Results.xls. Then it writes all the raw voltages and descriptive information to a text file. Figure 11 displays the process flow diagram for the save subroutine.

To save a data-acquisition run, click the *Save* button. This action calls subroutine *SaveRecord_Click*, which calls subroutine *SavePermData*. *SavePermData* activates sheet *Permeability Calculations* and selects range *StartPos1*. This cell is the reference point from which all other selections are made on this sheet. The next selection is made by adding the value of (*Count1* -2) to the reference cell. *Count1* is the value of the cell labeled number of records on the *RawData* sheet. This selection takes the cursor to the last row of data on the *Permeability Calculation* sheet. An active cell function then selects the row of data to the right of the current selection. Once selected, the row is copied to the *Permeability Histories* sheet in PermResults.xls. The code determines the correct location to paste the new data, by using a reference cell and the number of records located on the sheet. Once the permeability data is pasted, Perm Results.xls is saved and closed.

When PermResults is closed, *SaveRecord_Click* calls subroutine *WriteResults*. At the outset, the subroutine asks the user for a file name. This name will define the comma delimited text file that stores the current acquisition run's raw data. After the file name is entered, the new text file is opened. Write statements are then used to transport copies of the site information, calibration voltages, and raw voltages to the text file. A loop, using the value of the cell containing the number of records, determines how many rows of data need to be written to the text file. When all records have been written, the text file is closed and a message box displays "Save complete."

3.4.6 Reset: Before beginning another run, the user must click the *reset* button. This will clear out the site information form and delete all the raw voltages brought into the *RawData* sheet during the previous run.

Figure 11. Process-flow diagram for the *SaveRecord* subroutine

3.5 Data Analysis

The analysis of the incoming data is a real-time process. As soon as a new data point comes into the *RawData* sheet, it is plotted vs. time, converted to scientific units, and then used to solve for the in-situ permeability. The final step uses the calculated permeability and the Darcy spherical model to solve for a theoretical pressure profile. The theoretical pressure profile is placed on the same plot as the actual pressure vs. radial distance plot. This graph is displayed on the *RawData* sheet and can be viewed by the user during the data acquisition. Each time a complete row of data is brought into the spreadsheet, the pressure profile plot is updated.

3.5.1 Process Data Sheet: The *ProcessData* sheet contains the calibration “zero” voltages and the calibration curves produced during the Calibration routine. It also contains conversion equations, which are linked the incoming voltages located on the *RawData* sheet. Process data displays #N/A, if the linked cell on the *RawVoltage* sheet is empty. Table1 displays the calculations required to convert the raw voltages to their appropriate engineering units.

Table 2. Process data unit conversions.

Variable	Conversion
Air Flow (Vdc to kg/s)	=if (AirCheck = True then (AirFlow Voltage) * (0.5 lpm/Vdc) * (.001m ³ /l) * (1.23kg/m ³) * (60s/min))
Water Flow (Vdc to kg/s)	=if (AirCheck = False then (WaterFlow Voltage) * (1lpm/Vdc) * (.001m ³ /l) * (1000kg/m ³) * (60s/min))
Pressure Port 1 for Air (mv to Pa)	=((Slope1* Voltage1/PowerSupplyVoltage)+Yintercept1)+ZeroDelta1
Pressure Port 2 for Air (mv to Pa)	=((Slope2* Voltage2/PowerSupplyVoltage)+Yintercept2)+ZeroDelta2
Pressure Port 3 for Air (mv to Pa)	=((Slope3* Voltage3/PowerSupplyVoltage)+Yintercept3)+ZeroDelta3
Pressure Port 4 for Air (mv to Pa)	=((Slope4* Voltage4/PowerSupplyVoltage)+Yintercept4)+ZeroDelta4
Pressure Port 5 for Air (mv to Pa)	=((Slope5* Voltage5/PowerSupplyVoltage)+Yintercept5)+ZeroDelta5
Pressure Port 1 for Water (mv to Pa)	=((Slope1* Voltage1/PowerSupplyVoltage)+Yintercept1)+490.25 Pa
Pressure Port 2 for Water (mv to Pa)	=((Slope2* Voltage2/PowerSupplyVoltage)+Yintercept2)+784.42 Pa
Pressure Port 3 for Water (mv to Pa)	=((Slope3* Voltage3/PowerSupplyVoltage)+Yintercept3)+1470.78 Pa
Pressure Port 4 for Water (mv to Pa)	=((Slope4* Voltage4/PowerSupplyVoltage)+Yintercept4)+3922.08 Pa
Pressure Port 5 for Water (mv to Pa)	=((Slope5* Voltage5/PowerSupplyVoltage)+Yintercept5)+7844.15 Pa
Injection Zone Pressure (mv to Pa)	=(InjectionZoneSlope*InjectionZoneVoltage/PowerSupplyVoltage)+InjectionZoneYintercept
Uphole Pressure (Vdc to psig)	=(Uphole Pressure Voltage) * (40psig/Vdc)
Temp (°C to K)	=(TempVoltage/0.01)

3.5.2 History Plots: The *History Plots* sheet contains plots of “processed data vs. elapsed time.” These graphs are replotted each time a new record of data is brought into the *RawData* sheet and can be observed during or after the data-acquisition run. The purpose of the *History Plots* sheet is to provide the user with a “quick look” at the performance of the instrument package. The pressure plots also communicate to the user when the pressure readings have stabilized (see figure 12).

Figure 12. *History Plots* sheet.

3.5.3 Permeability Calculations: The *Permeability Calculations* sheet utilizes the process data variables for each new record and the Darcy spherical equation to solve for an in-situ permeability value. The spreadsheet notes whether an air or water test is being run and uses the appropriate spherical equation. The equation for air is as follows (see the full derivation in the appendix):

$$k = \frac{\mu R T m}{2\pi(P_o^2 - P_a^2)} \left(\frac{1}{r_o} - \frac{1}{r_a} \right) \quad (\text{Eq.1})$$

where

k = permeability (m^2)

μ = dynamic viscosity of air ($\text{N}\cdot\text{s}/\text{m}^2$)

R = gas constant ($\text{J}/\text{kg}\cdot\text{K}$)

T = downhole temp (K)

m = mass flow (kg/s)

π = 3.14159

P_o = port pressure (Pa)

P_a = pressure at the port, 0.80m from extraction zone (Pa)

r_o = distance from extraction zone to pressure port (m)

$$r_a = 0.80 \text{ radius (m)}$$

Whereas the equation for water is as follows:

$$k = \frac{\mu m \left(\frac{1}{r_o} - \frac{1}{r_a} \right)}{4\pi\rho(P_o - P_a)} \quad (\text{Eq. 2})$$

where

k = permeability (m^2)

μ = dynamic viscosity of water ($\text{N}\cdot\text{s}/\text{m}^2$)

m = mass flow (kg/s)

r_o = distance from center of extraction zone to pressure port (m)

$r_a = 0.80$ radius (m)

$\pi = 3.14159$

ρ = density of water (kg/m^3)

P_o = port pressure (Pa)

P_a = pressure at the port, 0.80m from extraction zone (Pa)

The most current value for permeability is also displayed in the run update chart on the *RawData* sheet.

3.5.4 Spherical Model: The last data analysis sheet solves for a theoretical pressure profile given the current permeability measurement, its corresponding measured values, and the Darcy spherical equation. The calculation uses the DGET function and the *Number of Records* cell, located in the run updates chart, as the criteria to determine the most current record. Therefore, the calculation is updated each time a complete record is imported in the *RawData* sheet. A plot of the theoretical pressure profile and the actual pressure profile is plotted on the *RawData* sheet.

3.6 Transducer Calibration Software

The pressure transducers used in the instrument package require a calibration procedure to ensure that precise pressure measurements are calculated. The pressure transducer's voltage readings are dependent upon the power supply voltage, which fluctuates in value around five volts. Since the supply voltage is variant, a ratiometric calibration is required, which linearly relates the applied pressure to the transducer voltage/supply voltage ratio.

The laboratory process requires an airtight calibration chamber, the cone pentrometer permeability measurement probe, the instrument package, and the calibration software. The calibration involves applying 5 predetermined pressures to the cone pentrometer (typically atmospheric, 20, 40, 60, 80, and 100 psia), acquiring the pressure transducers response to each of the applied pressures, producing a calibration curve for each pressure transducer, and saving the calibration equations to the data-acquisition

spreadsheet. Specifically, the cone penetrometer is placed inside the calibration chamber and air is injected until a desired pressure is obtained. Then the calibration software is run, which brings in a time stamp, an elapsed time, the applied pressure, the atmospheric pressure, the supply voltage, the temp, and the five transducer voltages. A total of 10 records are brought in for each applied pressure. This process is repeated until all five pressures have been applied to the probe. Once all sets of data have been obtained, the calibration is complete. The final step is saving the calibration equations to the InSituPermeability.xls.

3.6.1 Calibration Data-Acquisition Code: Three files and one executive routine are required in order to run the calibration data-acquisition code. These files include Calibration Transducers.xls, InSituPermeability.xls, WinWedge.exe, and PermSetup.SW3. Calibration.xls is an Excel workbook that contains the user interface for the program, the acquired raw data, the processed data, and calibration curves. The InSituPermeability.xls Excel workbook stores the most recent calibration equations. WinWedge.exe is the executable routine for the WinWedge 32TM Pro Software v3.0. This software provides a way of connecting the Adam Modules, RS232 and RS485 devices, to a computer through a serial communication port and allows data to be read or written to or from the device directly from within a Windows application. The last required file, PermSetup.SW3, is a WinWedge 32TM file setup specifically for the calibration hardware.

The calibration code is written in Visual Basic for Applications for Excel 97 and is stored in the Excel Visual Basic Editor. It contains seven subroutines, which are housed in Module1 and two small private subroutines, which are stored in the *Calibration* sheet code. Data-acquisition controls, which consist of two buttons and a calibration properties form, are located in the *Calibration* sheet of the Calibrate Transducers.xls. The user can control all aspects of the program, while the *Calibration* sheet is active. Figure 13 displays the *Calibration* sheet, while figure 14 displays the process diagram of the calibration subroutine.

Before clicking the *Acquire Data* button, the user must complete the *Calibration Properties* form. When complete, the *Acquire Data* button is pressed. This action calls subroutine *AcquireData_Click*, which calls the *OpenWedge* subroutine. Next WinWedge and the associated file, PermSetup.SW3, are opened (when the program cannot be found, a message box displays that WinWedge.exe cannot be found and the subroutine ends). Once WinWedge opens, focus is set back on Excel and a *SetLinkOnData* function is set up between the WinWedge and Cell (5,2) in the *Calibration* sheet. Next *OpenWedge* initializes variables that are needed later in other subroutines. *FieldIndex* is set to 1; *RowPt* and *ColPt* are set to 21 and 2; the seven *Prompt\$* variables are equal to the seven ASCII commands sent to the Adam Modules; and *StartTime* is set to the present time. The last line of the subroutine calls *Prompt\$(1)*, which asks an Adam Module 4017 for the first voltage from channel 4. When the Adam Module sends its response to WinWedge, the value of Cell (5,2) changes and the subroutine *GetField* is called.

First, *GetField* uses a two-second wait to correct an internal-timing problem between WinWedge and Excel. Next, it checks the value of *FieldIndex*. When *FieldIndex* equals 1 it calls subroutines *PlaceDateTime*, *PlaceElapsedTime*, *PlaceAppliedPressure*, and *PlaceAtmosphericPressure*. *PlaceDateTime* places the current date and time into *Cell(RowPt, ColPt)* in *RawData*. *PlaceElapsedTime*

increments the *Count1* variable, which is used to count the number of complete records placed into the *Calibration* spreadsheet. If the updated *Count1* variable equals eleven, a message box informs the user that the calibration is complete. If the *Count1* variable is less than eleven then it calculates the time elapsed since the *StartTime* variable was initialized and places the value of *ElapsedTime* into the *Cell(RowPt, ColPt+1)* in *Calibration*. *PlaceAppliedPressure* copies the value from the *Calibration Properties* form and places it into *Cell(RowPt, ColPt+2)*. *PlaceAtmosphericPressure* also copies the value from the *Calibration Properties* form and pastes it into *Cell(RowPt, ColPt+3)*.

Next, *Get Field* calls *PlaceData* and passes the value of *FieldIndex*. *PlaceData* initiates a link with WinWedge, assigns the value of the response to *MyVariantArray*, and then closes the link. Since *MyVariantArray* is a variant array data type, the value is reassigned to the string variable, *MyString\$*. *PlaceData* then places *MyString\$* into *Cell(RowPt, ColPt+FieldIndex+3)*.

Once back into subroutine *GetField*, *FieldIndex* is incremented by one and is then compared with the number of existing fields. If *FieldIndex* is greater than the number of fields, then *FieldIndex* is set to one, and *RowPt* is incremented by one. If *FieldIndex* is equal to 1, then Excel is asked to wait five seconds before going to the next command. The last line sends the next *Prompt\$()* command to one of the Adam Modules. When the value of *Cell(3,3)* receives the response from the Adam Module, then *GetField* is called, which begins the process again.

3.6.2 Save Calibration Data: The save calibration data code copies the calculated values of the slope and y-intercept for each pressure transducer and pastes them into the *InSituPermeability.xls* workbook. The *Save Completed Calibration* button initiates the subroutine *Save_Click*, which calls subroutine *SaveCalibrationData*.

SaveCalibrationData starts by activating the *ProcessData* sheet and selecting the range *CalibrationPaste*, which contains the calculated slopes and y-intercepts. Next it opens or activates *InSituPermeability.xls*, and pastes the selection into the *Process Data* sheet. *SaveCalibrationData* then saves and closes *InSituPermeability.xls* and alerts the user with a message box that the save is complete.

Microsoft Excel - CalibrateTransducers17.xls

File Edit View Insert Format Tools Data Window Help

A B C D E F G H

1 **Calibration:**

2

3

4 **Enter the following calibration properties:**

5

6 Applied Pressure (volts)

7

8 Atmospheric Pressure (Pa)

9

10

11

12

13

14 **Acquire Data** **Save Completed Calibration** **Reset Form**

15

16

17

Time Stamp	Elapsed Time	Applied Pressure	Atmospheric Pressure	Supply Voltage	Temp	Transducer Voltage	Transducer Voltage 1 Tra
(00:00:00.00.00)	(s)	(volts)	(Pa)	(volt)	(°C)	(mvolts)	
4/29/98 11:36	2	4.06125	100962	4.824	3.015	0.0070	
4/29/98 11:36	8	4.06125	100962	4.824	3.015	0.0100	
4/29/98 11:36	14	4.06125	100962	4.824	3.015	0.0070	
4/29/98 11:36	20	4.06125	100962	4.824	3.015	0.0100	
4/29/98 11:37	26	4.06125	100962	4.824	3.015	0.0100	
4/29/98 11:37	32	4.06125	100962	4.824	3.015	0.0100	
4/29/98 11:37	38	4.06125	100962	4.824	3.015	0.0070	
4/29/98 11:37	44	4.06125	100962	4.824	3.015	0.0070	
4/29/98 11:37	50	4.06125	100962	4.824	3.015	0.0070	
4/29/98 11:37	56	4.06125	100962	4.824	3.016	0.0120	
4/29/98 11:38	2	3.46955	100962	4.824	3.016	0.0120	

CalibrationData / ProcessData / ProcessData2

Figure 13. The *CalibrationData* sheet of *CalibrateTransducers.xls* contains the controls for the calibration data acquisition.

Figure 14. Calibration software process diagram.

3.7 Regression Formation of Calibration Curves

All data unit conversions and calibration calculations take place in the *ProcessData* sheet (see figure 15). The calibration equations and curves update themselves after each new set of data is brought into the *CalibrationData* sheet. Any number of calibration points can be used to formulate the calibration curves, but at least four applied pressures should be tested in order to achieve an accurate calibration curve.

Since 10 records are brought in for each new applied pressure, an average value and standard deviation are found for each measured variable. Next the ratio of transducer voltage (in millivolts) per supply voltage (in volts) is determined for the five transducers in each record. The applied pressures (psi) are then plotted vs. mv/v ratio to determine the calibration curves. The slope and y-intercept of the calibration curves are determined using Excel's SLOPE and INTERCEPT functions.

Figure 15. The *ProcessData* sheet displays results of a five-point calibration.

3.8 Cone PermeameterTM Measurement Procedures

The following procedures discuss the required equipment, sensor calibration, test setup, execution, disassembly, decontamination, and safety issues involved in using the Cone PermeameterTM.

3.8.1 Required Equipment and Materials

- A. Cone PermeameterTM Measurement System, consisting of the pump module and instrument module
- B. A laptop computer containing four required files and two programs:
 - 1. InSituPermeability.xls
 - 2. CalibrateTransducers.xls
 - 3. PermResults.xls
 - 4. PermSetup.SW3
 - 5. WinWedge 32TM
 - 6. Excel 97
- C. Cone PermeameterTM rod section with 150 ft. of signal and fluid transfer line tether
- D. Penetrometer truck
- E. Transducer calibration chamber
- F. 5 gallon bucket (source for water test)
- G. Approximately 30 gallons of potable water (assuming flow of 1 liter/min, 5 minutes/test, and 20 tests per hole)

3.8.2 Transducer Calibration: The transducer calibrations should be completed prior to and after each field measurement program, and no less than once every two weeks during field measurements. A 0.03% accuracy absolute pressure transducer is used as the precision transfer standard, read by a 6 ½ digit precision voltmeter. The produced calibration equations are used by the data-acquisition software to determine the port pressures. Calibrations should be completed at 20, 40, 60, 80 and 100 psi (137895, 275790, 413685, 551580, and 689475 Pa). Place the Cone PermeameterTM probe into the calibration chamber and seal the container (see figure 16).

- 1. Attach the tether extending from the cone penetrometer to the instrument package.
- 2. Power up the computer and open CalibrateTransducer.xls, located on the desktop.
- 3. Activate the *CalibrationData* sheet (see figure 13). Inject air into the chamber until the pressure gauge reaches 20, 40, 60, 80, or 100 psi.
- 4. Watch the pressure gauge to ensure that the chamber is not leaking air.
- 5. Complete the calibration properties form.
- 6. Activate the *Acquire Data* button on the *CalibrateTransducer* worksheet.

7. When the message *Acquisition Complete* flashes up on the screen, click on the ok button.
8. Repeat steps 4-8 four additional times at the pressures listed above.
9. Before saving the calibration data, check the calibration curves to determine their integrity. Check the r^2 (residual) value for each curve. This value should fall between 0.990 and 1.00.
10. If the curves meet the r^2 requirement, click the *Save Completed Calibration* button.
11. It may be necessary to repeat the transducer calibrations if the curves have poor r^2 values.

Figure 16. Calibration chamber.

3.8.3 In-Situ Permeability Tests: The in-situ permeability test consists of preparing the instruments, pushing the Cone Permeameter™ probe into the soil, connecting the probe to the instrument package, running the transducer zeroing code, running the measurement system/data-acquisition code, and saving the imported data to a text file. The following instructions step the user through the entire process.

A. Specific information required

1. Water table location
2. Basic geology and hydrology of site
3. Nature of possible contaminants
4. Training requirements for workers

B. On-site preparations

1. Read 3.6.6, Safety Considerations and Hazards, before proceeding with the setup.
2. Position the cone penetrometer truck.
3. Connect cables from pump package to instrument package as labeled (see figure 17). Connect serial cable on instrument package to laptop serial port.
4. Plug instrument package A/C cord into 120-outlet.

5. Connect water supply line to pump package water inlet. Place other end of supply line in five-gallon bucket. Fill bucket with potable water.
 6. Turn on main power to instrument package. Power must be on for a minimum of 15 minutes prior to step 'G'.
 7. With both pumps off, check 'zero' reading on both flowmeters in pump package. Display should read 0.00 *without* a negative sign. If 'zero' setting is acceptable, proceed to step B.8. If 'zero' reading is off, adjust flowmeter at zero potentiometer on side of flowmeter until display reads 0.00.
 8. Connect downhole supply tubing to pump package supply outlet.
 9. Power up the laptop.
 10. Open In-SituPermeability.xls and activate the *RawData* sheet. (Press "no" when asked to update links.)
 11. Click the *Reset* button to clear out old site information and raw data and to prepare the *RawData* sheet for the next acquisition.
 12. Push the Cone Permeameter™ rod to the first desired measurement depth.
- C. Zeroing the pressure transducers prior to air permeability measurements. Prior to air permeability measurements only, the pressure transducers should be zeroed. Zeroing should take place once the probe is in a proper position and before either pump has been turned on. This will determine a null reading for each pressure transducer.
1. Press the *Zero Transducers* button.
 2. Determine the zero tolerance. This value will determine when the voltage readings have equilibrated, i.e., when a value stays within a zero tolerance of 0.003 mvolts for 10 seconds, the transducer voltage has stabilized. Try .003 for zero tolerance.
 3. When the zeroing has finished, a message box will be displayed and the values will be placed on the *Process Data* sheet.

Figure 17. Cone Permeameter™ system setup.

D. Completing the site information (see figure 9)

1. Enter a unique location identification number and brief description of the area.
2. Enter the anticipated maximum depth of the cone penetrometer push.
3. Enter your name and check whether an air or water test is to be run. (If this form is not completed, the data-acquisition code will not run!)

E. Basic testing sequence

1. Air permeability tests will be run first starting at shallow depth and moving towards the water table
2. Water permeability test will be run second, starting at the top of the water table and moving down to a specified depth
3. If it is necessary to repeat an air permeability measurement after having run a water test, pull the Cone Permeameter™ just above the water table and run the air pump for five minutes to clear the tubing of water before moving up in the medium for air measurements

- F. Operating the instrument package (pump operation)
1. Locate the three-position “on-off-on” toggle switch in the lower left-hand corner of the instrument case control panel.
 2. If running an air permeability test, switch pump control to the “AIR PUMP ON” position.
 3. If running a water permeability test, switch pump control to the “WATER PUMP ON” position.
 4. Place the switch in the middle “OFF” position to stop pump operation.
- G. Running the data-acquisition code
1. Activate the *Start* button.
 2. Allow 10 records to be brought in before switching the pump on.
 3. Switch pump on and adjust flow.
 4. Watch the run updates to determine the number of records acquired, the total running time, the current flowrate, and the most recent air or water permeability value. Also observe the *Pressure vs. Radial Distance* plot to see the updated pressure profile.
 5. To view the acquired data vs. time, click the *History Plots* tab. Expect this action to be delayed, since there is a great quantity of calculational work being done, while the data is being brought into the spreadsheet. If it takes longer than 10 seconds, then click on the tab again.
 6. When the permeability value and pressure profile has stabilized, activate the *Stop* Button. Again, this may take some time, or you may have to click the button a second time.
 7. This action may cause an error message to be displayed if the program is stopped in a specific location. Just click the *End* button to disregard the error message.
- H. Saving the data
1. The *Save* button will save the last row of data on the *Permeability Calculations* sheet to another spreadsheet called PermResults.xls. It will also save the site information, the zero voltages, and the acquired raw voltages into a text file.
 2. Click the *Save* button.
 3. Enter a new name for the text file. (Don’t make the mistake of naming the file the same name twice because the new file will overwrite the previous file.)
- I. Repeat steps G and H until measurements have been made at all desired depths

3.8.4 Instrument Disassembly

- A. Make sure that the last set of data has been saved to file.
- B. Close the all open files and shutdown the computer.
- C. Turn off main power at instrument package.
- D. Disconnect the cabling from the instrument package and coil up in pump package.

- E. Disconnect water supply and discharge lines.
- F. Unplug computer power and serial cable.
- G. Close measurement system case for transport.
- H. Return computer to travel case.
- I. Retrieve the Cone Permeameter™ from the ground. (If the Cone Permeameter™ is located in a contaminated area, take the precautions listed in the decontamination section.)

3.8.5 *Decontamination*: Follow the decontamination process for cone penetrometer operations.

3.8.6 *Safety Considerations and Hazards*:

1. Measurement system uses 120 VAC. Disconnect power before removing instrument package front panel, opening pump junction box, or servicing pumps.
2. Pressures in pump package tubing may reach 200 psig. Do not disconnect any tubing, piping, gauges, etc., while system is running. Make sure to bleed entire system before disconnecting lines. To bleed system, turn pumps off and fully open flow control valve. When pump package gauge reads zero, the system is at ambient pressure and safe to disassemble.
3. Keep water away from instrument package. Damage to electronics or personal injury or death could result.
4. Use caution and recognized safety procedures when lifting, carrying, or transporting measurement system. The fully assembled system case weighs approximately 60 pounds.

3.9 Quality Assurance

The following activities were undertaken to ensure the quality of the Cone Permeameter™ data.

- Uncertainty analysis of prototype
- Analysis of non-ideal effects
- Inspection and calibration of instrumentation
- Testing, documentation, and version control of software
- Effective management and storage of data

The following list outlines the specific steps taken to assure the quality of the Cone Permeameter™ system operation and the quality of its resultant measurements:

Design

- An analysis of non-ideal effects was modeled using T2VOC (see section 5 for a description and results).
- An uncertainty analysis of the measurement system was performed to determine the measurement limitations of the system.

- Independent checks of all data system calculation work were performed prior to the laboratory testing phase.
- Version control of data acquisition and analysis software was maintained.

Verification:

- Periodic checks of instrumentation were performed.
- A laboratory scale validation was performed prior to deploying the Cone Permeameter™ in the field (see section 4 for results).
- Pressure transducer and flowmeter calibrations are performed prior to any measurement sequence.

Document and Data Control

- At the completion of each measurement, all raw data, calibration equations, and user inputs are saved to a text file.
- An Excel program called “Quick Look” allows the user to import a saved text file to recreate a measurement for further analysis.

3.10 System Operating Parameters

The Cone Permeameter™ measurement system used in the Savannah River Site (SRS) demonstrations is capable of characterizing the air permeability of a soil media in the $1\text{e-}5$ to 4.5 Darcy range (above the water table) and a saturated hydraulic conductivity range of $2.9\text{e-}6$ to .096 cm/s range. Table 3 lists the measurement range of the sensors used in the tests and the resulting limits of operation. These values are based on the digital precision of the a/d system, the spacing between the pressure measurement ports, and the smallest pressure differences that can be measured. It should be noted that these are only the theoretical limitations of the instrument system and that other environmental factors could further limit the system.

Table 3. Cone Permeameter™ measurement system measurement limits.

Parameter	Maximum	Minimum
Flow (air)	9 lpm	0.2 lpm
Flow (water)	5 lpm	0.2 lpm
Driving pressure (air)	60 psi (413,685 Pa)	1.08 e-2 psi (75 Pa)
Driving pressure (water)	200 psi (1,378,951 Pa)	1.08 e-2 psi (75 Pa)
Permeability (air)	4.5 Darcies	.00001 Darcies
	4.4e-12 m ²	9.9e-18 m ²
	.0043 cm/s	9.6e-9 cm/s
Permeability (water)	100 Darcies	.003 Darcies
	9.9e-11 m ²	3.0e-15 m ²
	.096 cm/s	2.9e-6 cm/s

3.11 Technology Limitations

Limitations of the system's effective operation were discovered during its deployment at SRS. Air permeability measurements were difficult to obtain in areas composed of saturated clays or silts because the pressure sensor response would become attenuated or totally blocked. The slight recessions located at each pressure port filled with clay during a push and seemed to cause this blockage. Several solutions for this problem, which would require additional field evaluation, have been proposed for the Phase III effort. One possible solution would be to replace the existing ceramic, covering the pressure ports, with a more porous material that is flush with the surface of the probe.

At SRS, saturated measurements were also hampered by the low permeability clays, where excessive pressure accumulated due to the rod emplacement. To perform a hydraulic conductivity measurement under these conditions, it would take a large fraction of an hour since pressure disperses very slowly in clays. Perhaps in this environment, the pressure dissipation technique would be a more suitable measurement method.

Although not encountered at SRS, another difficult environment that could pose measurement problems for the measurement system would be one composed a highly fractured media or coarse gravel. In highly permeable soils (>4.5 Darcies) the pressure transducers must detect very small pressure elevations less than the system is capable of measuring. With the Cone Permeameter™'s current design, it is not capable of measuring pressures with accuracy less than 350 Pa (0.05 psi). Since the Cone Permeameter™ has not been deployed in highly permeable soils, this is only an expected limitation of the system.

4. LABORATORY TEST OF PROTOTYPE SYSTEM

4.1 Objectives

Prior to taking the Cone Permeameter™ into the field, a series of air and water measurements was completed in the Phase I test cell (figure 18). The purpose of this series of laboratory testing was to check the system's performance in a homogenous 1 Darcy media and to work out any possible design complications with the instrument package, probe, or the data acquisition and analysis code. The 1 Darcy media was selected as the test cell fill, since a much higher permeability soil (30 Darcy) had been used in the Phase I testing. The performance of the measurement system was validated with permeability tests of soil samples taken from the test cell.

Figure 18. Soil test cell used for laboratory evaluation of the prototype permeameter rod section.

4.2 Procedures

The Phase I test cell was used for the laboratory testing of the Cone Permeameter™. This test cell is roughly a 4' by 4' box with an inner supportive level of screen mesh, and four removable pvc/wooden panels. The screen mesh retains the soil and promotes unimpeded flow into the annular space, while the removable panels seal against the outer frame so that water can be retained during an aqueous testing sequence.

The first step of the laboratory testing was to perform several calibrations of the pressure transducers in order to assess the stability of their voltage output over time. A detailed description of the calibration procedure is located in the design section of this report. Next, the test cell was filled with the 1 Darcy soil media. This involved emplacing and stabilizing the Cone Permeameter™ probe in the center of the box, while soil was carefully added in layers and tamped until the test box was filled. During filling, sample cylinders were placed in various positions in the sand and were tamped simultaneously to soil adjacent to the cylinders to ensure that the samples were compacted to a similar state as the bulk material in the test cell (see figure 19). The samples were then removed from the soil when it was filled to the level of the top of the sample container, and tested in the laboratory for air permeability and saturated hydraulic conductivity.

Figure 19. Locations of lab test cell samples obtained during filling.

An air measurement sequence involved conducting air injection tests at several different flowrates. A detailed procedure for conducting an air permeability test with the Cone Permeameter™ measurement system is located in the design section of this report. After all in-situ air permeability measurements were completed, laboratory air permeability (ASTM D4525-90) tests were conducted on all eight of the soil samples extracted from the test cell.

The water tests began with filling the box with water and allowing the air-filled pores to become saturated with water. Once the media was saturated, water tests were completed at various flowrates. The final step was to perform a falling head saturated conductivity test on each of the eight soil samples.

4.3 Lab Tests of Soil Samples

Tables 4 and 5 detail the results of the laboratory air permeability tests and the falling head tests. A thorough procedure of each laboratory test is located in the Phase I report (Lowry, Mason, and Merewether 1997).

Table 4. Air permeability laboratory test results.

Sample ID No.	Fluid Temp (T) [K]	Volumetric Flow (m) [m ³ /s]	Dynamic Viscosity (μ) [N*s / m ²]	Area of Container (A) [m ²]	Distance between ports (L) [m]	P _o - P _a (ΔP) [in.wc]	Source Fluid Pressure (P _o) [N/m ²]	Amb. Fluid Pressure (P _a) [N/m ²]	Perm. (K) [m ²]	Perm. (k) [Darcies]
A1	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.80	79699	79500	1.06E-12	1.1
A1	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.28	79819	79500	1.16E-12	1.2
A1	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.00	79998	79500	1.12E-12	1.1
A1	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.80	80197	79500	1.09E-12	1.1
A1	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.80	79699	79500	1.06E-12	1.1
A1	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.34	79833	79500	1.10E-12	1.1
A1	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.00	79998	79500	1.12E-12	1.1
A1	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.80	80197	79500	1.09E-12	1.1
Average Permeability									1.11	
Standard Deviation									0.03	
A2	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.70	79674	79500	1.21E-12	1.2
A2	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.20	79799	79500	1.23E-12	1.2
A2	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	1.80	79948	79500	1.24E-12	1.3
A2	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.54	80132	79500	1.20E-12	1.2
A2	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.70	79674	79500	1.21E-12	1.2
A2	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.20	79799	79500	1.23E-12	1.2
A2	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	1.80	79948	79500	1.24E-12	1.3
A2	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.52	80127	79500	1.21E-12	1.2
Average Permeability									1.24	
Standard Deviation									0.02	
B1	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.89	79721	79500	9.55E-13	1.0
B1	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.43	79856	79500	1.03E-12	1.0
B1	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.28	80067	79500	9.78E-13	1.0
B1	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.70	80172	79500	9.77E-13	1.0
B1	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.89	79721	79500	9.55E-13	1.0
B1	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.43	79856	79500	1.03E-12	1.0
B1	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.30	80072	79500	9.70E-13	1.0
B1	294.15	2.85E-06	1.82E-05	7.99E-03	0.1016	2.70	80172	79500	9.77E-13	1.0
Average Permeability									1.00	
Standard Deviation									0.03	
B2	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	1.05	79761	79500	8.09E-13	0.8
B2	294.15	1.24E-06	1.82E-05	7.99E-03	0.1016	1.35	79836	79500	8.53E-13	0.9
B2	294.15	1.99E-06	1.82E-05	7.99E-03	0.1016	2.20	80047	79500	8.40E-13	0.9
B2	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.68	80167	79500	8.32E-13	0.8
B2	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	1.05	79761	79500	8.09E-13	0.8
B2	294.15	1.24E-06	1.82E-05	7.99E-03	0.1016	1.35	79836	79500	8.53E-13	0.9
B2	294.15	1.99E-06	1.82E-05	7.99E-03	0.1016	2.20	80047	79500	8.40E-13	0.9
B2	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.70	80172	79500	8.25E-13	0.8
Average Permeability									0.84	
Standard Deviation									0.02	
C1	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.79	79697	79500	1.08E-12	1.1
C1	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.30	79823	79500	1.14E-12	1.2
C1	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.00	79998	79500	1.12E-12	1.1
C1	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.75	80184	79500	1.11E-12	1.1
C1	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.79	79697	79500	1.08E-12	1.1
C1	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.30	79823	79500	1.14E-12	1.2
C1	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	1.98	79993	79500	1.13E-12	1.1
C1	294.15	3.29E-06	1.82E-05	7.99E-03	0.1016	2.75	80184	79500	1.11E-12	1.1
Average Permeability									1.13	
Standard Deviation									0.02	
C2	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.80	79699	79500	1.06E-12	1.1
C2	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.38	79843	79500	1.07E-12	1.1
C2	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.10	80023	79500	1.06E-12	1.1
C2	294.15	2.85E-06	1.82E-05	7.99E-03	0.1016	2.50	80122	79500	1.06E-12	1.1
C2	294.15	9.15E-07	1.82E-05	7.99E-03	0.1016	0.80	79699	79500	1.06E-12	1.1
C2	294.15	1.59E-06	1.82E-05	7.99E-03	0.1016	1.39	79846	79500	1.06E-12	1.1
C2	294.15	2.41E-06	1.82E-05	7.99E-03	0.1016	2.09	80020	79500	1.07E-12	1.1
C2	294.15	2.85E-06	1.82E-05	7.99E-03	0.1016	2.50	80122	79500	1.06E-12	1.1
Average Permeability									1.08	
Standard Deviation									0.01	
Total Average Permeability									1.07	
Standard Deviation									0.13	

Table 5. Saturated hydraulic conductivity laboratory test results.

Soil Sample ID	X-Sectional Area Holding Cylinder (cm ²)	X-Sectional Area Permeameter (cm ²)	Length of Soil Specimen (cm)	h1 (cm)	h2 (cm)	Time (s)	Temp. (°C)	Perm. @ Amb. Temp. (cm/s)	Temp. Corr. Factor	Perm. @ 20 °C (cm/s)	Perm. @ 20 °C (Darcies)
A1	21.24	79.86	14.605	104.46	103.51	240	20	1.48E-04	1.0000	1.48E-04	0.15
A1	21.24	79.86	14.605	103.51	101.12	630	20	1.43E-04	1.0000	1.43E-04	0.15
A1	21.24	79.86	14.605	101.12	99.70	330	20	1.67E-04	1.0000	1.67E-04	0.17
Average Permeability											0.16
Standard Deviation											0.01
A2	21.24	79.86	14.605	113.19	112.08	330	20	1.16E-04	1.0000	1.16E-04	0.12
A2	21.24	79.86	14.605	112.08	110.65	400	20	1.25E-04	1.0000	1.25E-04	0.13
A2	21.24	79.86	14.605	110.65	109.54	345	20	1.13E-04	1.0000	1.13E-04	0.12
Average Permeability											0.12
Standard Deviation											0.01
B1	21.24	79.86	14.825	108.27	106.36	600	19	1.17E-04	1.0248	1.19E-04	0.12
B1	21.24	79.86	14.825	106.36	102.71	1120	19	1.23E-04	1.0248	1.26E-04	0.13
B1	21.24	79.86	14.825	102.71	101.60	360	19	1.19E-04	1.0248	1.22E-04	0.13
Average Permeability											0.13
Standard Deviation											0.00
B2	21.24	79.86	14.19	109.54	107.47	580	19	1.24E-04	1.0248	1.27E-04	0.13
B2	21.24	79.86	14.19	107.47	106.20	390	19	1.15E-04	1.0248	1.18E-04	0.12
B2	21.24	79.86	14.19	106.20	102.87	1033	19	1.16E-04	1.0248	1.19E-04	0.12
Average Permeability											0.13
Standard Deviation											0.01
C1	21.24	79.86	13.97	100.49	98.43	350	19	2.20E-04	1.0248	2.25E-04	0.23
C1	21.24	79.86	13.97	98.43	96.52	395	19	1.84E-04	1.0248	1.88E-04	0.20
C1	21.24	79.86	13.97	96.52	92.08	875	19	2.00E-04	1.0248	2.05E-04	0.21
Average Permeability											0.21
Standard Deviation											0.02
C2	21.24	79.86	14.19	106.52	102.55	600	19	2.39E-04	1.0248	2.44E-04	0.25
C2	21.24	79.86	14.19	101.92	99.38	432	19	2.20E-04	1.0248	2.26E-04	0.23
C2	21.24	79.86	14.19	99.38	96.84	447	19	2.18E-04	1.0248	2.24E-04	0.23
Average Permeability											0.24
Standard Deviation											0.01
Total Average Permeability											0.17
Standard Deviation											0.04

4.4 Test Cell Results

The soil used to fill the test cell was a 6:1 mix of clean sand to 250 mesh silica flour, which measured approximately 1 darcy ($9.87 \times 10^{-13} \text{ m}^2$) in laboratory air permeability tests, and nominally 0.20 Darcies ($1.9 \times 10^{-4} \text{ cm/s}$) in laboratory falling head tests. Table 6 displays the results of the air permeability measurements, while table 7 displays the results of the water permeability conductivity tests. The displayed Cone Permeameter™ results utilize the pressure difference between the ports at 0.40 meters and 0.80 meters or 0.15 meters and 0.80 meters. These two pressure differences should theoretically produce the most accurate permeabilities (assuming a homogeneous media), since the pressure vs. radial distance profiles become more spherical as they radiate away from the injection zone. Pressure profiles for a typical air permeability test are shown in figure 20, illustrating the spherical pressure field.

Table 6. Cone Permeameter™ measurements compared to laboratory air permeability measurements of the soil samples.

Flow (lpm)	Permeability (Darcies)	Sample Test (Darcies)	
1.08	0.75	Top	1.15
1.10	0.75	Middle	0.90
1.66	0.70	Bottom	1.10
2.15	0.72	<i>Average = 1.07 Darcies</i>	
2.42	0.71		
4.12	0.66		
4.13	0.68		
5.02	0.65		
<i>Average = 0.70 Darcies</i>			

Table 7. Summary of Cone Permeameter™ water measurements and falling head permeability measurements of the soil samples.

Flow (lpm)	Permeability (Darcies)	Sample Test (Darcies)	
0.66	0.18	Top	0.14
1.10	0.15	Middle	0.13
1.66	0.16	Bottom	0.24
2.15	0.22	<i>Average = 0.17 Darcies</i>	
2.42	0.23		
<i>Average = 0.19 Darcies</i>

Figure 20. Pressure profile measured by the prototype Cone Permeameter™ during a typical air permeability measurement in the test cell.

4.5 Discussion

The laboratory testing phase was intended to provide insight on the design and performance of the Cone Permeameter™ measurement system. After noting a few difficulties with the hardware, some minor modifications were made to the system during and after the testing sequence.

Midway through a set of air measurements, the air flowmeter was tested against a precision variable-area flowmeter, and failed the check. The flowmeter was consequently returned to the manufacturer, where it was repaired and recalibrated. The possible cause of its failure was over pressurizing (> 100 psi) the flowmeter. To ensure that the flowmeter is performing within specifications in future field activities, a two-point check against the variable-area flowmeter or other flowmeter standard should be performed prior to any testing sequence. A relief valve was installed in the sytem to prevent overpressurization. The final difficulty faced during the laboratory sequence was the unexpected restriction of water flow caused by the 1/8-in.diameter tubing running from the top of the probe to the injection zone. This size was initially selected to minimize the space occupied by the tubing inside the instrumented probe section. Plastic tubing (1/4 in ID) runs from the instrumented rod section to the surface. The maximum water flow with the existing tube diameter was 2.5 lpm. The probe was returned to ARA after the laboratory testing, so that the 1/8-in. tubing could be replaced with a length of ¼ inch stainless steel tubing. This design modification allowed the full 0-5 lpm range of water flow.

The test cell measurements produced positive results for air permeability and convincing results for the water measurements, considering the presence of an unconfined media. The air measurements went smoothly, after the flowmeter was repaired and reinstalled. The average permeability measured with the Cone Permeameter™ was less than the average permeability of the sample cylinders by about 35%. This difference was not a serious concern, since the sample chambers and test cell were not handled identically after being filled. The filled test cell was pushed about 10 ft. to a more suitable location in the laboratory prior to the testing sequence. The vibration associated with the move is thought to have caused the soil to settle, thus filling a greater percentage of the pore space, which would in turn cause a decrease in the permeability of the soil.

Problems arose during the water testing sequence, since the saturated media was not confined. When flowrates above 1 liter per minute were injected into the extraction zone, the water flow short-circuited and channeled up the interface between the soil and the probe. The channeling effect disturbed the pressure response of the ports nearest the extraction zone by providing a path for the pressure near these ports to escape. This was seen as a flattening of the pressure vs. radial distance profile of the sand/silica flour media. The ports furthest from the extraction zone (at 0.40 and 0.80 meters) continued to exhibit reasonable pressure responses, therefore, the pressure difference between these two ports was used to solve for the permeability of the soil. The permeabilities results from the test cell were slightly higher than the falling head test results. The channeling allowed a more conductive flow path for the water, resulting in a higher calculated permeability.

5. ANALYSIS OF NON-IDEAL EFFECTS

Measuring permeability using direct push techniques offer significant advantages over conventional well or straddle packer tests. Direct push techniques offer better spatial resolution of the permeability distribution in geologic and hydrogeologic settings because (1) the area of influence is significantly smaller and (2) more measurements can be made in a given time. However, direct push measurements also pose special problems to permeability measurements, such as the added complication of compacted soil adjacent to the rod.

In response to review comments of the Phase I topical report (Lowry, Mason, and Merewether 1997), a more exhaustive computer modeling effort was performed during Phase II to theoretically characterize soil heterogeneity and anisotropic effects on the permeability measurement system.

5.1 Purpose and Methodology

The purpose of this computer modeling was to theoretically characterize the effects of heterogeneous and anisotropic soil conditions on the permeability measurement made with the Cone Permeameter™ measurement system. For the sake of simplicity, only completely unsaturated or saturated soil conditions were modeled. Partially saturated soil conditions pose significant complications, such as relative permeability and capillary pressures, hysteresis, and increased computer simulation time, all of which were beyond the scope of this modeling effort. The Cone Permeameter™ models do not consider partially saturated permeability.

To begin, a Cone Permeameter™ measurement was modeled under ideal conditions (i.e., homogeneous and isotropic soil conditions with no compacted annulus around the rod). This simulation served as a basis for comparison for all other Cone Permeameter™ simulations.

Four cases were examined for both unsaturated and saturated media:

- Case 1: Layered heterogeneous and isotropic ($K_H / K_V = 1$) soil conditions
- Case 2: Layered heterogeneous and anisotropic ($K_H / K_V = 20$) soil conditions
- Case 3: Layered heterogeneous and isotropic ($K_n / K_v = 1$) soil conditions with a compacted annulus around the Cone Permeameter™ rod
- Case 4: Layered heterogeneous and anisotropic ($K_n / K_v = 20$) soil conditions with a compacted annulus around the Cone Permeameter™ rod

For each case examined, a series of six Cone Permeameter™ pushes was modeled. Each of the six pushes was simulated to be progressively deeper than the previous, placing the Cone Permeameter™ injection zone and pressure ports in different locations with respect to the layered heterogeneities.

Cone Permeameter™ pushes into unsaturated and saturated media were modeled using T2VOC. T2VOC is a finite difference numerical simulator capable of modeling three-phase (gas, aqueous, NAPL), three component (water, air, volatile organic compound), nonisothermal flow and transport through porous media (Falta, Pruess, Finsterle, Battistelli 1995). Air or water injection from the Cone Permeameter™ into the

surrounding geologic media was simulated. Resultant pressures from T2VOC simulations were used to analytically calculate the permeability of the modeled media. These permeability values were then compared to the actual input permeability of the modeled media.

5.2 Analytical Permeability Equations

The basic premise of the Cone PermeameterTM measurement system is that fluid (air or water) injected from a discrete location on the Cone PermeameterTM rod into the surrounding geologic media will tend to create a spherical flow and pressure field as steady state conditions are achieved. Pressure measurements are taken from discrete locations on the Cone PermeameterTM rod by imbedded pressure transducers as shown in figure 21. Measured pressure differences are then used to compute permeability using equation 1 for air injection, or equation 2 for water injection (see section 3.5). Note that the pressure measurement locations are numbered sequentially, the first (P_1) nearest the injection point and the last (P_5) the farthest from the injection point.

Figure 21. Cone PermeameterTM rod with pressure sensors at discrete locations above the injection zone.

5.3 Numerical Modeling

Cone PermeameterTM pushes into unsaturated and saturated heterogeneous and anisotropic media were modeled using a two-dimensional radial symmetric mesh. The mesh represented a 10-meter diameter, by 10-meter high cylindrical block of soil. Assigning different material properties to different layers and cells of the mesh simulated heterogeneous and anisotropic soil conditions. Table 8 summarizes the Cone PermeameterTM numerical simulations performed. Figure 22 demonstrates how a Cone PermeameterTM push was simulated.

Table 8. Summary of the Cone Permeameter™ numerical simulations.

Case	Air Injection Into:					
	Push 1	Push 2	Push 3	Push 4	Push 5	Push 6
Baseline	Sand	N/A	N/A	N/A	N/A	N/A
Heterogeneous, Isotropic	Sand	Sand	Sand	Gravel	Clay	Sand
Heterogeneous, Anisotropic	Sand	Sand	Sand	Gravel	Clay	Sand
Heterogeneous, Isotropic, Compacted Annulus	Sand	Sand	Sand	Gravel	Clay	Sand
Heterogeneous, Anisotropic, Compacted Annulus	Sand	Sand	Sand	Gravel	Clay	Sand
	Water Injection Into:					
	Push 1	Push 2	Push 3	Push 4	Push 5	Push 6
Heterogeneous, Isotropic	Sand	Sand	Sand	Gravel	Clay	Sand
Heterogeneous, Anisotropic	Sand	Sand	Sand	Gravel	Clay	Sand
Heterogeneous, Isotropic, Compacted Annulus	Sand	Sand	Sand	Gravel	Clay	Sand
Heterogeneous, Anisotropic, Compacted Annulus	Sand	Sand	Sand	Gravel	Clay	Sand

Figure 22. Cone Permeameter™ pushes were simulated by progressively changing the material properties of the mesh layers (note that the figure is not drawn to scale and represents only a portion of the 10 meter by 10 meter mesh).

5.4 Model Assumptions

The Cone Permeameter™ and surrounding media was modeled using a two-dimensional radial symmetric mesh. It should be noted that the same mesh discretization and boundary conditions used for the Phase I topical report was used for this modeling addendum. The basic assumptions and conditions for all Cone Permeameter™ numerical simulations were:

- The Cone Permeameter™ rod was modeled as a 2.5 centimeters (1 inch) radius cylinder located at the center of the mesh
- A total seal existed between the Cone Permeameter™ rod and the soil (i.e., no air or water flow was allowed along the rod and soil interface)
- The mesh was bordered by constant pressure boundaries at the top, bottom, and sides, as well as a no-flow condition through the cells that represented the Cone Permeameter™ rod

- Constant and fixed rate fluid injection occurred through a single cell at the center of the mesh which represented the injection zone directly above the tip of the Cone Permeameter™ rod
- The height of the injection zone was 2.5 centimeters (1 inch)

5.4.1 Model Design and Input Parameters: The two-dimensional radial symmetric mesh represented a 10 meter diameter by 10 meter high cylindrical block of soil. The mesh nodalization was localized around the simulated injection zone. Soil heterogeneity was simulated using a 2 inch horizontal layer of a gravelly soil on top of a 10 inch horizontal clay layer, all sandwiched between a sandy soil. Isotropic permeability of the sand, gravel, and clay were 10, 100, 0.0001 Darcies respectively. Anisotropy was simulated by changing the ratio of horizontal permeability versus vertical permeability in the sandy soil from 1 to 20 (i.e., $K_h / K_v = 1$ for isotropic conditions, and $K_h / K_v = 20$ for anisotropic conditions). The compacted annulus formed from pushing a cone penetrometer into soil was simulated by lowering the permeability of the sandy soil and clay layer in the vicinity of the rod by two orders of magnitude. For the unsaturated Cone Permeameter™ pushes, air was injected at a mass flow rate of 0.0022 kg/s. For the saturated pushes, water was injected at a mass flow rate of 0.0022 kg/s.

5.5 Modeling Results

In-situ soil pressures from each computer modeled Cone Permeameter™ push were output after equilibrium was achieved. Pressures were taken at 0.05 (P_1), 0.075 (P_2), 0.15 (P_3), 0.40 (P_4), and 0.80 (P_5) meters directly above the injection zone. For the appropriate injection fluid, pressures were input into one of the analytical equations (1 – air, 2 – water), permeabilities were calculated, and then compared to the permeability of the modeled medium at the injection zone. Pressures were also contoured to observe the impact heterogeneity, anisotropy, and a compacted annulus had on the theoretical spherical pressure profile.

5.5.1 Unsaturated Cone Permeameter™ Pushes: The unsaturated Cone Permeameter™ cases modeled were (1) a layered heterogeneous, isotropic case, (2) a layered heterogeneous, anisotropic case, (3) a layered heterogeneous, isotropic case with a compacted annulus, and (4) a layered heterogeneous, anisotropic case with a compacted annulus. Tables 9 through 12 summarize the calculated analytical permeabilities and compare them using a percent error to the model permeability of the layer where air injection took place (this permeability varies depending on the location or push of the Cone Permeameter™ probe).

Tables 9 through 12 were generated in the following way:

5. The pressure differential from ports 1 and 2, 1 and 3, 1 and 4, 1 and 5, 2 and 3, 2 and 4, 2 and 5, 3 and 4, 3 and 5, and 4 and 5 were calculated from the model output for each of the six simulated pushes for the baseline case and each of the four non-ideal cases.
6. The pressure differentials calculated in step 1 were used in one of the analytical equations derived in section 3.5 to calculate permeability. Thus, for each push of each case, 10 values of permeability are calculated.

7. The calculated values of permeability were then compared to the actual value used as input to the model at the point of air or water injection (i.e., 100 Darcy, 10 Darcy, or .0001 Darcy if the Cone Permeameter™ injection zone was in the gravel, sand, or clay layer respectively). The following equation was used to express this difference between calculated and actual permeability:

$$\% \text{ Error} = \frac{K_{\text{Calculated}} - K_{\text{Actual}}}{K_{\text{Actual}}} \quad (\text{Eq. 3})$$

8. For each table, 9 through 12, the baseline case values for permeability and % errors are displayed for comparison purposes. This represents the best values or % error the Cone Permeameter™ model is capable of attaining.

Table 9. Air injection simulations, heterogeneous, isotropic cases.

	ΔP_{1-2}	ΔP_{1-3}	ΔP_{1-4}	ΔP_{1-5}	ΔP_{2-3}	ΔP_{2-4}	ΔP_{2-5}	ΔP_{3-4}	ΔP_{3-5}	ΔP_{4-5}
<i>Baseline Isotropic Case, Injection into Sand, $K_{\text{model}} = 1.00\text{e-}11 \text{ m}^2$</i>										
K (m ²)	1.11e-11	1.12e-11	1.11e-11	1.11e-11	1.15e-11	1.12e-11	1.11e-11	1.10e-11	1.08e-11	1.00e-11
Error	11%	12%	11%	11%	15%	12%	11%	10%	8%	0%
<i>Heterogeneous Case – Push 1, Injection into Sand, $K_{\text{model}} = 1.00\text{e-}11 \text{ m}^2$</i>										
K (m ²)	1.11e-11	1.12e-11	1.12e-11	1.11e-11	1.15e-11	1.13e-11	1.11e-11	1.11e-11	1.09e-11	1.02e-11
Error	11%	12%	12%	11%	15%	13%	11%	11%	9%	2%
<i>Heterogeneous Case – Push 2, Injection into Sand, $K_{\text{model}} = 1.00\text{e-}11 \text{ m}^2$</i>										
K (m ²)	1.11e-11	1.12e-11	1.11e-11	1.10e-11	1.15e-11	1.12e-11	1.10e-11	1.10e-11	1.07e-11	9.71e-12
Error	11%	12%	11%	10%	15%	12%	10%	10%	7%	-3%
<i>Heterogeneous Case – Push 3, Injection into Sand, $K_{\text{model}} = 1.00\text{e-}11 \text{ m}^2$</i>										
K (m ²)	1.12e-11	1.14e-11	1.14e-11	1.13e-11	1.18e-11	1.15e-11	1.13e-11	1.14e-11	1.11e-11	9.91e-12
Error	12%	14%	14%	13%	18%	15%	13%	14%	11%	-1%
<i>Heterogeneous Case – Push 4, Injection into Gravel, $K_{\text{model}} = 1.00\text{e-}10 \text{ m}^2$</i>										
K (m ²)	2.66e-11	2.68e-11	2.55e-11	2.43e-11	2.77e-11	2.42e-11	2.22e-11	2.19e-11	1.96e-11	1.38e-11
Error	-73%	-73%	-75%	-76%	-72%	-76%	-78%	-78%	-80%	-86%
<i>Heterogeneous Case – Push 5, Injection into Clay, $K_{\text{model}} = 1.00\text{e-}16 \text{ m}^2$</i>										
K (m ²)	1.16e-16	1.18e-16	1.55e-16	1.64e-16	1.21e-16	2.65e-16	3.01e-16	3.02e-11	2.66e-11	1.78e-11
Error	16%	18%	55%	64%	21%	165%	201%	na	na	na
<i>Heterogeneous Case – Push 6, Injection into Sand, $K_{\text{model}} = 1.00\text{e-}11 \text{ m}^2$</i>										
K (m ²)	na	5.07e-12	6.62e-12	7.01e-12	1.34e-12	2.93e-12	3.32e-12	1.79e-10	2.23e-10	na
Error	na	-49%	-34%	-30%	-87%	-71%	-67%	1690%	2129%	na

Table 10. Air injection simulations, heterogeneous, anisotropic cases.

	ΔP_{1-2}	ΔP_{1-3}	ΔP_{1-4}	ΔP_{1-5}	ΔP_{2-3}	ΔP_{2-4}	ΔP_{2-5}	ΔP_{3-4}	ΔP_{3-5}	ΔP_{4-5}
<i>Baseline Anisotropic Case, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	7.68e-12	8.01e-12	8.41e-12	8.60e-12	9.10e-12	9.54e-12	9.93e-12	9.94e-12	1.06e-11	1.43e-11
Error	-23%	-20%	-16%	-14%	-9%	-5%	-1%	-1%	6%	43%
<i>Heterogeneous Anisotropic Case – Push 1, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	7.68e-12	8.01e-12	8.84e-12	8.61e-12	9.10e-12	9.54e-12	9.93e-12	9.94e-12	1.06e-11	1.44e-11
Error	-23%	-20%	-16%	-14%	-9%	-5%	-1%	-1%	6%	44%
<i>Heterogeneous Anisotropic Case – Push 2, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	7.69e-12	8.02e-12	8.41e-12	8.61e-12	9.10e-12	9.54e-12	9.93e-12	9.94e-12	1.06e-11	1.44e-11
Error	-23%	-20%	-16%	-14%	-9%	-5%	-1%	-1%	6%	44%
<i>Heterogeneous Anisotropic Case – Push 3, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	7.76e-12	8.12e-12	8.54e-12	8.75e-12	9.30e-12	9.79e-12	1.02e-11	1.02e-11	1.09e-11	1.46e-11
Error	-22%	-19%	-15%	-13%	-7%	-2%	2%	2%	9%	46%
<i>Heterogeneous Anisotropic Case – Push 4, Injection into Gravel, $K_{model} = 1.00e-10 m^2$</i>										
K (m^2)	1.38e-11	1.55e-11	1.67e-11	1.69e-11	2.40e-11	2.27e-11	2.27e-11	2.17e-11	2.19e-11	2.28e-11
Error	-86%	-84%	-83%	-76%	-77%	-77%	-78%	-78%	-78%	-77%
<i>Heterogeneous Anisotropic Case – Push 5, Injection into Clay, $K_{model} = 1.00e-16 m^2$</i>										
K (m^2)	1.16e-16	1.18e-16	1.55e-16	1.64e-16	1.21e-16	2.65e-16	3.01e-16	1.33e-11	1.38e-11	1.67e-11
Error	16%	18%	55%	64%	21%	165%	201%	na	na	na
<i>Heterogeneous Anisotropic Case – Push 6, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	8.50e-10	4.46e-12	5.81e-12	6.16e-12	1.18e-12	2.58e-12	2.92e-12	1.47e-10	1.83e-10	na
Error	8401%	-55%	-42%	-38%	-88%	-74%	-71%	1369%	1729%	na

Table 11. Air injection simulations, heterogeneous, isotropic, compacted annulus cases.

	ΔP_{1-2}	ΔP_{1-3}	ΔP_{1-4}	ΔP_{1-5}	ΔP_{2-3}	ΔP_{2-4}	ΔP_{2-5}	ΔP_{3-4}	ΔP_{3-5}	ΔP_{4-5}
<i>Baseline Isotropic Case, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	1.11e-11	1.12e-11	1.11e-11	1.11e-11	1.15e-11	1.12e-11	1.11e-11	1.10e-11	1.08e-11	1.00e-11
Error	11%	12%	11%	11%	15%	12%	11%	10%	8%	0%
<i>Heterogeneous Isotropic Compacted Annulus – Push 1, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	1.05e-12	1.36e-12	1.73e-12	1.81e-12	7.01e-12	8.98e-12	9.12e-12	1.17e-11	1.14e-11	1.04e-11
Error	-89%	-86%	-83%	-82%	-30%	-10%	-9%	17%	14%	4%
<i>Heterogeneous Isotropic Compacted Annulus – Push 2, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	1.05e-12	1.36e-12	1.72e-12	1.81e-12	7.00e-12	8.91e-12	9.01e-12	1.16e-11	1.12e-11	9.84e-12
Error	-89%	-86%	-83%	-82%	-30%	-11%	-10%	16%	12%	-2%
<i>Heterogeneous Isotropic Compacted Annulus – Push 3, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	1.05e-12	1.36e-12	1.73e-12	1.81e-12	7.10e-12	9.13e-12	9.23e-12	1.20e-11	1.16e-11	1.00e-11
Error	-89%	-86%	-83%	-82%	-29	-9	-8%	20%	16%	0%
<i>Heterogeneous Isotropic Compacted Annulus – Push 4, Injection into Gravel, $K_{model} = 1.00e-10 m^2$</i>										
K (m^2)	1.15e-11	1.74e-11	1.86e-11	1.82e-11	3.04e-11	2.63e-11	2.39e-11	2.37e-11	2.09e-11	1.41e-11
Error	-85%	-83%	-84%	-82%	-70%	-74%	-76%	-76%	-79%	-86%
<i>Heterogeneous Isotropic Compacted Annulus – Push 5, Injection into Clay, $K_{model} = 1.00e-16 m^2$</i>										
K (m^2)	1.16e-16	1.18e-16	1.55e-16	1.64e-16	1.21e-16	2.65e-16	3.01e-16	2.96e-11	2.63e-11	1.81e-11
Error	16%	18%	55%	64%	21%	165%	201%	na	na	na
<i>Heterogeneous Isotropic Compacted Annulus – Push 6, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	2.45e-11	1.19e-12	1.54e-12	1.63e-12	3.27e-13	7.04e-13	7.98e-13	1.81e-11	2.25e-11	na
Error	145%	-88%	-85%	-84%	-97%	-93%	-92%	81%	125%	na

Table 12. Air injection simulations, heterogeneous, anisotropic, compacted annulus cases.

	ΔP_{1-2}	ΔP_{1-3}	ΔP_{1-4}	ΔP_{1-5}	ΔP_{2-3}	ΔP_{2-4}	ΔP_{2-5}	ΔP_{3-4}	ΔP_{3-5}	ΔP_{4-5}
<i>Baseline Anisotropic Case, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	7.68e-12	8.01e-12	8.41e-12	8.60e-12	9.10e-12	9.54e-12	9.93e-12	9.94e-12	1.06e-11	1.43e-11
Error	-23%	-20%	-16%	-14%	-9%	-5%	-1%	-1%	6%	43%
<i>Heterogeneous Anisotropic Compacted Annulus – Push 1, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	9.60e-13	1.23e-12	1.55e-12	1.63e-12	5.27e-12	6.85e-12	7.15e-12	9.14e-12	9.40e-12	1.06e-11
Error	-90%	-88%	-85%	-84%	-47%	-32%	-29%	-9%	-6%	6%
<i>Heterogeneous Anisotropic Compacted Annulus – Push 2, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	9.60e-13	1.23e-12	1.55e-12	1.63e-12	5.27e-12	6.85e-12	7.14e-12	9.13e-12	9.38e-12	1.06e-11
Error	-90%	-88%	-85%	-84%	-47%	-32%	-29%	-9%	-6%	6%
<i>Heterogeneous Anisotropic Compacted Annulus – Push 3, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	9.57e-13	1.22e-12	1.55e-12	1.63e-12	5.34e-12	7.01e-12	7.31e-12	9.47e-12	9.71e-12	1.09e-11
Error	-90%	-88%	-85%	-84%	-47%	-30%	-27%	-5%	-3%	9%
<i>Heterogeneous Anisotropic Compacted Annulus – Push 4, Injection into Grav, $K_{model} = 1.00e-10 m^2$</i>										
K (m^2)	1.06e-11	1.23e-11	1.37e-11	1.41e-11	2.20e-11	2.18e-11	2.20e-11	2.17e-11	2.19e-11	2.30e-11
Error	-89%	-88%	-86%	-86%	-78%	-78%	-78%	-78%	-78%	-77%
<i>Heterogeneous Anisotropic Compacted Annulus – Push 5, Injection into Clay, $K_{model} = 1.00e-16 m^2$</i>										
K (m^2)	1.16e-16	1.18e-16	1.55e-16	1.64e-16	1.21e-16	2.65e-16	3.01e-16	1.33e-11	1.38e-11	1.67e-11
Error	16%	18%	55%	64%	21%	165%	201%	na	na	na
<i>Heterogeneous Anisotropic Compacted Annulus – Push 6, Injection into Sand, $K_{model} = 1.00e-11 m^2$</i>										
K (m^2)	2.37e-11	1.07e-12	1.38e-12	1.47e-12	2.94e-13	6.32e-13	7.17e-13	1.58e-11	1.97e-11	na
Error	137%	-89%	-86%	-85%	-97%	-94%	-93%	58%	97%	na

5.5.2 Pressure Contours: The pressure contours resulting from each of the simulation cases (both air and water) are depicted in figures 23-35. The most pronounced feature in all cases is the distortion of the pressure field by the clay layer. The anisotropy simulations illustrate the classic elliptical profiles resulting from the high horizontal permeability.

Figure 23. Air injection test, homogeneous, isotropic baseline case.

Figure 24. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 1.

Figure 25. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 2.

Figure 26. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 3.

Figure 27. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 4.

Figure 28. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 5.

Figure 29. Air injection test: heterogeneous, isotropic, and anisotropic cases – push 6.

Figure 30. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 1.

Figure 31. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 2.

Figure 32. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 3.

Figure 33. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 4.

Figure 34. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 5.

Figure 35. Water injection test: heterogeneous, isotropic, and anisotropic cases with a compacted annulus – push 6.

5.5.3 *Saturated Cone PermeameterTM Pushes:* The saturated Cone PermeameterTM pushes produced results identical to the unsaturated cases, hence the error tables are not reproduced for those runs..

5.6 Data Reduction and Analysis

Pressure contours for the baseline, homogeneous, isotropic case are spherical (figure 23). Figures 24 through 35 depict pressure fields for the deviations from the baseline case. The analytically calculated permeabilities for the baseline, homogeneous and isotropic case were found to be within 15 percent of the modeled permeability. 0 percent error was calculated by using the pressure differential between pressure sensors 4 and 5. This suggests the pressure distribution becomes more spherical farther from the injection zone, most likely due to overcoming the cylindrical nature of the injection zone.

The first three pushes of the Cone PermeameterTM for the heterogeneous, isotropic case closely resemble the baseline case. Injection for these cases occurred in the sandy layer. As the injection zone is pushed closer to the low permeability clay layer, pressure contours below the injection zone become distorted and the pressure gradient increases sharply. However, the pressure contours above the injection zone still appeared spherical. As with the baseline case, the pressure differential between ports 4 and 5 provided the best correlation between calculated and modeled permeability for the first three Cone PermeameterTM pushes. Significant error occurs when the injection occurs in the 2 inch gravel layer. The error between the calculated and modeled permeability is attributed the fact that although the injection occurs in the gravel, all the pressure ports are located in the sandy layer. When the injection zone is pushed into the clay layer, relatively good correlation occurs between the calculated and modeled permeability using ports 1 and 2. Pressure ports 3, 4, and 5 lie above the clay layer in the sandy soil. While the permeability calculated by the pressure differential between ports 3 and 4, 3 and 5, and 4 and 5 is not indicative of the permeability of the clay layer, they are indicative of the permeability of the sandy soil. This would suggest the permeability of the geologic media should be assigned to the location of the pressure ports rather than the injection zone itself. The final push revealed that pore gas pressure is unaffected by air injection when pressure sensors and the injection zone are separated by a relatively impermeable media.

Anisotropic soil conditions had a significant impact on the spherical pressure distribution. Correlation between calculated and modeled permeability for the heterogeneous, anisotropic Cone PermeameterTM pushes was markedly worse than the baseline case. There were instances when calculated and modeled permeability correlated very well (pressure differential between ports 2 and 5, and 3 and 4 for pushes 1, 2, and 3). The reasons for this good correlation is unclear. It may have to do with the distance between ports in relation to the anisotropic ratio.

The compacted annulus had a significant impact on near field pressure differentials for the heterogeneous, isotropic Cone PermeameterTM pushes. However, the effect was negated by using pressure differentials from the two pressure sensors farthest from the injection zone. The pressure contours for this case show a pressure profile distortion near the injection zone, which turns spherical farther from the injection zone.

The most significant impact on the spherical pressure distribution occurred when combining the heterogeneous, anisotropic soil conditions with a compacted annulus. While there were occasions when the calculated permeability correlated well with the modeled permeability, the reasons were unclear.

5.7 Conclusions and Recommendations

Results from modeling heterogeneous, anisotropic geologic media, and a compacted annulus around the cone penetrometer rod appear promising for field implementation of the system. Although the properties of the geologic media may vary, the theory behind calculating the permeability based on the pressure distribution resulting from air or water injection generally generates permeabilities at least on the same order of magnitude as the actual soil permeability. Specific conclusions from the modeling effort that may be applied directly to field implementation include:

- The permeability calculated from the pressure differential of two discrete pressure sensors is more indicative of the actual permeability of the media at the location of the pressure sensors rather than the location of the injection zone.
- The permeability based on the pressure differential using the two pressure sensors farthest from the injection zone is generally the best estimate of the actual permeability of the media.
- By design, the effects of the compacted annulus caused by pushing the cone penetrometer into the soil is negated by using the pressure differential from the pressure sensors farthest from the injection zone.
- The quantitative effects of anisotropy on the Cone Permeameter™ results are unclear. It may be possible to discern the degree of anisotropy by evaluating the deviation of the measured pressure profile from the spherical profile. To do this requires an additional modeling and analysis effort.

6. FIELD TEST RESULTS

6.1 Test Objectives

The purpose of the Savannah River Site field effort was to demonstrate the use of the Cone Permeameter™ system in various soil media (above and below the water table) and to validate the resulting in-situ permeability measurements with permeability characterization records of the area.

6.2 Cone Penetrometer Truck

The Cone Permeameter™ was integrated with a standard CPT cone tip and deployed by Applied Research Associates using a 30-ton truck loaded to 26 tons. The truck placement at the M area is shown in figure 36, and the rod prior to the first push is shown in figure 37. CPT data (pore pressure, sleeve stress, tip stress) was obtained simultaneously with the permeameter measurements.

6.3 Site Characteristics

The first demonstration of the Cone Permeameter™ measurement system was conducted at the Savannah River Site, D Area Coal Pile Runoff Basin near well DCB-25 (see figure 38). The area is composed of a series of interbedded sand, silt, and clay layers. Borings logs of soil samples from DCB-25, reveal the existence of at least 11 different layers from 4 to 60 feet (see figure 39).

The groundwater beneath the site is divided into two aquifer systems, a shallow and deep artesian system. The shallow aquifer system contains a water aquifer table, which is anywhere from 0 to 15 ft. deep, and a semiconfined aquifer, which is 50 to 60 feet deep. These aquifers are separated by a dark silty clay semiconfining unit that is 10 to 15-feet thick. Groundwater flow near the Coal Pile Runoff Basin is primarily towards the Savannah River.

The second and third demonstrations were performed in the M Area Integrated Demonstration Site and the 321 M Area. These sites are also underlain with interbedded sand, silt and clay layers. A schematic diagram of the stratigraphy of the M area site is displayed in figure 40. The water table in these locations is at a depth of approximately 130 ft. to 140 ft. below ground level.

Figure 36. Cone penetrometer truck in position for SRS Area M measurements.

Figure 37. Cone Permeameter™ rod prior to initial push during SRS demonstration.

Figure 38. Location of coal pile runoff basin and well DCB-25 (Phifer, Sappington, Pemberton, and Nichols 1996).

Figure 39. Core sample descriptions of DCB-25 (Rust Environmental & Infrastructure 1996).

Figure 40. General stratigraphy of the M area.

6.3 Testing Chronology

The saturated and unsaturated zone demonstration measurements were completed at the Savannah River Site in April of 1998. The general chronology of the field tests is as follows:

April 21 (Tuesday) - Neva Mason and Bill Lowry of SEA arrived at SRS in the morning and toured the measurement areas. Mike Serrato and Bill Jones of Westinghouse Savannah River provided documents of characterization activities of the demonstration sites. A temporary office area was provided for instrument checkout and data analysis. The Cone Permeameter™ equipment arrived mid-day and setup/checkout was started. Chris Bianchi of Applied Research Associates (ARA) arrived that evening.

April 22 (Wednesday) - Measurement system tests and calibrations showed that the electronic air flowmeter had failed, so it was sent back to the manufacturer for repair. A replacement (0-10 lpm) flowmeter was ordered as backup. One of the pressure sensors embedded in the CPT rod section also indicated sporadic signals, so the rod was disassembled and the bad sensor replaced. When the rod was reassembled, it tested out satisfactorily. The test plan was changed to conduct saturated zone tests first, allowing sufficient time for the replacement airflow sensor to be express shipped to the site.

April 23 (Thursday) - The ARA CPT truck was mobilized to the D Area Coal Pile Runoff Basin for the saturated zone tests. At this location the water table is between 4 and 5 ft. below ground surface. Saturated hydraulic conductivity tests were started at shallow depths. Initial tests showed that the injection zone was repeatedly plugging. The rod was retrieved and cleaned, and the procedure changed to always sustain water flow into the injection zone during the push to prevent clay from plugging the injection screen. Compounding this was the occasionally very high pore pressure generated during the rod push (as high as 200 psi in some cases) in clays, caused by the compaction of the pore spaces adjacent to the rod. This pressure probably forced clay into the injection screen plugging the injection water flow. Injecting water (at a very low rate) continuously during the push almost entirely eliminated the injection zone impedance problem.

April 24 (Friday) - The CPT truck was moved laterally to another location (about 10 ft. from the first push) to start a clean measurement series. By the end of the day several measurements were completed to the 15 ft. depth.

April 27 (Monday) - The measurements in the D Area saturated zone were completed to the total depth of 60 ft. Thirty-five measurements were conducted in five hours. In some cases the permeability was so low that water could not be injected into the clays (consistent with very high pore pressures and very slow dissipation of these pore pressures).

April 28 (Tuesday) - The CPT truck was relocated to the Integrated Demonstration site (Area M) for the unsaturated zone air permeability measurements. Plugging of the pressure sensor filters with clay impeded initial measurement attempts. Removal of the rod, cleaning, and reinsertion would temporarily allow air measurements, but the ports rapidly plugged as soon as the rod was advanced through the clay. High pore pressures were measured during the push in the clay zones, indicating that the clays were close enough to saturation that they could accumulate elevated pore pressure as if they were in the saturated zone. Because of the field schedule constraints, the CPT truck was moved over to the 321 M Area, which was the site selected for the Visitors' Day.

April 29 (Wednesday) - The CPT truck was located at the building 321 M Area site, where air permeability measurements were planned. Two airflow meters were available. Several measurements were conducted, with similar results due to clay layers plugging the pressure port filters. The geophysical data obtained by the standard cone measurements indicated the location of higher permeability (sand) layers, and measurements were successful in those regions. Preparations were made for the Visitors' Day.

April 30 (Thursday) - The Visitors' Day activities started at 8:30 am, with a briefing on the technology and the site characteristics. Mike Serrato introduced the project and site information, and Bill Lowry presented the technology description and results obtained to date. Fifteen people attended the briefing. The attendees were then transported to the 321 M Area to see the Cone Permeameter™ measurements in progress. That morning the probe was retrieved from the soil, cleaned, and pushed back to depth. A successful air measurement was obtained at that location, and the balance of the air measurements completed in the remaining workday. The operations were completed and the hole grouted up.

6.4 Saturated Zone Hydraulic Conductivity Measurements

The measurements in the saturated zone were considered highly successful. The permeability at the Area D Coal runoff basin is highly variable, corresponding with the detailed layering of clay, sand, and silt. Concurrent measurement of the cone penetrometer geophysical data proved to be extremely useful in anticipating the measurement conditions, and frequently explained difficulty in obtaining permeability data. When the measurement system was in the production mode, approximately 8 to 10 minutes were required for the average measurement (including the time to push the rod to the next depth). A total of 38 successful measurements were obtained at 1- 2 ft. intervals from a depth of 15 ft. to a depth of 57 ft. Table 13 and figure 41 display these results.

The hydraulic conductivity measurements were performed near well DCB-25 (approximately 12 feet from the well). The general sequence of each run consisted of pushing the probe to a desired location (while injecting a minimal water flow through the injection zone), starting the data-acquisition system, increasing the water flow, and running the acquisition system and water pump until the injection-zone pressure and water flow simultaneously stabilized. The escalation of pore pressures sometimes caused by the cone push required a 10-20 minutes to dissipate. At the completion of a test, all input variables and raw voltages were saved to a user-named text file.

For the analysis work, each text data file was imported into the data analysis spreadsheet. Plots of port pressures, injection pressure, and flow vs. elapsed time were studied to identify the most representative permeability value for each depth location. The majority of the calculated permeabilities reported in table 13 use the pressure difference between ports 3 and 4, located at 0.15 and 0.40 meters from the injection zone respectively. These ports were selected for the permeability calculation, because both port pressures exhibited a positive pressure response once the water flow was increased and because they were located a reasonable distance from the injection zone.

Table 13. Results of the saturated hydraulic conductivity tests performed near well DCB-25 with the Cone Permeameter™ measurement system.

				Radial Distance from Injection Source (m)					
				0.08	0.15	0.40	0.8		
Depth (ft)	Elapsed Time (s)	Flow (kg/s)	Injection Zone Pressure (Pa)	Port 2 Pressure (Pa)	Port 3 Pressure (Pa)	Port 4 Pressure (Pa)	Port 5 Pressure (Pa)	Permeability (Darcies)	Sat. Hyd. Cond. (cm/s)
15.00	2013	3.17E-03	673474	449400	227433	192530	201844	0.0245	2.35E-05
16.00	452	2.27E-03	340157	307749	208967	178975	230147	0.0200	1.92E-05
17.00	100	2.21E-03	676526	589070	253308	253150	232857	3.5343	3.40E-03
18.00	304	2.12E-03	569250	214180	166244	135014	227840	0.0179	1.72E-05
20.00	752	4.05E-03	774666	209919	206900	190583	157358	0.5590	5.37E-04
22.00	404	7.98E-03	313337	185613	152393	172956	149787	0.1006	9.67E-05
24.00	798	1.36E-02	375509	149930	156609	153040	157909	1.0001	9.61E-04
25.00	707	4.13E-03	252437	233402	204097	159340	156607	0.0241	2.31E-05
26.00	898	3.17E-03	487848	363032	340440	162838	156749	0.0047	4.52E-06
27.00	695	7.51E-03	393908	205147	184283	249417	168805	0.1512	1.45E-04
28.00	452	6.37E-03	512892	476803	346128	211135	232868	0.0119	1.15E-05
29.00	502	1.34E-03	698550	699820	719448	171134	178375	0.0006	6.11E-07
30.00	801	8.16E-03	604462	583733	461203	296367	171676	0.0128	1.24E-05
31.00	500	6.80E-04	732569	290964	208212	327823	180615	0.0034	3.26E-06
32.00	625	1.48E-03	873177	739845	742866	224976	334127	0.0007	7.13E-07
33.00	398	7.63E-04	870553	776277	753110	572248	183282	0.0011	1.05E-06
34.00	923	2.32E-02	553839	256483	214657	432340	377193	0.2163	2.08E-04
35.00	503	3.48E-03	671927	187248	201634	192841	496822	0.0997	9.58E-05
36.00	317	7.79E-03	535422	193888	204961	193294	200468	0.1670	1.61E-04
37.00	402	3.56E-03	795454	191851	207135	195000	202158	0.0739	7.11E-05
38.00	396	2.92E-03	654742	199217	210797	197506	198707	0.0551	5.30E-05
39.00	253	7.63E-04	831028	199422	213500	199665	199766	0.0138	1.33E-05
40.00	396	2.92E-03	484088	209949	219852	206682	205346	0.0555	5.34E-05
41.00	301	2.20E-03	746798	271701	224541	214029	208177	0.0526	5.05E-05
42.00	448	1.16E-04	902706	264838	225580	215805	217403	0.0030	2.88E-06
44.00	252	6.61E-03	457554	317520	242879	223623	225754	0.0852	8.19E-05
45.00	349	3.15E-04	904424	255168	257265	245161	221191	0.0065	6.27E-06
46.00	320	1.11E-02	700030	366213	355703	270617	231130	0.0326	3.14E-05
48.00	252	4.23E-03	789843	543770	504448	253623	242312	0.0042	4.03E-06
49.00	298	6.80E-04	926138	281936	266132	253797	231619	0.0138	1.33E-05
50.00	150	7.74E-03	816568	649989	363719	268702	237016	0.0204	1.96E-05
51.00	181	6.80E-04	918073	418159	298138	268493	250132	0.0057	5.50E-06
52.00	254	4.38E-03	787887	598163	474200	284093	239582	0.0058	5.60E-06
53.00	503	1.13E-03	907717	347677	292788	260518	239582	0.0089	8.51E-06
54.00	553	6.61E-03	639185	284230	287740	261232	265041	0.0625	6.01E-05
55.00	399	9.95E-04	887578	590786	520536	253623	258422	0.0009	8.96E-07
56.00	301	1.33E-04	940359	776010	523920	269207	254450	0.0001	1.27E-07
57.00	139	1.33E-04	982116	1201896	982479	627920	254552	0.0001	9.11E-08

Figure 41. Depth vs. hydraulic conductivity of D area coal runoff basin (near DCB-25).

6.5 Unsaturated Zone Gas Permeability Measurements

Air measurements were problematic, primarily due to plugging of the pressure ports with clay. When the ports were cleaned, good measurements were obtained in the higher permeability zones (in particular, the sand layers). In the clay layers, it was frequently not possible to flow air at all, because of the clay's inherent low permeability and probable zero air permeability (possibly due to the compaction of the clay by the penetrometer during the push). Several changes in the pressure port filter design are being considered to prevent the accumulation of clay over the porous filter. Greater success is anticipated with air permeability measurements at sites with lower moisture and/or less clay.

Air measurements were completed at two locations in the M area. The first testing location was in the M area between wells MHV-10 and MHV-11. The measurement sequence at this location proved to be a less successful demonstration. The ports continually showed little or no pressure response to air injection, even when pushed through layers identified as a sand mix with the CPT geophysical tool.

The probe was eventually pulled up for evaluation. During a visual inspection it was noted that the recesses above the pressure ports were filled with wet clay. Prior to cleaning the probe, it was inserted into the calibration chamber for pressure checks. The pressure sensors were very slow to respond to an increase or decrease of pressure, when the ports were filled with clay. After the probe was cleaned the pressure transducers responded in a normal fashion.

Since the standard Cone Permeameter™ measurements were not always successful, another method was utilized to solve for the gas permeability. This method uses the measured flow and the injection zone pressure measured by a sensor inside the injection zone. The model is essentially identical to the standard model used for Cone Permeameter™ measurements, except that the source pressure is the injection zone pressure and the source radius is nominally the radius of the injection zone in the rod. Because of this difference in source radius definition, the injection pressure/flow model will result in artificially low calculated permeabilities if compacted soil exists next to the permeameter rod. Table 14 and figure 42 display permeability results that were resolved with the injection zone pressure and flow model.

The second testing location for air permeability measurements was at the 321 M Area tank burial ground. This measurement sequence was more successful with the added knowledge of the pressure sensor response problems. The Cone Permeameter™ was pulled up twice during the measurement sequence, in order to clean the clay from the port recessions. Each time, the permeameter would achieve two to three good measurements before becoming clogged again. Since pulling the probe was a labor and time intensive activity (and schedule constraints were limiting the available time), the remainder of the measurements were completed using the injection pressure and airflow measurement to resolve the air permeability measurements. Table 15 and figure 43 display the results of the air measurements at the 321 M area.

Table 14. Results of the unsaturated zone air permeability measurements performed in the M area, between SEAMIST boreholes MHV-10 and MHV-11.

				Radial Distance from Injection Source (m)					
				0.08	0.15	0.40	0.8		
Depth (ft)	Elapsed Time (s)	Flow (kg/s)	Injection Zone Pressure (Pa)	Port 2 Pressure (Pa)	Port 3 Pressure (Pa)	Port 4 Pressure (Pa)	Port 5 Pressure (Pa)	Inj.Zone/Flow Permeability (Darcies)	Inj.Zone/Flow Permeability (m ²)
30.00	285	3.16E-07	523301	511393	577090	429307	439444	0.0138	1.36E-14
32.00	1203	1.90E-04	463077	147000	155085	120573	124226	0.0137	1.35E-14
33.00	400	1.91E-04	460201	146415	149176	112770	105546	0.0143	1.41E-14
34.00	30	1.90E-04	436334	145641	146733	110203	100724	0.0155	1.53E-14
35.00	298	1.80E-04	176242	142769	140786	108296	97583	0.1531	1.51E-13
36.00	204	1.72E-04	283787	138090	142092	111157	104256	0.0369	3.64E-14
41.00	1504	2.48E-05	562492	150328	145555	138645	96228	0.0012	1.19E-15
44.00	268	1.92E-04	472852	458100	239594	143762	158026	0.0823	8.12E-14
46.00	414	1.75E-04	139269	209477	168232	147491	173933	0.2751	2.71E-13

Figure 42. Area M (between MHV-10 and MHV-11) using the injection zone/flow equation.

Table 15. Results of the unsaturated zone air permeability measurements performed in the 321 M area.

				Radial Distance from Injection Source (m)					
				0.08	0.15	0.40	0.8		
Depth (ft)	Elapsed Time (s)	Flow (kg/s)	Injection Zone Pressure (Pa)	Port 2 Pressure (Pa)	Port 3 Pressure (Pa)	Port 4 Pressure (Pa)	Port 5 Pressure (Pa)	Cone Permeameter™ Permeability (m ²)	Injection Press/ Flow Permeability (m ²)
25.00	329	1.44E-04	478989	106882	190008	107179	96500	6.27E-15	2.60E-14
26.00	205	2.63E-05	519847	86607	229143	84934	80856	6.22E-16	2.15E-14
27.00	404	7.54E-06	532950	87659	227497	84643	79754	1.81E-16	2.63E-15
28.00	449	1.59E-07	532198	86693	106636	86004	86066	N/A	1.92E-14
29.00	453	1.64E-04	475091	86075	86412	85987	85540	N/A	7.14E-13
30.00	453	1.69E-04	475185	85975	86365	86180	86876	N/A	1.01E-13
31.00	902	1.69E-04	308699	85500	85867	85859	85565	N/A	3.15E-12
31.00	703	1.76E-04	413379	99220	99238	99339	99378	N/A	2.51E-14
31.00	141	1.16E-04	468178	284021	265110	87809	88304	1.99E-15	4.71E-15
32.00	359	1.87E-04	180312	147823	86067	85538	84215	2.22E-14	1.54E-13
33.00	285	1.59E-04	467052	198591	198439	86683	86843	5.34E-15	1.96E-14
34.00	147	1.82E-04	106782	85956	84778	86076	86004	N/A	6.30E-16
34.00	283	1.85E-04	315908	93058	93787	92643	92677	N/A	2.96E-14
35.00	199	1.84E-04	221824	86397	86724	86252	87194	N/A	3.37E-15
36.00	251	1.85E-04	223794	86352	86521	86144	86678	N/A	7.35E-16
36.00	225	1.48E-04	358454	86178	85286	86195	86192	N/A	1.10E-15
37.00	652	1.86E-04	261388	85898	86333	85343	86751	N/A	2.17E-13
38.00	173	1.87E-04	348616	86209	86307	86316	86402	N/A	1.36E-13
39.00	504	1.07E-04	469265	219608	160182	94291	93551	6.87E-15	2.09E-13
40.00	170	1.89E-04	214119	154362	134376	86878	85262	5.64E-14	9.15E-14
41.00	204	1.07E-04	439496	85820	74039	84992	82690	N/A	6.67E-14
42.00	155	1.77E-04	177964	85131	84394	85009	83532	N/A	1.65E-14
44.00	103	1.75E-04	156037	85469	85437	85278	85272	N/A	6.73E-14
45.00	99	1.75E-04	174067	85209	85108	84950	84991	N/A	6.77E-14
46.00	173	1.49E-04	352960	84829	84648	84414	84662	N/A	3.95E-15

Figure 43. The permeability vs. depth profiles of the 321 M area.

6.6 Comparison with other Measurement Data

In 1996, well DCB-25 was evaluated using a pump test (Phifer, et al. 1996). Nearby monitoring wells DCB-24A, DCB-24B, and DCB-24C were used to calculate the saturated hydraulic conductivity. A borehole flowmeter test during the pumping of well DCB-25 was used to characterize the borehole production at 1 ft intervals. The pump tests resulted in saturated hydraulic conductivities (horizontal) ranging from $5.9\text{E-}5$ to $1.1\text{E-}3$ cm/s, depending on the monitor well used. The bulk conductivity data was combined with borehole flowmeter data to develop a profile of the conductivity vs. depth on 1 ft. intervals. The Cone PermeameterTM data is plotted in figure 44, compared with the previous borehole flowmeter tests in DCB-25. Borehole flowmeter data for both the high ($1.1\text{E-}3$ cm/s) and low ($5.9\text{E-}5$ cm/s) bulk conductivity cases are plotted, indicating the range of uncertainty in the borehole flowmeter data. The Cone PermeameterTM data generally falls between the high and low conductivity values.

The air permeability measurements obtained at both the Integrated Demonstration site and the 321 M area were typically less than 1 Darcy, and in most cases less than 0.1 Darcy. The only discrete permeability measurement data reviewed was from SEAMISTTM air permeability measurements obtained in 1992 (letter report to Dr. Carol Eddy-Dilek, Aug. 20, 1992, Bill Lowry, Science and Engineering Associates). These measurements resulted in air permeabilities higher than 4 Darcies for almost all measurements. In the upper regions of the MHV-10 and MHV-11 boreholes the permeabilities tended to drop as the depth decreased, and in the 30 to 39 ft. depth regions were 5 Darcies or below (never less than 3 Darcies). The Cone PermeameterTM measurements taken in these regions ranged from 0.01 to 0.15 Darcies, and similar ranges were measured in the 321 M area. The MHV-10 and MHV-11 measurements were obtained using the injection pressure/flow relationship, therefore, the results may be indicating artificially low permeabilities. It is also likely that the SEAMISTTM measurements indicated artificially high permeabilities due to the uncertainty of the quality of the membrane seal to the borehole wall. If quantitative measurements are required in these areas independent measurements should be obtained for comparative purposes.

6.7 Integration with Other Tools

ARA acquired standard CPT geophysical measurements in conjunction with the Cone PermeameterTM tests. This dual technique proved to be very useful. Since the geophysical instrument was located in the tip of the cone, it provided a forecast of the media the injection zone and pressure ports would be traveling through. Figures 45, 46, and 47 display the results of the geophysical and permeability tests at the three sites tested. A positive correlation exists between the data sets (i.e., the permeability was higher in sand layers than in areas composed of clay and silt).

Figure 44. Comparison of Cone Permeameter™ saturated hydraulic conductivity measurements with minimum and maximum values obtained in previous borehole flowmeter measurements.

Figure 45. CPT cone and Cone Permeameter™ measurements taken near DCB -25.

Applied Research Associates South Royalton, VT 05068 802-763-8348 Email: CPT@ara.com http://www.ara.com	Northing: Easting: Elevation:	Date: 04/28/98 Test ID: PERM-03 Project: 4606
	Client: Sience & Engineering Associates, Inc. Site: SRS, M-AREA Integrated Demo Site

Figure 46. CPT cone and Cone Permeameter™ measurements taken between MHV-10 and MHV-11.

Applied Research Associates South Royalton, VT 05068 802-763-8348 Email: CPT@ara.com http://www.ara.com	Northing: Easting: Elevation:	Date: 04/30/98 Test ID: PERM-04 Project: 4606
	Client: Sience & Engineering Associates, Inc. Site: SRS, M-AREA 321 Tank Storage Area

Figure 47. CPT cone and Cone Permeameter™ measurements taken at the 321 M Area.

7. COST EFFECTIVENESS OF THE CONE PERMEAMETER™ MEASUREMENT SYSTEM

7.1 Baseline Technologies Comparison

Soil gas permeability and hydraulic conductivity are conventionally either measured in-situ through boreholes or wells, or on core samples at a laboratory. Generally, in-situ techniques are preferred for large-scale analysis due to the potential for hydrogeologic heterogeneity. Alluvial materials consisting of interbedded deposits can be particularly variable, both in vertical and horizontal directions. Measurements of transport properties such as hydraulic conductivity are more variable than retention properties such as water content (Jury 1991). Therefore, to properly characterize the soil gas permeability and hydraulic conductivity of an alluvial environment the spatial resolution capability of each measurement technique should be considered.

7.2 Laboratory Analysis

Common laboratory methods which directly measure soil air permeability and hydraulic conductivity include Constant Head Test, Falling Head Test, UFA Method, and Permeability of Rocks by Flowing Air Method; indirect measurement can be made by Permeability Estimates Using Empirical Relationships of Soil Properties. Brief discussion of these techniques is found in the Phase I topical report (Lowry, Mason, and Merewether 1997).

Direct measurement of transport properties in the laboratory is performed with a permeameter device. The basic design consists of a sample holding device capable of retaining the sample for pressure and flow measurement without altering the physical properties of the matrix. Permeameter devices require samples to be contained in six-inch brass sleeves or equivalent. Analysis consists of applying a vertical gradient across the length of the sample, monitoring the flow and pressure at both ends of the sample, and applying Darcian flow equations to determine transport properties along the axis of the core. Laboratory permeameter devices have been designed to accommodate specific matrices with unique physical properties such as rigid rock or loose sediments. The accuracy of all the laboratory analyses is highly sensitive to the integrity of the sample; therefore sample collection should be performed in a manner which minimizes alteration to the structure and matrix properties (Springer 1995). Permeameter devices typically only measure the transport properties along the axis of the sample and therefore are limited in characterizing sites with highly stratified or interbedded soils.

The transport properties of nonindurated sediments can also be characterized by the relationship between grain size and permeability (Shepherd 1989). This method requires grain size analysis (ASTM D422-63) of field collected samples and is only effective for relatively high permeability unconsolidated homogeneous soils.

The scale at which transport properties are analyzed in the laboratory is small compared to the scale at which the soil gas permeability and hydraulic conductivity can be considered constant. The effects of field scale features such as macro pores, fractures,

and soil structure may not be adequately characterized by laboratory scale samples. In response to these limitations multiple samples distributed across the site can be measured and averaged to estimate site transport properties. The variability of the measurements should also be characterized to display the validity of any site wide estimates of transport properties.

7.3 Field Testing

Common methods for field techniques for measuring transport properties of porous media include drawdown tests, slug tests, and pneumatic packer tests. Brief discussion of these techniques is found in the Phase I topical report (Lowry, Mason, and Merewether 1997).

The methodology of these techniques consists of measuring the potential field response to controlled injection or extraction, of air or water, and applying Darcian flow equations to determine the effective hydraulic conductivity or soil air permeability. Tests are conducted within stable boreholes, established either within indurated material, or with an appropriate cased well design.

Drawdown tests, slug tests, and pneumatic packer tests measure effective transport properties on different scales. Drawdown tests measure the effective transport properties between an observation well and an extraction well; slug tests measure the effective transport properties in the immediate vicinity of the test well; and packer tests measure the effective transport properties across a pneumatically sealed interval. Therefore the hydrogeologic heterogeneity of a site can be best characterized with the appropriately scaled method.

7.4 Cost Comparison

Table 20 shows a cost comparison utilizing standard methods of characterizing the transport properties of porous media. The cost of each option was estimated for the task of characterizing the initial 50 feet of alluvial material at a site with ground water present at 25 feet below ground surface. The options represent different levels of effort and resolution scales for transport property characterization at the site. Mobilization, permitting, and waste management costs are not considered. Costs of conventional measurement techniques were obtained by soliciting quotes from laboratories and contractors who perform the services, and are not escalated for use at DOE sites.

Option 1 utilizes drawdown testing in both the saturated and unsaturated zones. This option requires construction of two pairs of wells for each zone, consisting of an extraction well and a monitoring well. The primary advantage of this option is it's ability to measure the effective transport properties through the vertical and horizontal heterogeneity expected in interbedded and/or stratified alluvial deposits. Geologic logs of the wells would provide qualitative characterization of the extent and scale of these features. Option 1 is the most expensive due to the relatively high costs of well construction. Well construction costs may be offset if utilized for future environmental remediation by soil vapor and/or water extraction. Additional and significant waste

management costs may result if contaminated water or soil vapor is extracted during testing. These costs may be avoided by switching to an injection system for similar cost and comparable characterization.

Option 2 consists of performing pneumatic packer testing of both the saturated and unsaturated zones in a single well. The construction of the well through the unsaturated zone would consist of screened intervals with an appropriate sand pack for packer measurements, alternating with sealed intervals such as bentonite plug. The saturated zone of the well should be constructed with screened casing and sand pack with a conductivity not divergent from that of the matrix. Packer measurements would be made at five-foot intervals throughout the well. The benefits of Option 2 include the characterization of the effective soil air permeability and hydraulic conductivity, and their variability with depth. This option's capability to characterize lateral heterogeneity such as discontinuous clay lenses is dependent on the number and distribution of wells. The cost of Option 2 (\$5,400) is low relative to Option I (\$14,000), however at large sites or at sites with extensive lateral heterogeneity additional wells would be necessary for proper characterization and the costs would be more equivalent.

Option 3 includes performing an aquifer slug test and laboratory analysis of core samples from the unsaturated zone. This option is the least expensive of the conventional techniques (\$3,750) and provides the most limited characterization of soil air permeability and hydraulic conductivity. Option 3 would be most cost effective at relatively small hydrogeologically homogeneous sites. Like Option 2, its capability to characterize lateral heterogeneity is dependent on the number and distribution of wells. Additionally, the validity of laboratory analysis is limited by the ability to collect undisturbed core samples. Collecting valid core samples in loose alluvial material is difficult and often requires sample recompaction. Option 3's characterization of the effective soil air permeability would be at best qualitative under these conditions.

The cost of performing one day of Cone PermeameterTM measurements is also listed on table 16. Under the conditions of the three cost comparison options, 40 soil air permeability and/or hydraulic conductivity measurements could be made for a cost of \$2,550 in a single day. These measurements could be distributed throughout the site or be performed in a single location. It is important to note that in the course of performing these measurements the standard suite of CPT geophysics measurements would also be obtained.

Table 16. Cost comparison of Cone Permeameter™ measurements compared with conventional techniques.

Option 1: Perform aquifer drawdown test and soil vapor extraction test	
Task	Cost
Drill and construct ground water extraction well	\$3,500
Drill and construct ground water observation well	\$1,500
Conduct aquifer drawdown test and data analysis	\$2,500
Drill and construct soil vapor extraction well	\$1,500
Drill and construct soil vapor observation well	\$1,000
Conduct soil vapor extraction test and data analysis	\$4,000
Total	\$14,000
Option 2: Perform aquifer slug test and perform laboratory analysis of core for soil air permeability	
Task	Cost
Drill and construct temporary monitoring well, collect core samples at 5' intervals for first 25'	\$1,500
Perform slug test and data analysis	\$1,000
Perform laboratory analysis of core for soil air permeability (\$250/sample)	\$1,250
Total	\$3,750
Option 3: Perform packer tests in saturated and unsaturated zone	
Task	Cost
Drill and construct monitoring well with screened intervals in the saturated and unsaturated zones	\$4,200
Perform 10 packer tests at 5 foot intervals (\$120/test)	\$1,200
Total	\$5,400
Cone Penetrometer testing of saturated and unsaturated zone	
Task	Cost
Push and perform approximately 40 measurements in one working day (cost reflects daily cost of CPT truck with 2 operators)	\$2,550
Total	\$2,550

8. PROPOSED PHASE III ACTIVITIES

The Phase II testing completed at the Savannah River Site demonstrated the measurement capability of the Cone PermeameterTM in alluvial saturated and unsaturated soils. The clays at SRS posed unique challenges to the measurement system, due to their extremely low permeability and their tendency to plug pressure measurement ports. Some of these problems were overcome by altering the testing procedures (such as constantly injecting water during penetrometer pushes through clay in the saturated zone to preclude plugging of the injection screen). Fabricating them in a configuration that will not allow accumulation of clay over the filter material can reduce plugging of the pressure measuring ports. Minor design changes will be incorporated to address these two problems, prior to execution of the Phase III demonstration program.

Phase III field tests are intended to demonstrate and evaluate the modified Cone PermeameterTM system in environments different from the Phase II tests. These tests will include measurements in both the saturated and unsaturated zones, preferably at different DOE or federal sites. Likely sites, due to the potential for successful direct push applications and need for permeability data, include Hanford, Brookhaven National Laboratory, and Cape Canaveral. These and others sites will be evaluated in the process of planning for the Phase III effort.

It is anticipated that at the completion of the Phase III activities the Cone PermeameterTM system will be available for commercial use.

9. SUMMARY AND RECOMMENDATIONS

This effort designed, fabricated, and field tested the engineering prototype of the Cone Permeameter™ system. The integrated system includes the instrumented penetrometer probe, air and water pumps, flowrate controls, flow sensors, and a laptop-controlled data system. All of the equipment is portable and can be transported as luggage on airlines.

The data system acquires and displays the process measurements (pressures, flows, and downhole temperature) in real time and calculates the resulting permeability. The measurement probe is a 2" diameter CPT rod section, incorporating a screened injection zone near the lower end of the rod and multiple sensitive absolute pressure sensors embedded in the probe at varying distances from the injection zone.

Laboratory tests in a large test cell demonstrated the system's ability to measure nominally 1 Darcy permeability soil (30 to 40 Darcy material had been successfully measured in the Phase I effort). These tests also provided a shakedown of the system and identified minor instrument problems, which were resolved.

Supplemental numerical modeling was conducted to evaluate the effects of layered permeability (heterogeneity) and anisotropy on the measurement system's performance. The general results of the analysis were that the Cone Permeameter™ could measure accurately, in heterogeneous media, the volume represented by the sample port radii if the outer pressure ports were used. Anisotropic permeability, while readily analyzed numerically, is more complicated to resolve with the simple analytical approach of the 1-D model, and will need further work to quantify.

This phase culminated in field demonstrations at the DOE Savannah River Site. Saturated hydraulic conductivity measurements were completed at the D-Area Coal Pile Runoff Basin, and air permeability measurements were conducted at the M Area Integrated Demonstration Site and the 321 M area. The saturated hydraulic conductivity measurements were the most successful and compared well to relevant existing data. Air permeability measurements were more problematic, primarily due to clay covering pressure measuring ports and preventing pressure communication with the sensors. Very little discreet air permeability data existed for the sites.

Lessons learned include:

- During saturated measurements in clay rich soil, water should be injected continuously during the penetrometer push to prevent clay and silt from filling and plugging the injection zone.
- Frequently, in measurements above the water table, clay was encountered that caused high pore pressure accumulations during the CPT push. This occurs when the clay is at or very near water saturation. The CPT rod displaced pore space available for air flow. In these regions it is virtually impossible to obtain air permeability measurements because the clay is essentially impermeable to air flow, and prevents pressure communication to the sensors.

- In the saturated zone, if high pore pressures accumulate and dissipate slowly, it may not be effective to measure with the standard Cone PermeameterTM method. The pore pressure dissipation technique is more suitable for regions of such low permeability.

The Cone PermeameterTM integrated well with CPT operations. The probe was designed to allow concurrent measurements with the standard geophysical cone sensors (tip pressure, sleeve stress, pore pressure), and this capability was demonstrated in the field tests. Permeability measurements require periodically stopping at the selected depths for 3 to 10 minutes to perform the test.

The field conditions for which this technique is most suitable include saturated and unsaturated media with little or no clay. Saturated tests in clayey soils, as demonstrated at the Coal Pile Runoff Basin can be successful if excessive pore pressure accumulation does not occur. Air permeability tests in clay soils can be successful if the moisture content is low and plugging of the pressure ports can be avoided. The current system is capable of measuring in the milliDarcy to tens of Darcy range in both saturated and unsaturated soils.

Recommended changes to the Cone PermeameterTM system include:

- Redesigning the pressure port filters to prevent plugging with clay. This will be accomplished by designing the filter material to be flush with (or extend beyond) the rod surface, and experimenting with different filter porosities.
- Problems with the air flow sensor will be avoided by providing the air line with its own dedicated outlet, to avoid moisture backing into the air flow sensor.

10. ACKNOWLEDGMENTS

The authors wish to acknowledge the support of several individuals key to the success of this project. Karen Cohen, the FETC technical manager, has been highly supportive over the course of the entire project. Mike Serrato and Bill Jones of the Savannah River Site were key to organizing the site demonstrations, taking care of the logistics, and supporting the field operations. Glenn Bastiaans of the CMST program has facilitated reviews and program interactions. And finally, Applied Research Associates, Inc. did an excellent job of designing the probe and conducting the Cone PermeameterTM pushes at the field demonstrations. We thank Wes Bratton, Chris Bianchi, and the ARA Savannah River Site CPT truck operators.

11. APPENDIX: PERMEABILITY MEASUREMENT MODEL

Quantitative in-situ permeability measurements (gas or liquid) are typically conducted in boreholes using a cylindrical flow model and geometry. Long screened or uncased sections of the borehole are subjected to pressure gradients and the resultant flow into or out of the well is measured to infer the soil permeability. For one-dimensional radial symmetric (cylindrical) flow geometries such as these, the test region is relatively long and a radius of influence is either measured or assumed to determine permeability. This approach results only in an average permeability over the test region, and cannot delineate stratigraphic features within the test region.

A spherical flow geometry, on the other hand, can provide a detailed log of permeability as a function of depth. This is because its region of influence is relatively small (measured in fractions of a meter versus meters for the cylindrical model), allowing discrete measurements at high resolution in boreholes. This approach is typically applied using inflatable packers in uncased boreholes to isolate a test zone, where air is injected or extracted to apply the pressure gradient.

For this project the spherical flow geometry is applied to the Cone Permeameter™ and other direct push deployment systems. This model is well suited to direct push applications:

- Because its region of influence is small and discrete, the amount of fluid injected into (or extracted from) the test region is small. This is important because of the limited space inside penetrometer rods for fluid transfer lines.
- The method does not require a long time period to reach a steady state condition. This allows multiple measurements in relatively short periods of time providing high spatial resolution.
- The test geometry is constructed such that the compaction of soil adjacent to the rod, caused by the penetrometer emplacement, has minimal impact on the inferred permeability.

The basic premise of this approach is that as fluid is injected (or extracted) from a discrete section of the penetrometer string, it will tend to result in a spherical flow field as the fluid moves outward from the rod (see the conceptual schematic in figure A1). The flow field will become essentially spherical even if the soil adjacent to the rod is of a much lower permeability (due to compaction). Eventually, for a given injection rate, the radial pressure profile along the axis of the penetrometer rod is identical to that which would occur if the rod (and compacted soil) did not exist. Measurement of the pressure gradient at a distance from the injection point produces adequate information to accurately infer the permeability.

The following derivation applies to liquid and vapor flow under one-dimensional spherical flow geometry. Parameters and units of usage are listed in table A1, and the flow geometry is depicted in figure A2. The injection or extraction source is represented as a spherical volume with radius r_0 . Fluid is added (or removed) from the zone at a known rate. The medium has a permeability, k , which is assumed homogeneous. At some distance r_∞ the pore fluid pressure is at ambient conditions (P_A).

Figure A1. Schematic of spherical flow geometry resulting from fluid injection.

Table A1. Parameters and units.

Parameter	Description	Units
u	fluid flux (flow per unit area)	m/s ($\text{m}^3/\text{m}^2\text{-s}$)
k	permeability	m^2 (1 Darcy = $9.87 \times 10^{-13}\text{m}^2$)
μ	dynamic viscosity	$\text{N}\cdot\text{s}/\text{m}^2$ (dyne-s)
Δx	thickness of media	m
p_o	source pressure	Pa (N/m^2)
P	pressure at radial position r	Pa (N/m^2)
$\bar{R}$	Gas constant	
r_o	Inner radius of cylindrical or spherical flow volume	m
r	Radial position outward from r_o	m
ρ	Fluid density	kg/m^3
$\dot{m}$	Mass flow of fluid across flow area A	kg/s
A	Flow area	m^2

Figure A2. Conceptual flow field of penetrometer permeability measurement configuration

Darcy's law defines the steady state volumetric flow rate per unit area (u , also known as the Darcy velocity) in a one-dimensional geometry as

$$u = \frac{-k}{\mu} \frac{dp}{dx} \quad (\text{Eq. A1})$$

where dp/dx is the applied pressure gradient causing the flow, k is the permeability of the medium and μ is the dynamic viscosity of the fluid. For one-dimensional flow, the volumetric flow rate Q over the entire area of interest is

$$Q = \int_A u \cdot dA = - \int_A \frac{k}{\mu} \cdot \frac{dp}{dx} \cdot dA \quad (\text{Eq. A2})$$

The mass flow rate can then be determined as

$$\dot{m} = - \int_A \rho \cdot \frac{k}{\mu} \cdot \frac{dp}{dx} \cdot dA \quad (\text{Eq. A3})$$

To apply this in the measurement of effective soil gas permeability, the derivation considers gas flow in the accessible porosity of the soil. For an ideal compressible gas the equation of state can be written as

$$\rho = \frac{P}{RT} \quad (\text{Eq. A4})$$

where R is the gas constant (the universal gas constant divided by the gas molecular weight, $\bar{R}/mw$), and T is the absolute temperature. Substitution of equation A4 into equation A3 yields

$$\dot{m} = - \int_A \frac{k}{\mu RT} \cdot \frac{dp}{dx} \cdot dA \quad (\text{Eq. A5})$$

For one-dimensional spherical flow, dp/dx can be replaced by dp/dr . The area of integration is over a sphere and is equal to $4\pi r^2$. Thus, integrating equation A5 gives

$$\dot{m} = - \frac{4\pi k}{\mu RT} \cdot \frac{r^2}{dr} \cdot p dp \quad (\text{Eq. A6})$$

Separation of variables gives

$$\int_{r_0}^r \dot{m} \frac{dr}{r^2} = \frac{-4\pi k}{\mu RT} \int_{P_0}^P p dp \quad (\text{Eq. A7})$$

where P_0 is the pressure at the source location r_0 and P is the pressure at some distance r . Integration of equation A7 results in

$$\dot{m} \left(\frac{1}{r_0} - \frac{1}{r} \right) = \frac{-2\pi k}{\mu RT} \bullet (P^2 - P_0^2) \quad (\text{Eq. A8})$$

Solving for k yields

$$k = \frac{\mu RT \dot{m}}{2\pi (P_0^2 - P^2)} \bullet \left(\frac{1}{r_0} - \frac{1}{r} \right) \quad (\text{Eq. A9})$$

As r gets very large with respect to r_0 , the pressure approaches ambient P_A and equation 8 can be written as

$$k = \frac{\mu RT \dot{m}}{2\pi r_0 (P_0^2 - P_A^2)} \quad (\text{Eq. A10})$$

A similar derivation is used for saturated hydraulic conductivity measurements with the spherical geometry. The only difference in this case is that the fluid density (ρ) is constant, instead of pressure dependent. Equation A3 is restated

$$\dot{m} = - \int \rho \bullet \frac{k}{\mu} \bullet \frac{dp}{dx} \bullet dA \quad (\text{Eq. A3})$$

Since ρ is constant, integrating over the surface of a sphere ($A=4\pi r^2$) gives

$$\dot{m} = \frac{4\pi k \rho}{\mu} \bullet \frac{r^2}{dr} \bullet dp \quad (\text{Eq. A11})$$

Separation of variables gives

$$\int_{r_0}^r \dot{m} \frac{dr}{r^2} = \frac{-4\pi \rho}{\mu} \int_{P_0}^P dp \quad (\text{Eq. A12})$$

where P_O is the pressure at the source location and P is the pressure at some radial distance r . Integrating equation A12 results in

$$\dot{m} \left(\frac{1}{r_O} - \frac{1}{r} \right) = \frac{-4\pi k \rho}{\mu} (P - P_O) \quad (\text{Eq. A13})$$

Solving for k gives

$$k = \frac{\mu \dot{m} \left(\frac{1}{r_O} - \frac{1}{r} \right)}{4\pi \rho (P - P_O)} \quad (\text{Eq. A14})$$

12. REFERENCES

- Falta, Pruess, Finsterle, Battistelli. 1995. *T2VOC User's Guide*. LBL 36400. Berkeley, CA: Lawrence Berkeley National Laboratory.
- Jury, William A., Wilford R. Gardner, and Walter H. Gardner. 1991. *Soil Physics*. 5th ed. New York: John Wiley & Sons.
- Lowry, William, Neva Mason, and Dan Merewether. "In-Situ Permeability Measurements with Direct Push Techniques: Phase I Topical Report." SEASF-TR-96-147. Science and Engineering Associates, Santa Fe, NM.
- Phifer, M. A., F. C. Sappington, B. E. Pemberton, and R. L. Nichols. 1996. "Interim Report: D-Area Interceptor Well, DIW-I Water Table Aquifer (U)." Westinghouse Savannah River Co., Aiken, SC.
- Rust Environment & Infrastructure, Inc. 1996. "Mag*Sep Demonstration Drilling, Abandonment, and Well Installation." Report to Savannah River Technology Center. Subcontract C001014P - Task Order Assignment 21. Rust Environment & Infrastructure, Inc., Aiken, SC.
- Shepherd, Russel G. 1989. "Correlations of Permeability and Grain Size." *Ground Water* 27, no. 5 (September-October): 633-38.
- Springer, David S., Stephen J. Cullen, and Lorne G. Everett. 1995. "Laboratory Studies on Air Permeability." In *Handbook of Vadose Zone Characterization and Monitoring*, ed. L. G. Wilson, Lorne G. Everett, and Stephen J. Cullen, 217-47. Boca Raton, FL: Lewis Publishers.