2

FEB 28 1994
OSTI

IN SITU TESTING TO DETERMINE FIELD-SATURATED CONDUCTIVITY OF UMTRA PROJECT DISPOSAL CELL COVERS, LINERS, AND FOUNDATION AREAS

SPECIAL STUDY

February 1994

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.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

875

INTENDED FOR PUBLIC RELEASE

This report has been reproduced from the best available copy. Available in paper copy and microfiche.

Number of pages in this report: 172

DOE and DOE contractors can obtain copies of this report from:

**Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
(615) 576-8401**

This report is publicly available from:

**National Technical Information Service
Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650**

**IN SITU TESTING TO DETERMINATION
FIELD-SATURATED HYDRAULIC CONDUCTIVITY
OF UMTRA PROJECT DISPOSAL CELL COVERS,
LINERS, AND FOUNDATION AREAS**

SPECIAL STUDY

February 1994

**Prepared for
U. S. Department of Energy
UMTRA Project Office
Albuquerque, New Mexico**

**Prepared by
Jacobs Engineering Group Inc.
Albuquerque, New Mexico**

EXECUTIVE SUMMARY

This special study was conducted to prepare a guidance document for selecting *in situ* hydraulic conductivity (K) tests, comparing *in situ* testing methods, and evaluating the results of such tests. This report may be used as a practical decision-making tool by the Uranium Mill Tailings Remedial Action (UMTRA) Project staff to determine which testing method will most efficiently achieve the field-saturated K results needed for long-term planning.

A detailed section on near-surface test methods discusses each method which may be applicable to characterization of UMTRA disposal cell covers, liners and foundation materials. These potentially applicable test methods include the sealed double-ring infiltrometer (SDRI), the air-entry permeameter (AEP), the guelph permeameter, the two-stage borehole technique (TSB), the pressure infiltrometer, and the disk permeameter. Analytical solutions for these methods are provided, and limitations of these solutions are discussed, and a description of testing equipment design and installation are provided.

This special study also examines applicable regulations and American Society for Testing and Materials (ASTM)-approved technical standards for testing. The regulations that refer to *in situ* testing for the UMTRA Project are not specific; the U.S. Department of Energy (DOE) is responsible for determining protocols for *in situ* testing when it is required by sound technical judgment. In addition, only two ASTM-approved test methods are available to assist in determining K for covers and liners; the SDRI and open double-ring infiltrometer (ODRI) methods. Of these two methods, only the SDRI ASTM method is applicable to UMTRA Project disposal cells because determination of hydraulic conductivities of less than 10^{-6} centimeters per second (cm/s) are generally required.

This special study also discusses why *in situ* testing is perceived to be necessary, the possible roles that laboratory testing should play in overall testing programs, and considerations to make when testing covers or liners versus foundation materials.

Using information obtained from the analysis of each method, and in-depth interviews with several internationally recognized experts, the SDRI and AEP were found to be best suited for determination of field-saturated vertical K of low-K materials. However, the AEP, because of its shorter test times (1 week to 1 month), should be used in situations where materials being tested (i.e., bedrock) are highly heterogeneous.

None of the methods examined in this report are well suited for testing highly heterogeneous materials (i.e., bedrock). In fact, because the assumptions of homogeneity and isotropy are inherent in their application, precise values of K are generally not attainable. Therefore, the more rapid AEP method will save time and money for equally reliable results and is recommended.

The use of the AEP instead of the SDRI method is supported by recent work performed at the Rifle (Estes Gulch) disposal cell. This testing indicated that the SDRI and AEP methods are capable of providing results that are in close agreement, but that AEP tests were conducted much more cost effectively.

In general, SDRI tests should be used only to test well constructed (relatively homogeneous) clay cover and liner test pads when schedule and budget constraints will not be impacted.

It is recommended that the pressure infiltrometer developed by Reynolds and Elrick (1993), which is similar in design to the AEP and accounts for capillarity and divergence of flow from the inner ring, be tested along with the AEP or SDRI method as soon as possible.

Although this report primarily discusses near-surface testing, a general discussion of moderate-to-deep test methods is included. Moderate-to-deep test methods discussed include the BAT (after its developer, B. A. Tortstenson) probe and the constant-head borehole permeameter.

Past *in situ* testing of cell foundation materials on the UMTRA Project was assessed through examination of the testing performed at the Cheney and Rifle disposal sites. In general, the evaluation indicated that better quality planning may be necessary to meet future data quality objectives relative to K testing.

To gain insight into the way other projects are handling the problems associated with testing of liners, covers and foundation materials, U.S. Nuclear Regulatory Commission (NRC) representatives of the Title II program in Denver, Colorado, were questioned on their protocol. However, the NRC reports they do no *in situ* testing on these materials. NRC attributes this lack of concern over verifying K to the fact that Title II sites have been monitored for 40 to 50 years. Because of this long monitoring period, NRC considers Title II sites living models. The NRC reported that bathtubbing has never been a problem at Title II sites. After clay caps are constructed on the tailings piles, water levels in the piles and contaminant concentrations in surrounding wells continue to diminish with time. This Title II "observational" approach appears to be practical, and is worthy of further detailed investigation.

If conditions encountered at UMTRA Project sites continue to require detailed *in situ* testing of cell covers, liners, and foundation materials, formal data quality objectives should be developed to make the overall testing more efficient and consistent.

TABLE OF CONTENTS

Section	Page
1.0 INTRODUCTION	1-1
1.1 Purpose and objectives	1-1
1.2 Scope	1-1
1.3 Approach	1-2
2.0 COVER, LINER, AND FOUNDATION TESTING REQUIREMENTS FOR DETERMINATION OF FIELD-SATURATED HYDRAULIC CONDUCTIVITY	2-1
2.1 Historical relationship between regulatory and technical standards for <i>in situ</i> testing	2-1
2.2 Applicable regulatory standards for tailings disposal at UMTRA sites	2-1
2.3 Approved technical standards for determination of field-saturated hydraulic conductivity	2-2
3.0 TESTING RATIONALE	3-1
3.1 Why conduct <i>in situ</i> tests?	3-1
3.2 What role should laboratory testing play?	3-2
4.0 APPLICABLE <i>IN SITU</i> TEST METHODS TO DETERMINE FIELD-SATURATED HYDRAULIC CONDUCTIVITY	4-1
4.1 Present state of the art for <i>in situ</i> testing to determine field-saturated hydraulic conductivity	4-1
4.2 Testing considerations for cell covers versus liners and foundation materials	4-1
4.2.1 Physical considerations	4-1
4.2.2 Chemical considerations	4-2
4.3 Near-surface test methods potentially applicable to the UMTRA Project	4-3
4.3.1 Sealed double-ring infiltrometer	4-3
4.3.2 Air-entry permeameter	4-8
4.3.3 Guelph permeameter	4-11
4.3.4 Two-stage borehole technique	4-14
4.3.5 Constant head pressure (single-ring) infiltrometer method	4-18
4.3.6 Disc permeameter/tension infiltrometer	4-21
4.4 Moderate-to-deep test methods potentially applicable to the UMTRA Project	4-24
4.4.1 BAT permeameter (probe)	4-24
4.4.2 Constant head borehole permeameter	4-25
4.5 Results of expert interviews	4-26
5.0 HISTORICAL UMTRA TESTING TO DETERMINE FIELD-SATURATED HYDRAULIC CONDUCTIVITY	5-1
5.1 Cheney disposal site	5-1

TABLE OF CONTENTS (Concluded)

<u>Section</u>	<u>Page</u>
5.1.1 Testing background	5-1
5.1.2 Testing evaluation	5-1
5.2 Rifle disposal site	5-3
5.2.1 Testing background	5-3
5.2.2 Testing evaluation	5-3
5.3 Summary of observations upon review of historical UMTRA Project testing to determine field-saturated hydraulic conductivity	5-6
6.0 <i>IN SITU</i> TESTING OF CELL COVERS, LINERS, AND FOUNDATIONS AT TITLE II SITES	6-1
6.1 Technical differences between Title I and Title II disposal sites	6-1
6.2 Title II perspective regarding <i>in situ</i> testing at uranium mill tailings disposal site	6-1
7.0 PRACTICAL GUIDELINES FOR <i>IN SITU</i> TEST SELECTION IN THE DETERMINATION OF FIELD-SATURATED HYDRAULIC CONDUCTIVITY OF NEAR-SURFACE MATERIALS ON THE UMTRA PROJECT	7-1
8.0 SUMMARY AND CONCLUSIONS	8-1
9.0 LIST OF CONTRIBUTORS	9-1
10.0 REFERENCES	10-1
APPENDIX A LIST OF AVAILABLE REFERENCES IN DOCUMENT CONTROL, UMTRA PROJECT OFFICE, ALBUQUERQUE, NEW MEXICO	
✓ APPENDIX B AMERICAN SOCIETY FOR TESTING AND MATERIALS METHODS	
APPENDIX C RIFLE FIELD PHOTOGRAPHS	
APPENDIX D INTERVIEWS	

✓ Reports removed

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
4.1 Sealed double-ring infiltrometer	4-4
4.2 Air-entry permeameter	4-9
4.3 Guelph permeameter	4-12
4.4 Two-stage borehole permeameter	4-15
4.5 Pressure infiltrometer	4-19
4.6 Disc permeameter	4-23
5.1 SDRI and AEP K_{fs} testing results at Rifle, Colorado (Estes Gulch), disposal cell site	5-5

LIST OF TABLES

<u>Table</u>	<u>Page</u>
5.1 K_{fs} testing results at Estes Gulch disposal cell (cm/s) (October 1992 - February 1993)	5-4
7.1 Practical guidelines for <i>in situ</i> K_{fs} test selection for near-surface materials on the UMTRA Project	7-2

LIST OF ACRONYMS AND ABBREVIATIONS

<u>Acronym</u>	<u>Definition</u>
AEP	air-entry permeameter
ASTM	American Society for Testing and Materials
cm/s	centimeters per second
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
I	infiltration
K	hydraulic conductivity
K_f	field-tested hydraulic conductivity
K_{fs}	field-saturated value of K
K_L	laboratory-tested hydraulic conductivity
K_v	vertical hydraulic conductivity
L	depth to the wetting front
m	meter
m^2	square meter
MK-ES	Morrison Knudsen-Environmental Services
NRC	U.S. Nuclear Regulatory Commission
ODRI	open double-ring infiltrometer
QA	quality assurance
SDRI	sealed double-ring infiltrometer
SHB	Sergeant, Hauskins & Beckwith
TAC	Technical Assistance Contractor
TSB	two-stage borehole technique
UMTRA	Uranium Mill Tailings Remedial Action
UMTRCA	Uranium Mill Tailings Radiation Control Act
UPDCC	UMTRA Project Document Control Center
USDA	U.S. Department of Agriculture

1.0 INTRODUCTION

1.1 PURPOSE AND OBJECTIVES

The objective of this special study is to prepare a guidance document for selecting and specifying *in situ* permeability tests, comparing *in situ* testing methods, and evaluating the results of such tests. This report may be used as a practical decision-making tool by the Uranium Mill Tailings Remedial Action (UMTRA) Project staff to determine which testing method will most efficiently achieve the field-saturated hydraulic conductivity (K) results needed for long-term planning.

Hydraulic conductivity (K) is one of several hydraulic properties that control the infiltration rate of water through disposal cell covers and cell foundations. An accurate estimation of K is an important factor in the long-term performance and management of UMTRA Project tailings disposal cells.

The K of unsaturated materials is lower than those of saturated materials. To conservatively estimate K, saturated conditions are assumed and *in situ* tests are performed to determine the field-saturated value of K (K_{fs}).

Recently, there have been questions regarding which test methods are most efficient and accurate for determining *in situ* field-saturated K at UMTRA sites.

Excessively slow permeability testing work can seriously impact project budgets and also may cause construction schedule difficulties. However, if fast but inappropriate permeability testing is done, the additional expenses to repeat or substitute alternative testing methods can also cause considerable difficulty. This special study report should help UMTRA Project personnel avoid these problems.

1.2 SCOPE

The primary scope of work of this special study includes:

- Literature study of current techniques for the determination of *in situ* field-saturated K.
- Interviews with experts in the field and individuals who are uniquely qualified to comment on past UMTRA testing.
- Discussion of applicable regulatory and technical standards for *in situ* testing in relation to the UMTRA Project.
- Review and/or analysis of test results from recent investigations at the Cheney disposal cell in Grand Junction, Colorado, and at the Estes Gulch disposal cell in Rifle, Colorado. Testing protocol at UMTRA sites will be compared with protocol at non-UMTRA disposal cell sites.

- Discussion of analytical solutions and their limiting assumptions (i.e., discussion of the flow field involved in each type of test).
- Discussion of applications for each test method, limitations of each test, and how to perform each test.
- Discussion of practical guidelines for *in situ* test selection in determining field-saturated hydraulic conductivity on the UMTRA Project.
- Preparation of a report containing the preceding items.

1.3 APPROACH

Due to variation in testing techniques and rapid evolution of current ideas regarding *in situ* testing of cell foundations and covers, this special study includes an extensive literature review, interviews with experts in the field, and interviews with individuals who are qualified to comment on past UMTRA Project testing activities and testing guidelines. Because research in this field has been most active for the past 15 years and many of the individuals who have designed testing equipment and/or formulated theory for various methods are easily accessible, we have exhausted many key sources of information within the budget constraints of this special study. The following specific sources of information utilized during compilation of this special study include:

- Libraries/information centers.
 - Remedial Action Program Information Center, Oak Ridge, Tennessee.
 - Centennial Science and Engineering Library, University of New Mexico, Albuquerque, New Mexico.
 - New Mexico Institute of Mining and Technology library, Socorro, New Mexico.
 - Sergeant, Hauskins & Beckwith (SHB) AGRA Geotechnical Engineering Library, Phoenix, Arizona.
 - UMTRA Project Document Control Center (UPDCC), UMTRA Project Office, Albuquerque, New Mexico.
- Personal interviews (all interviews are listed in Appendix A).
 - Mark Ankeny, laboratory manager, Daniel B. Stephens & Associates, Albuquerque, New Mexico.
 - J. Blount and A. Meijer, UMTRA geochemists, Jacobs Engineering Group Inc., Albuquerque, New Mexico.

- G. P. Boutwell, President, Soil Testing Engineers, Baton Rouge, Louisiana.
- Herman Bouwer, chief engineer, U.S. Department of Agriculture (USDA), Phoenix, Arizona.
- Jose Cercone, Morrison Knudsen-Environmental Services (MK-ES), geologist, San Francisco, California.
- Steve Cullen, principal scientist/hydrologist, Geraghty & Miller, Inc., Santa Barbara, California.
- David Daniel, The University of Texas at Austin, Austin, Texas.
- Lorne Everett, chief scientist and vice president, Geraghty & Miller, Inc., Santa Barbara, California.
- Jeff Havlena, senior hydrogeologist, Daniel B. Stephens & Associates, Albuquerque, New Mexico.
- Gary Konwinski, U.S. Nuclear Regulatory Commission (NRC), Denver, Colorado.
- Don Metzler, U.S. Department of Energy (DOE) hydrologist, Albuquerque, New Mexico.
- Richard Papusch, UMTRA hydrologist, Jacobs Engineering Group Inc., Albuquerque, New Mexico.
- W. D. Reynolds, soil physicist, Agriculture Canada, Research Branch, Ottawa, Canada.
- Rolf Schmidt-Petersen, hydrogeologist, Daniel B. Stephens & Associates, Albuquerque, New Mexico.
- Greg Smith, former UMTRA engineer, currently with Geotech in Grand Junction, Colorado.
- Steve Trautwein, President, Trautwein Soil Testing Equipment Company, Houston, Texas.

The comprehensive approach used during this special study provides assurance that UMTRA Project engineers and scientists have current information when specifying future *in situ* permeability testing. Appendix A of this special study includes a complete list of papers compiled during the literature review. The papers are compiled in several binders which will be stored in the UPDCC, UMTRA Project Office, Albuquerque, New Mexico.

Since results of testing at the Rifle site and previous UMTRA permeability testing were evaluated simultaneously with the literature review and interviews, this special study has provided a tangible, practical benefit to the project while also providing a long-term planning tool.

2.0 COVER, LINER, AND FOUNDATION TESTING REQUIREMENTS FOR DETERMINATION OF FIELD-SATURATED HYDRAULIC CONDUCTIVITY

2.1 HISTORICAL RELATIONSHIP BETWEEN REGULATORY AND TECHNICAL STANDARDS FOR *IN SITU* TESTING

Before the mid-1980s, compliance evaluation of covers, liners, and foundation materials was based solely on the results of small-diameter laboratory tests. Field testing was not as common due to increased cost, interpretation problems, and long testing times.

The change in emphasis from laboratory to field testing began in the mid-1980s after the reliability of laboratory tests on small-diameter samples was questioned. There was extensive debate over the compatibility of laboratory and field test values. Several investigators collected data indicating that *in situ* K could be as much as 10,000 times greater than laboratory test values (Trautwein and Boutwell, 1993).

As the debate continued, the regulating community became concerned and shifted from laboratory testing to field testing. At the federal level, the U.S. Environmental Protection Agency (EPA) suggested field testing in its guidance documents. In 1986, California became the first state to require field testing as part of compliance evaluation. Other states, such as Pennsylvania, Texas, and Ohio, soon followed (Trautwein and Boutwell, 1993). Currently, each state either has its own *in situ* testing requirements or has adopted another state's requirements. This was a rapid shift in policy because at the time no widely accepted or standardized techniques for *in situ* testing of layers of low-K soils existed.

2.2 APPLICABLE REGULATORY STANDARDS FOR TAILINGS DISPOSAL AT UMTRA SITES

The proposed final EPA rule for ground water protection standards under (52 FR 36000 [1987]), "Standards for Remedial Actions at Inactive Uranium Processing Sites," states that under the provisions of the Uranium Mill Tailings Radiation Control Act (UMTRCA) (42 USC §7901 *et seq.*), the DOE is responsible for the design of disposal cells that will ensure compliance with EPA standards. The remedial action will be selected and performed with the concurrence of the NRC.

The proposed final EPA rule for uranium mill tailings protects ground water by requiring that disposal cells be designed to avoid new ground water contamination that could impact human health and the environment. EPA standards state that the disposal cell should be designed to control migration of radioactive materials and their constituents for up to 1000 years or to the extent reasonably achievable. EPA standards also state that implementation of the disposal standard for protection of ground water will require a judgment that the method chosen provides a reasonable expectation that the provisions of the standards will be met.

EPA standards for disposal also state that the remedial actions required to comply with the standard will vary from site to site. Actual site data, computational models, and judgment will be the major tools in determining if a proposed disposal system will satisfy the standards.

Although the EPA and the states may suggest or require field testing as part of a compliance evaluation, no specific protocol for testing cell covers, liners, and foundation materials is required. On the UMTRA Project, the decision to install covers and pile liners and to perform *in situ* testing on them and the underlying foundation materials is seen as a technical judgment.

2.3 APPROVED TECHNICAL STANDARDS FOR DETERMINATION OF FIELD-SATURATED HYDRAULIC CONDUCTIVITY

Of the currently available test methods that enable determination of K_{fs} , only two have approved American Society for Testing and Materials (ASTM) standards: ASTM Standard Test Method D3385 (ASTM, 1988) for the open double-ring infiltrometer (ODRI), and ASTM Standard Test Method D5093 (ASTM, 1990) for the sealed double-ring infiltrometer (SDRI). Each method minimizes the effect of lateral flow in the measurement of vertical infiltration. The ODRI was developed for soils having K greater than 10^{-6} centimeters per second (cm/s) and the SDRI was developed for soils having K less than 10^{-6} cm/s. These standards are included in Appendix B.

It is important to note that the ODRI and SDRI standard methods do not provide for estimation of gradient, which is required to determine a representative K . Without hydraulic gradient, these methods determine a vertical infiltration rate but not a K value. In addition, the effects of lateral flow from the inner ring on the vertical infiltration rate are not fully understood. These lateral flow effects will be discussed further in later sections of this report.

Another important consideration regarding the ODRI and SDRI methods is that their exclusive use for determining field-saturated K may not always be defensible simply because they have approved ASTM standards. For example, the SDRI method involves long testing times, often up to several months. If funding and site conditions do not support the use of SDRI testing, an alternative method or methods should be selected. The SDRI method is limited by analytical assumptions, as are all other methods. Results provided through use of any of the available methods will always be impacted by natural heterogeneities. An assessment must be made of each method, the site conditions, the data requirements, and time and budget constraints. Standards are not established for other methods primarily because these methods are relatively new, and achieving ASTM approval can be lengthy.

According to Lorne Everett, who is currently chairing ASTM D18-21-02 entitled, "Vadose Zone Hydrology," all of the test methods mentioned in this special study are under consideration for ASTM method approval. Mr. Everett stated that each method is being considered, since each method has a particular applicability and no

one method is applicable at all sites. However, due to the rigorous testing and educational effort required for acceptance, their approval may take many more months or years.

3.0 TESTING RATIONALE

3.1 WHY CONDUCT *IN SITU* TESTS?

Expending considerable financial resources to obtain field K values, when less costly laboratory tests are available, requires justification.

The underlying difficulty in comparing laboratory and field (K_f) test results is in the inherent uncertainties of each. It could be argued that the uncertainties in field testing to determine K_f are somewhat more definable than those of laboratory tests.

Assuming that test methods are appropriate for site conditions, the analytical assumptions are realistic, and tests are conducted according to documented methods, the uncertainties in K_f can be limited to the natural heterogeneity and anisotropy of the field-tested material. Natural heterogeneities and anisotropy can be accounted for through macroscopic (or if necessary, microscopic) analysis of the tested material.

Uncertainty in laboratory testing to obtain laboratory hydraulic conductivity (K_L) can come from numerous sources. One of the most significant sources of error, which is almost impossible to account for, results from incorrect sample collection and handling before laboratory testing. Considerable alteration in material fabric may also occur because of varying moisture and pressure conditions after sample collection. In addition, laboratory permeameters may exert unnatural stresses on samples. This laboratory equipment may also leak around the sides, causing unrepresentative K values.

The primary advantage of performing *in situ* testing to determine saturated K is that theoretically it should more accurately approximate the K range than will laboratory tests. This is largely due to two factors: 1) there has been limited disturbance of the tested material, and 2) *in situ* testing permits testing of larger, more representative samples. Many authors state that larger samples are more likely to contain heterogeneities that are not present in smaller laboratory samples. Because macroporosity controls leakage through cell foundation materials and covers, measuring a representative K range requires a test specimen large enough to measure macroporosity.

Investigators have not yet determined the optimum size of a test specimen (Trautwein and Boutwell, 1993), particularly for foundation materials that have greater inherent heterogeneity and anisotropy than clay covers. For clay cover or liner test pads constructed with appropriate quality assurance (QA), Williams (1988), Trautwein and Williams (1990), and Benson et al. (1993) have investigated the influence of specimen size on K_f . Their results indicate that specimens of at least 30 centimeters in diameter are needed to detect the influence of macropores. These investigators also found that in properly compacted liners and caps where macropores are minimized or eliminated, specimen size had little or no influence on K_f .

3.2 WHAT ROLE SHOULD LABORATORY TESTING PLAY?

Because of convenience, lower cost, and the ability to control certain test conditions, laboratory testing will continue to play an important role in determination of saturated K for cell liners, covers and cell foundation areas at UMTRA Project sites. Use of laboratory testing is helpful when studying permeability of deep formations, and it is particularly useful in preliminary site investigations when test boring samples are obtained.

Some authors feel that K_L should be used as a lower limit for the range in K. These authors have generally found that *in situ* tests yield higher values of K. Others feel that assuming K_L to be a lower limit is an oversimplified way of looking at laboratory results, and that problems could develop from using this approach. A third group of authors feels that laboratory results should be compared to *in situ* test results on a case-by-case basis using all available data to determine their relationship. Most authors agree that if laboratory test results are to be compared to *in situ* results, care must be taken to select a laboratory testing method that limits unnatural stresses and strain on the sample.

4.0 APPLICABLE *IN SITU* TEST METHODS TO DETERMINE FIELD-SATURATED HYDRAULIC CONDUCTIVITY

4.1 PRESENT STATE OF THE ART FOR *IN SITU* TESTING TO DETERMINE FIELD- SATURATED HYDRAULIC CONDUCTIVITY

Techniques for *in situ* testing for determination of K_{fs} were developed primarily over the past several decades. Most early equipment and analytical solutions were developed for agricultural purposes, to determine infiltration rates in fairly permeable soils. The search for an accurate determination of field-saturated K began in the 1960s with the development of the air-entry permeameter (AEP) by Herman Bouwer. Through the late 1970s, Elrick, Reynolds, Stephens, and others worked with borehole infiltration to present a more rigorous mathematical solution for the influence of unsaturated materials on saturated K . The work of these researchers provides a better understanding of the relationship between unsaturated and saturated flow in boreholes and also provides more accurate estimates of K .

By the early 1980s, researchers were questioning whether laboratory-determined K values were representative of field conditions. Regulators began to require *in situ* testing for determination of field-saturated K . The open-ring infiltrometer (originally accepted by ASTM in 1975) was adapted for testing high-permeability materials. To test for low- K materials, this infiltrometer was sealed to minimize evaporation so low infiltration rates could be measured. This change produced the SDRI test. A larger sample size and outer ring were developed for the ODRI and SDRI, and accurate water temperature control and recording methods were adapted to those tests. Using an inner and an outer ring reportedly produced a vertical flow from the inner ring by limiting lateral flow between the rings. The SDRI and ODRI are accepted by many regulators as the most appropriate field method for measuring field-saturated K .

Authors in the field of *in situ* K testing indicate that many types of equipment and methods of data analysis are now available. Changes in this field will likely come from incremental changes in field techniques which provide increased support for analytical solutions. According to some authors, changes will also come in the form of wider acceptance of alternate techniques as regulators become more familiar with new technologies.

4.2 TESTING CONSIDERATIONS FOR CELL COVERS VERSUS LINERS AND FOUNDATION MATERIALS

The following inherent differences between a cell cover or liner and a cell foundation must be considered before an *in situ* testing program is established.

4.2.1 Physical considerations

Cell covers and liners are generally more homogeneous than natural foundation materials. In addition, covers and liners are normally only a few feet thick; they often are tested by constructing a prototype test pad with the same soil and

equipment that will be used to construct the cover or liner. Heterogeneous foundation materials may require more test locations at greater depths to account for heterogeneity and/or anisotropy.

Calculation of K requires determination of the hydraulic gradient (i.e., $K = I/i$, where I = infiltration rate, and i = hydraulic gradient). To calculate the hydraulic gradient, the depth-of-flow penetration into the tested material must be measured. This distance of flow penetration is called the depth of the wetting front. Measuring the wetting front depth is often more difficult in low-permeability foundation materials than in constructed cover or liner layers. Increased heterogeneity causes the wetting front to be more uneven.

When liners or foundation materials are tested to determine field-saturated K , overburden pressures on the tested surface should be considered to obtain an accurate estimation of K . Overburden pressure effects may include laboratory testing to simulate both preexisting and potential future overburden stresses.

4.2.2 Chemical considerations

The quality of the water used in testing cell covers, liners, and foundation materials should be considered. Cell covers usually receive most moisture from above through precipitation or runoff; liners and foundation materials potentially receive seepage directly from the disposal cell. This seepage water may approximate the quality of tailings leachate. Studies show that acid leachate potentially alters the *in situ* K of some naturally occurring materials. For this reason, water having the approximate quality of tailings leachate should be considered when *in situ* testing on cell liners or foundations is planned.

Although the impact of organic permeating contaminants on the integrity of clay liners has been studied extensively, less research has been done on the impact of acid leachate containing radionuclides.

The experts interviewed for this special study differ in their opinions about the effects of water quality in determining field-saturated K . However, the majority feel that it is worthy of consideration. Although many experts agree that knowledge of the impact of water quality would be helpful in determining a range of K , they do not agree on the best way to determine the leachate's probable impact. The most prevalent opinion was that, to obtain conclusive results, water quality testing should be done in a laboratory under controlled conditions; the results of laboratory K testing data should be compared with *in situ* test results. To determine which constituents may naturally precipitate out or go into solution, geochemical modeling can be performed before a water quality testing program begins.

Interviews with UMTRA geochemists and experts in the field of *in situ* testing also provided information on the specific impacts of acid leachate interaction with materials having a high clay content. The results of the interviews indicate that the following processes may influence K :

- Collapse of certain clay minerals due to interaction with acid leachate may cause an increase in K.
- Swelling of clay minerals may cause a decrease in K.
- Ion exchange.
- Secondary deposition or dissolution of minerals. Estimating these effects requires knowledge of the long-term kinetics of the shallow system underlying a disposal cell; K may increase or decrease.

4.3 NEAR-SURFACE TEST METHODS POTENTIALLY APPLICABLE TO THE UMTRA PROJECT

The following testing methods may be applicable to *in situ* testing of UMTRA disposal cell covers, liners, and foundation materials that have low hydraulic conductivities:

- Sealed double-ring infiltrometer (SDRI).
- Air-entry permeameter (AEP).
- Guelph permeameter.
- Two-stage borehole technique (TSB).
- Constant head pressure infiltrometer method.
- Disk permeameter.

In the following sections each of these potentially applicable test methods will be examined in detail. Analytical solutions are presented as well as limiting analytical factors and assumptions, limitations of testing equipment design and installation, and testing and equipment costs.

4.3.1 Sealed double-ring infiltrometer

The SDRI is illustrated in Figure 4.1. A comprehensive series of photographs shows the SDRI's field operation (Appendix C, photographs 3 through 20).

The SDRI was developed specifically to test compacted cover or liner soils with infiltration rates less than 10^{-6} cm/s. The developers of this method generally do not recommend it to test bedrock foundation materials.

Testing details

ASTM standard test method (D5093) was recently adopted for the SRDI. This test method is included in Appendix B. Trautwein and Boutwell (1993) report a significant advantage of the double-ring design is the large-diameter, moderately deep rings used to overcome the problem of lateral flow. Flow is measured by connecting a flexible bag, filled with a known weight of water, to a port on the inner ring. As water infiltrates the ground from the inner ring, an equal amount of water is drawn into the inner ring from the flexible bag. After a known time, the

SEALED DOUBLE-RING INFILTROMETER (SDRI)

PARAMETERS FOR GRADIENT CALCULATION

MODIFIED FROM TRAUTWEIN AND BOUTWELL, 1993

FIGURE 4.1
SEALED DOUBLE-RING INFILTROMETER

bag is removed and weighed. The weight loss (converted to volume) equals the amount of water that has infiltrated the ground. An infiltration rate is then determined from this volume of water, the area of the inner ring, and the interval of time.

Ring diameter sizes commonly used in testing covers are a 3.7-square meter (m^2) outer ring and a 1.5- m^2 inner ring. Square rings are used to facilitate trench excavation. Metal panels that bolt together at the corners form the outer ring. The one-piece inner ring is made of fiberglass. The outer ring is typically imbedded 45 cm into the tested material; the inner ring is embedded 10 cm. According to several authors, the deep embedment of the outer ring forces one-dimensional flow to a depth of at least 45 cm. During testing, tensiometers, a swell gauge, and a thermometer are used to collect additional information which in turn is used in determining vertical K (K_v) from infiltration measurements.

Tensiometers can track the wetting front location during testing (see Appendix C). A tensiometer is a sealed plastic tube with a porous tip on one end and a vacuum gauge on the other. The tensiometer is saturated with water and inserted into the test zone so the porous tip contacts the unsaturated soil. Pore water is hydraulically connected to water in the tensiometer through the porous tip and pore water pressure is indicated on the gauge. Initially, soil around the tip is unsaturated and the gauge registers a suction. When the wetting front passes the tip, the soil becomes saturated, and suction decreases to zero. By installing tensiometers at several depths, the wetting front position can be determined by noting when the gauge reads zero.

Typically, a tensiometer is installed by driving a pipe into the ground to form a hole and then pushing the tensiometer into place. This installation procedure may cause cracking of a compacted soil. In the preferred method of installation, an oversized hole is augered, the tensiometer is inserted, and the hole is backfilled by compacting the soil in layers. Typically, nine tensiometers are used per SDRI test: three at each depth of 15 cm, 30 cm, and 45 cm.

Altitude corrections for gauge suction readings are often neglected and can significantly influence infiltration measurements. Appropriate altitude corrections should be made to maintain data accuracy.

Change in viscosity is also important and should be accounted for. K values are based on a water temperature of 20° Celsius. K may appear lower if colder water is used. If water used in testing is colder than the tested material, bubbles may form as the water warms, which could retard infiltration.

Soil swell can also significantly affect infiltration measurements. It is monitored during testing by noting changes in inner ring elevation. The inner ring is used as the reference because of difficulty in obtaining a stable reference on the soil surface. A pair of constant tension reference wires is strung across the test setup, positioned over the corners of the inner ring. The vertical distance between the

wires and a reference point on each inner ring corner is then measured with a swell gauge, which consists of a dial caliper mounted on a metal rod.

Changes in water temperature also affect infiltration measurements, causing expansion and contraction of the inner ring and the water. A thermometer is used to record temperature changes. The test setup is insulated to minimize temperature changes by berming soil against the outer ring and topping this ring with a cover of plywood and insulation. To protect against extreme temperature fluctuation, shelters such as a tent or a plywood structure are used. Heated shelters are required to protect against freezing.

Analytical solution

Trautwein and Boutwell (1993) report that when the SDRI is used, infiltration and K_v are determined by the following equations:

$$I = Q/(At)$$

where

I = infiltration, cm/s

Q = volume of flow, cm^3

A = area of flow, cm^2

t = time interval in which Q was determined, seconds

$$K_v = Q/(iAt) = I/i$$

where

K_v = field-saturated vertical K

i = gradient = $\Delta h/\Delta z$

Δh = head loss

Δz = length of flow path over which Δh is measured

As with other infiltration tests, the gradient calculation is complicated by the fact that the test zone is initially unsaturated. Expressed in the form of an equation, i is calculated as follows:

$$i = (H + Z_w + H_s)/Z_w$$

where

i = gradient = $\Delta h/\Delta z$

H = depth of water in infiltrometer

Z_w = depth of wetting front

H_s = suction head at wetting front

Three methods, each with different assumptions for the above terms, are proposed for estimating the gradient. The simplest procedure used to determine gradient is the apparent K method. This method yields the most conservative value of K_v . The gradient is calculated by assuming $Z_w = Z$ (where Z = the depth to the upper drainage layer or depth of the tested zone) and $H_s = 0$. The advantage of this method is not having to know the wetting front location or suction at the wetting front. The disadvantage is that correct values of K_v are obtained only if the wetting front has passed through the test zone; otherwise I will be underestimated, resulting in a higher than actual K_v . Using this method to verify compliance may be adequate; however, it should not be used to judge noncompliance because of the predictably high values of K_v that can occur when Z_w/Z is small.

The second method (the suction head method) requires a known wetting front location and ambient soil suction. The assumption in this method is that H_s equals the ambient suction, and that it can be added directly to the gravity terms. From this method, higher gradients are calculated which yield lower K . It is not unusual to measure suction heads in excess of 6 m, which correspond to gradients in excess of 100 for small wetting depths. The disadvantage of this method is that the actual suction at the wetting front is unknown and is probably less than the ambient suction. Using an excessive suction value will result in less than actual K_v . Accounting for the effect of suction on infiltration rate requires a nonlinear analysis that uses the moisture characteristic curve and the relationship between degree of saturation and K for the soil being tested. While the suction below the wetting front has some effect on infiltration rate, the full impact is offset by a low K in the unsaturated zone beneath the wetting front, which is diffuse. As water ahead of the average wetting front depth enters the high-suction zones, the degree of saturation increases and suction decreases dramatically below the ambient suction value. This method is not recommended because of the unconservatively low K_v values it can produce.

The third method is the wetting front method. The assumption in this method is that $H_s = 0$. Observed decreases in infiltration rate compare well with those determined using this method. Because suction effects are fully understood, this third method may be the most practical procedure. As suction may have a small effect on infiltration, this method is considered conservative (i.e., the calculated K_v will be slightly larger than the actual K_v).

Limiting analytical factors and assumptions

Limiting analytical factors and assumptions of the SDRI method include the following:

- The wetting front suction head must be estimated or taken as zero.
- Testing times are long.
- Material in the tested zone is homogeneous and uniformly soaked behind a wetting front.

- Temperature fluctuations in the inner ring are minimal.
- Flow from the inner ring is one-dimensional.
- Soil swelling is complete by the end of the test.
- Effects of boundaries beneath the rings are negligible.

Limitations of testing equipment design and installation

Because it was designed to test K of clay covers and liners, rather than *in situ* materials, SDRI testing equipment has the following limitations:

- This method is difficult to use on sideslopes unless a flat bench is cut.
- Installation and monitoring are labor intensive. The rings are large and awkward, and the method does not lend itself to easy replication.

Testing and equipment costs

Testing times range from a few weeks to several months, after long-term equilibrium conditions are reached. SDRI equipment costs approximately \$3300 for each testing apparatus. The cost per test ranges from \$10,000 to more than \$20,000.

4.3.2 Air-entry permeameter

The AEP developed by Bouwer (1986; 1978; 1966) is illustrated in Figure 4.2. Photographs taken during installation and operation are included in Appendix C (Photographs 21 through 31).

The AEP consists of a sealed ring (about 60 cm in diameter and 25 cm deep) embedded about 10 cm into the soil. A water supply reservoir is mounted on top of an adjustable standpipe. The total head applied to the soil surface can be preset for the characteristics of the material to be tested (30 to 60 cm is generally sufficient for sands and silts, while 180 cm or more may be required for clays).

Bouwer suggests using the AEP to determine the vertical, field-saturated K of geologic materials above the water table. Application of the AEP has generally been limited to fairly homogeneous sands and silty sands, although recently it has been used with low-permeability clays, sandstones, and shales and clay liners.

Testing details

In the first stage of the AEP test, the rate of infiltration (I) is determined from a falling head test or preferably from a constant head test (Daniel, 1989). When the wetting front is estimated to be near the base of the ring, Stage I is complete.

MODIFIED FROM DANIEL B. STEPHENS & ASSOCIATES, 1993

FIGURE 4.2
AIR-ENTRY PERMEAMETER

To initiate Stage II, a valve to the flow measuring device is closed, sealing the AEP. Negative pressure (measured with a gauge) develops as the unsaturated soil attempts to suck water out of the AEP. When the vacuum gauge yields its peak reading, the AEP is disassembled and the depth to the wetting front (L) is measured, usually by taking a relatively undisturbed soil sample and measuring the variation of water content with depth (Daniel, 1989).

According to Bouwer (1966), the minimum water pressure during the second testing stage occurs when the air-entry value of the wetted zone is reached. At that point, air moves up through the wetted zone. Bouwer suggests, based on experience with various soils, that the water entry suction pressure at the wetting front is approximately one-half the air entry suction pressure (Daniel, 1989).

Analytical solution

Determination of the vertical, field-saturated K is based on the infiltration rate and the assumption that the air-entry pressure approximates the critical pressure, or the wetting front pressure head. The wetting front pressure head is known to be the effective capillary drive during infiltration and is a major component of the overall applied hydraulic gradient. The infiltration rate and hydraulic gradient are used to solve the following Green-Ampt type formulation of the infiltration equation (Daniel B. Stephens & Associates, 1993).

$$K_v = 2(dH/dt) = (Rr/Rc)^2 / (H_f + L - 0.5Y_a)$$

where

- K_v = vertical hydraulic conductivity
- dH/dt = rate of decline (assuming falling head) of water (level) in water supply reservoir (cm/s)
- L = depth to wetting front from soil surface (cm)
- Rr = radius of water supply reservoir (cm)
- Rc = radius of permeameter ring (cm)
- H_f = final head of water applied to soil surface (cm of water)
- Y_a = air-entry pressure (cm of water)

Limiting analytical factors and assumptions

The following limiting analytical factors and assumptions apply to use of the AEP:

- Soil gas pressure does not impede the downward movement of the wetting front.
- The material is homogeneous and the wetting front is distinct and easily identified.
- Clay dispersion within the surface layer of finer soils is insignificant.

- The soil is nonswelling or an adjustment for the affects of swelling can be easily accomplished.

The mathematical solution for K_v using an AEP assumes the following:

- Air-entry pressure of the material within the permeameter ring approximates the critical pressure along the wetting front.
- Critical pressure during drainage is approximately twice that for imbibition. Imbibition refers to the absorption or adsorption of water by certain clays and the resultant swelling.

Limitations of testing equipment design and installation

The use of AEP testing equipment is limited in the following ways:

- It permeates a relatively small volume of soil.
- It cannot be used on slopes without constructing a horizontal surface.
- Care must be taken when the permeameter ring is installed to avoid disturbing the structure of the tested soil.

Testing and equipment costs

Testing times for low-K materials are generally several days to a week. The equipment costs approximately \$1500, with the cost per test ranging from \$4000 to \$7000, depending on the K of the tested material. However, cost per test may be considerably less when multiple tests are required.

4.3.3 Guelph permeameter

Figure 4.3 illustrates the guelph permeameter. Photographs 32 and 33 of Appendix C shows the instrument in the field.

The guelph borehole permeameter is a small-diameter borehole permeameter that maintains a constant head in the test hole. Reynolds and Elrick (1987; 1985) have presented detailed studies of the guelph permeameter.

Borehole permeameters have been used for several years to determine values of horizontal and vertical (i.e., three-dimensional) saturated K above the water table. Stephens and Neuman (1982) describe the borehole permeameter method in detail; they suggest testing geometries and mathematical solutions, including tests for a cased open-bottom borehole and uncased open-bottom boreholes in the presence of both shallow and deep water tables.

MODIFIED FROM DANIEL B. STEPHENS & ASSOCIATES, 1993

FIGURE 4.3
GUELPH PERMEAMETER

Testing details

Tests using the guelph permeameter require that water is maintained at a constant level within the borehole by use of a constant head device. The flow that maintains the constant water level must be measured. The testing equipment typically consists of a borehole 5 to 15 cm in diameter, a water supply reservoir, and a means of controlling the head of water within the borehole. For a guelph permeameter, a Marriott device often is used to maintain a constant water level within the borehole. Other types of borehole permeameters may install a float-type, stock-tank valve within the borehole that is connected to a remote water supply reservoir (Havlena and Stephens, 1992).

Borehole permeameters have an advantage over other test methods because they can easily be installed at depth. Borehole permeameters can measure the variability of field-saturated K with depth by conducting a series of tests at different depths while drilling a borehole.

Analytical solution

The standard solution and testing method of the guelph permeameter requires a steady flow rate at a constant head, with a fixed permeameter geometry. This solution assumes a free water surface. Inside the water surface, the soil is assumed saturated. The following solution by Glover (1953) was rederived by Stephens (1979):

$$K_s = q/C_u r H$$

where

- K_s = saturated hydraulic conductivity (cm/s)
- q = steady-state volumetric flow rate into borehole (cm³/s)
- r = borehole radius (cm)
- H = constant head of water in borehole (cm)
- $C_u = [2\pi(H/r)]/\sinh^{-1} (H/r)^{-1}$

This and other free-surface solutions disregard the component of flow due to capillarity. That is, they do not account for the affects of unsaturated flow away from the borehole. This may lead to erroneously large K values in dry, fine-textured materials where capillary draw is great, often giving values two or three times greater than the actual saturated K. In spite of this, for some soils and test conditions, the Glover equation produces reasonable results.

Stephens et al. (1987), Reynolds and Elrick (1985), and Philip (1985) require that certain capillarity parameters be measured in the laboratory or estimated from other soil properties. The Reynolds and Elrick (1985) method overcomes this requirement by using a two-headed approach in which the steady-state flow rate is measured for each of two different head settings within a single borehole test. This approach is the basis for the guelph permeameter and associated solution. Although the

two-headed solution used for the guelph permeameter can provide accurate measurements in the field, each field test requires more time to complete than the other methods because a steady flow rate must be achieved for each of two different heads.

The guelph permeameter method is not suited for heterogenous materials such as thinly bedded sediments, structured soils, or materials with fractures, rootholes or other macropores. For more detailed sources of information on the theory regarding guelph permeameters, see the list of papers which have been compiled separately for this special study (Appendix A).

Limiting analytical factors and assumptions

- This method measures field-saturated K in three dimensions. Vertical K is generally of interest in the characterization of UMTRA clay cover layers and foundation materials.
- This method is not well suited to testing heterogenous materials such as thinly bedded sediments, structured soils, or materials with fractures, rootholes, or other macropores.

Limitations of testing equipment design and installation

Limitations due to the design and installation of the guelph permeameter include the following:

- The guelph permeameter method yields essentially a point measurement and therefore usually requires replication.
- Sidewall smear in the borehole during installation of the permeameter can cause unrepresentatively low K. Investigations suggest that the efficiency of smear layer removal in clays declines with increasing wetness. It is therefore recommended that clays not be augered when they are in a very wet state.

Equipment and testing cost

The guelph permeameter is relatively inexpensive, simple, and easily operated by one person. Cost of equipment is approximately \$1500 and testing is generally within the range of \$3000 per test.

4.3.4 Two-stage borehole technique

The TSB test combines procedures and techniques from two established borehole test methods (U.S. Bureau of Reclamation E-18 and E-19). In addition, a varying geometry is used with Horslev equations to estimate the K_h/K_v ratio. Figure 4.4 illustrates the TSB permeameter.

Schematic Diagram of Two-Stage *In Situ* Hydraulic Conductivity Test with Boutwell Permeameter for Case in which Potentiometric Level is below Base of Permeameter: (a) Stage I; (b) Stage II

MODIFIED FROM DANIEL, 1989

FIGURE 4.4
TWO-STAGE BOREHOLE PERMEAMETER

Testing details

The concept of the TSB method is to vary the geometry of the wetted zone. The relative effect of vertical and horizontal conductivities is varied in a calculable manner (Daniel, 1989). Two different test stages yield two equations by which the two unknowns (K_v and K_h) can be determined.

The device is installed by drilling a hole, placing a casing in the hole, and sealing the annular space between the casing and borehole with grout. Falling head tests are performed and the K from Stage I is computed from the Hvorslev (1949) equation. When steady conditions are reached (which takes from a few days to two weeks), Stage I is complete and K_1 is determined. Flow during Stage I is governed primarily by K_v .

Next, the hole is deepened by augering or by pushing a thin-walled sampling tube into the soil. Smeared soil is removed from the hole surface with a wire brush. The permeameter is reassembled and falling head tests are performed again. The K from Stage II (K_2) is calculated from Hvorslev's (1949) equations. Stage II continues until K_2 ceases to change significantly.

Analytical solutions

Observing the illustration of the TSB method in Figure 4.4 and solving the appropriate Hvorslev (1949) equation (below) during Stage I, values of K_1 are computed and plotted versus time.

$$K_1 = \frac{\pi d^2}{11D(t_2 - t_1)} \ln (H_1/H_2)$$

where

- K_1 = hydraulic conductivity determined from Stage I
- D = diameter of casing
- d = diameter of water supply reservoir
- t_2 = time at beginning of test
- t_1 = time at end of test
- H_1 = head at beginning of test
- H_2 = head at end of test

After Stage I is complete, the hole is deepened, additional falling head tests are performed, and the K from Stage II (K_2) is calculated.

$$K_2 = \frac{A}{B} \ln (H_1/H_2)$$

where

$$A = d^2 \left\{ \ln \left[\frac{L}{D} + \sqrt{1 + (L/D)^2} \right] \right\}$$

$$B = 8D (L/D) (t_2 - t_1) \{ 1 - 0.562 \exp [-1.57(L/D)] \}$$

L = distance from bottom of cased borehole to bottom of newly completed uncased borehole

Next, we account for anisotropy by relating the ratio of K_2/K_1 to the degree of anisotropy. This is defined by selecting values of m where m is defined as

$$m = \sqrt{k_h/k_v}$$

(k_h and k_v = the hydraulic conductivities in the horizontal and vertical directions, respectively) and calculating the corresponding values of K_2/K_1 from the expression

$$K_2/K_1 = \frac{\ln [L/D + \sqrt{1 + (L/D)^2}]}{\ln [mL/D + \sqrt{1 + (mL/D)^2}]} \cdot m$$

Values of K_2/K_1 are plotted versus m and L/D (see Figure 3, in Daniel, 1989). The value of m that corresponds to the actual value of K_2/K_1 is found from this graph. The K in the vertical and horizontal directions are then computed as follows: $K_v = K_1/m$ and $K_h = m^2 K_v$. For a more detailed discussion of the theory related to the TSB method, see Trautwein and Boutwell (1993).

Limitations involving testing equipment design and installation

The primary limitation of TSB testing is sidewall smear during borehole construction. Sidewall smear can cause measured K to be much lower than actual. Another limitation of the TSB method is that it cannot be easily performed at the ground surface.

Limiting analytical factors and assumptions

When applying the TSB technique, the following limiting assumptions should be considered:

- The Hvorslev falling-head solution was developed for saturated ground water tests and is not supported by a rigorous mathematical foundation applicable above the water table. However, corrections for unsaturated soils have been developed by Boutwell (1992.)
- The solution may ignore the effect of capillarity.

- Unrealistic assumptions must be made regarding the pore water pressure at certain points within the soil immediately adjacent to the permeameter (i.e., pore water pressure is assumed to be zero at the base of the permeameter during Stage I and at the center of the uncased section during Stage II).
- Field testing requires that steady state be achieved for each of two test components.
- K_h is generally considered to be of less importance when characterizing disposal cell covers and foundation areas because the primary potential route for migration of contaminants is vertical. Testing to determine K_h in many instances may be unwarranted.

Equipment and testing cost

According to Boutwell (1993) a typical testing program for compliance evaluation of liners and caps consists of five or more TSB tests. Equipment costs for such a program range between \$1000 to \$2000, depending on whether the permeameters are self-built or bought commercially. Installation and data collection requires 24 to 36 hours of technician time. Data reduction and report writing can be performed by a professional in 1 to 2 days. A complete test program typically costs from \$5000 to \$10,000, depending on the remoteness of the site and whether personnel are already available at the site.

4.3.5 Constant head pressure (single-ring) infiltrometer method

This method was originated by Reynolds and Elrick (1990) and is a variation of the AEP method. Figure 4.5 illustrates the apparatus.

The pressure infiltrometer method determines *in situ* field-saturated K and matrix flux potential and measures the steady-state infiltration rate (recharge) required to maintain steady depth of water within a single ring inserted a small distance into the porous medium.

An important difference between the pressure infiltrometer method and the traditional single-ring infiltrometer method (Bouwer, 1986)) is the theoretical approach used to model water flow out of the ring and into the unsaturated soil.

In the traditional single ring infiltrometer approach, K_{fs} is determined assuming one-dimensional vertical flow through and below the ring. According to Reynolds and Elrick (1993), it is well established that the flow beneath the ring is not one-dimensional but diverges laterally. This divergence is due to the capillarity of the unsaturated soil, and the hydrostatic pressure of the ponded water in the ring (Bouwer, 1986). This divergence results in an overestimate of K when using the one-dimensional analysis. Attempts to prevent the flow divergence by adding a concentric outer guard ring (i.e., the SDRI) are reportedly unsuccessful (Swartzendrucker and Olson, 1961; Bouwer, 1986). Some have concluded that the traditional one-dimensional analysis can be accurate only for shallow ponding in

MODIFIED FROM REYNOLDS AND ELRICK, 1993

FIGURE 4.5
PRESSURE INFILTRMETER

rings so large they are impractical for field use. The pressure infiltrometer is designed to take flow divergence into account by using a three-dimensional flow analysis which should give a more realistic estimation of K_v .

Testing details and analytical solution

K_{fs} can be calculated for results obtained from utilization of the constant head pressure infiltrometer using a single head or a multiple head procedure. For the single head approach, K_{fs} is given by the following equation:

$$K_{fs} = \alpha^* G A R_1 / [a(\alpha^* H_1 + 1) + G \alpha^* \pi a^2]$$

where

- K_{fs} = field-saturated hydraulic conductivity
- α^* = a soils structure/texture parameter obtained from Table 56.1 in *Soil Sampling and Methods of Analysis* (Reynolds and Elrick, 1993) (cm^{-1})
- A = cross-sectional area of the infiltrometer reservoir (cm^2)
- R_1 = steady rate of fall of the water level in the infiltrometer reservoir (cm/s)
- a = inside radius of the ring (cm)
- H_1 = steady pressure head on the infiltration surface [set by the height of the air tube and determined by measuring the height of water in the standpipe (cm)]
- G = dimensionless shape factor obtained using $G = 0.316 (d/a) + 0.184$

where

- d = depth of ring insertion into soil (cm)

For the multiple head approach,

$$K_{fs} = (G/a) [\Delta(AR)/\Delta H]$$

where $\Delta(AR)/\Delta H$ is the slope of the linear least squares regression line through a plot of (AR) versus H and the parameters defined above.

The above equation applies when two or more heads (H values) are sequentially set in ascending order (i.e., H , set first H_1 , $< H_2 < H$) and without intervening drainage to obtain the corresponding (AR) values (i.e., $A_1 R_1$, $A_2 R_2$, $A_3 R_3$).

For a more detailed discussion of the pressure infiltrometer testing method and analytical solution, the reader should refer to the Canadian Society of Soil Science publication, *Soil Sampling and Methods of Analysis* (Reynolds and Elrick, 1993).

Limitations of testing equipment design and installation

The testing equipment may encounter the following limitations:

- Macrostructure collapse can occur during insertion of the ring, and cutoff of the nonvertical macropores by the ring wall.
- The range of K_{fs} that can be measured practically with a pressure infiltrometer is on the order of 5×10^{-2} to 1×10^{-7} cm/s.

An attempt should be made to minimize smearing and siltation of the infiltration surface during installation and testing.

Limiting analytical factors and assumptions

Soil heterogeneity such as of layering, cracks, worm holes, root channels, or similar conditions may result in an unrealistic and invalid determination of K. However, the pressure infiltrometer method is not highly susceptible to soil heterogeneity and success rates for multiple head measurement are often greater than 90 percent (Reynolds and Elrick, 1993).

Equipment and testing costs

The cost of equipment and testing is in the same range or slightly less than for the AEP (\$4000 to \$7000 per test). Costs per test could be less if multiple tests are required. Cost advantages of this method include that it may be slightly faster than the AEP since greater pressures can be applied and it can be directly attached to the guelph permeameter reservoir. This type of equipment compatibility could save time, especially if a three-dimensional estimation of K was also required.

4.3.6 Disc permeameter/tension infiltrometer

The disc permeameter and tension infiltrometer were developed by Perroux and White (1988) and Ankeny et al. (1988). These techniques can rapidly determine saturated and unsaturated K. Disc permeameters and tension infiltrometers are similar in design and operation. They differ primarily in the equations used to determine K. They both incorporate a Mariott siphon head control device and a disc-shaped membrane through which water infiltrates under tension into the underlying soil. They both can infiltrate water into the soil under positive-head, saturated conditions. The K measured under a small finite tension can be compared with the K measured under a positive-head condition. This comparison is an important feature of the disc permeameter and tension infiltrometer, because it allows assessment of the relative contribution of macropores and fractures to the overall saturated K (Daniel B. Stephens and Associates, 1993).

To use the disc permeameter, the soil must be dry initially. Dry soil is required because the mathematical solution used assumes that the K at the initial tension is negligible compared to the saturated K. It is difficult to determine the sorptivity

during gravity-dominated infiltration. For these reasons, the equations developed for the disc permeameter are not applicable for soils which are initially at or near saturation. For soils which are initially at or near saturation, the solution developed for the tension infiltrometer may be most appropriate (Daniel B. Stephens and Associates, 1993).

Testing details

Figure 4.6 illustrates a disc permeameter and Appendix C contains a field photograph (Photograph 34) of the tension infiltrometer/disc permeameter. Although the utility of the disc permeameter for UMTRA use was explored as part of this special study, since an attempt was made to use it at Rifle, its use is generally restricted to determining K_{fs} of more permeable (greater than 10^{-5} cm/s) material. Because of theoretical limitations and because the equipment is relatively fragile, its use is probably not applicable to the UMTRA Project. This statement is supported by results obtained using the disc permeameter during recent Rifle disposal cell testing. Therefore, a detailed discussion of testing using the disc permeameter is not presented in this report. A detailed step-by-step description of the field setup procedure for the tension infiltrometer/disc permeameter is presented by Ankeny (1992).

Analytical solution

The mathematical determination of K used with tension infiltrometers (Ankeny et al., 1988) is based on the Wooding equation. Solution of this equation requires that two tests be conducted at the same location, each at a different tension. This approach is similar to that used with the guelph permeameter. A detailed discussion of the theory regarding the solution for tension infiltrometers can be found in a number of papers which are included in Appendix A.

Limiting analytical factors and assumptions

The following limiting analytical factors and assumptions apply to this test method:

- K of tested materials should be greater than 10^{-6} cm/s.
- Material is homogenous, isotropic, and uniformly unsaturated and the initial soil water tension is below the air-entry pressure.
- Disc permeameters induce a three-dimensional flow field. Accordingly, all measurements reflect this three-dimensional orientation.

Limitations of testing equipment design and installation

The following limitations apply to this test method:

- No driving head; dependence on capillarity.
- Testing equipment is not held firmly in place.

REDRAWN FROM DANIEL B. STEPHENS & ASSOCIATES, 1993

FIGURE 4.6
DISC PERMEAMETER

Equipment and testing costs

Equipment cost is generally in the range of \$1500. Field testing costs about \$2500 per test. Although this method is relatively inexpensive, the utility of this method for UMTRA-related investigations is very questionable due to its inability to measure low K and its relatively fragile equipment.

4.4 MODERATE-TO-DEEP TEST METHODS POTENTIALLY APPLICABLE TO THE UMTRA PROJECT

Although this report deals primarily with near-surface testing, this section includes a general discussion on moderate-to-deep test methods. General discussions deal with use of the BAT probe and the constant head borehole permeameter. For detailed discussions of theory regarding these methods, the reader is directed to alternate sources.

4.4.1 BAT permeameter (probe)

The BAT probe, which was named after B. A. Torstensson (1984), is a porous probe that can be applied quickly (as little as a few hours) to determine K_{fs} as low as 10^{-10} cm/s of unsaturated compacted clay. The BAT probe can be used at a range of depths (from near surface to very deep). However, it has not been recommended for near-surface testing at UMTRA disposal sites because it provides only a point measurement, and the K that is measured is primarily horizontal, or an average of horizontal and vertical. Its primary application on the UMTRA Project would be in the characterization of moderate and deep foundation materials. The BAT probe could provide numerous, relatively low-cost measurements of K_{fs} , providing more data to establish the statistical range of K_h or K_{v+h} at specific depths of concern.

Testing details

With the BAT permeameter, a porous probe is pushed or driven into the soil beneath the bottom of a borehole and the casing is brought to the surface. A chamber is lowered down the casing and brought into contact with the porous probe using a hypodermic needle and septum. The chamber contains both air and water. The air in the chamber is pressurized (or evacuated) to any desired pressure. As water flows out of (or into) the probe, the air pressure in the chamber changes. A pressure transducer monitors the pressure change. The quantity of flow and heads are computed from Boyle's law and the measured change in the gas pressure in the chamber (Daniel, 1989).

Analytical solution

For a detailed discussion of the theory regarding the BAT probe, the reader is directed to Daniel (1989).

Limiting analytical factors and assumptions

The following limiting analytical factors and assumptions apply to the BAT method:

- Hvorslev's (1949) equations are correct.
- The test material is homogeneous, isotropic, uniformly soaked, and incompressible.
- Boundaries are at infinity.
- Soil is not smeared across the surface of the porous element.
- Effects of soil suction are negligible.
- Conditions are isothermal.
- There is no effect from dissolutioned gas in the pressure chamber.
- Unsaturated nature of soil not properly taken into account.

Limitations of testing equipment design and installation

The following limitations apply to equipment design and installation:

- Volume of soil tested is very small.
- Soil smearing can lead to underestimation of K.
- K measured is primarily horizontal or an average of vertical and horizontal.

Equipment and testing costs

BAT probe equipment is relatively expensive compared to other test methods. Daniel (1989) indicates that equipment costs greater than \$6000 can be incurred. As with any method of testing where depth of penetration is concerned, the deeper the testing, the more expensive the program. However, the testing times (as little as several hours for clay) for the BAT probe are among the fastest of any method.

4.4.2 Constant head borehole permeameter

As with the BAT probe, borehole permeameters have the advantage over other test methods in that the equipment can be installed at depth. This allows borehole permeameter tests to be used to measure the variability of field-saturated K with depth by conducting a series of tests at different depths while drilling a borehole. Unlike theory behind the BAT probe, the theoretical foundation of the constant head borehole permeameter takes unsaturated conditions into consideration. However, since steady-state conditions usually must be obtained, constant rate borehole permeameter tests may take considerably more time to complete than tests utilizing BAT probes.

Testing details

Constant head borehole permeameter tests require that water be maintained at a constant level within a borehole by use of a constant head device. The constant, steady-state flow rate is measured at the same time. Testing needs typically consist of a borehole 5 to 15 cm in diameter, a water supply reservoir, and a means of controlling the head of water within the borehole. The equipment used to maintain a constant level of water in the borehole most commonly consists of a float-type, stock-tank valve installed within the borehole and connected to a remote water supply reservoir (Havlena and Stephens, 1992). A seal is used to prevent evaporative loss from the borehole.

Analytical solution

There are several different solutions for determination of K_{fs} using constant head borehole permeameters. More detailed discussions of these methods are found in Stephens et al. (1987) (see Appendix A) and Daniel (1989).

Limiting analytical factors and assumptions

The following limiting analytical factors and assumptions apply to constant head borehole permeameters:

- The tested material is homogeneous, isotropic, and uniformly soaked.
- Boundaries are at infinity.
- Soil is not smeared across the surface of the borehole.
- The soil does not swell when wetted.
- Unsaturated conditions are accounted for.
- K which is measured may be primarily horizontal.

Equipment and testing costs

Equipment costs are commonly less than \$1000. Testing times for low- K materials are typically several days. As with the BAT probe method, depth of testing can greatly influence costs. However, if this testing is done in conjunction with borehole construction for wells, tests can be more cost-efficient.

4.5 RESULTS OF EXPERT INTERVIEWS

A total of nine interviews were conducted with recognized experts in the field of *in situ* determination of field-saturated K . Results of the interviews are included in Appendix D. Among those interviewed were Lorne Everett, chief scientist and vice president, Geraghty & Miller, Inc.; David Daniel, Department of Civil Engineering, The University of Texas at Austin; Herman Bouwer, chief engineer at the USDA, Phoenix, Arizona; Steve Trautwein, President, Soil Testing Equipment Company, Houston, Texas; and W. D. Reynolds, Agriculture Canada, Ottawa, Ontario. These and other interviewed individuals were greatly responsible for development of highly

respected testing methods, testing equipment, and/or analytical work associated with determining the influences on flow in the unsaturated zone.

The interview process provided an opportunity to obtain a spectrum of technical opinions from a representative population of experienced experts in the international scientific and engineering community.

The interviews provided current technical opinions regarding the perceived best testing methods. They also included discussions of pros and cons of various methods. The following are key findings of the interviews.

- The results of any attempt at measurement of K or K_{fs} are highly dependent on the methodology employed. To improve the utility of measurement values, it is imperative that methodologic protocol be clearly identified and strictly adhered to. ASTM standards are an example of the formal recognition of this need. It is also advisable that some measurement redundancy be built into the testing plan when the K measurement is of a highly critical nature.
- Interviews provided information indicating that of the potentially useful methods applicable to *in situ*, near-surface testing of cell covers, liners and foundation materials on the UMTRA Project, the AEP, SDRI and possibly the pressure infiltrometer and guelph permeameter will provide the most utility. Upon consideration of the full spectrum of opinion regarding the TSB method, use of this method should be restricted to testing liners and covers when unsaturated conditions are accounted for. The disc permeameter method seems much less appropriate for UMTRA-related use because of design and theoretical reasons.
- Potentially applicable methods for *in situ* testing at depth in naturally occurring foundation materials which were supported by experts include borehole permeameter methods and the BAT method.
- Quite a bit of supporting evidence was provided during the interview process that disputes the validity of the use of the outer ring of the SDRI for controlling divergence of flow from the inner ring. Several experts suggested that the SDRI method does not guarantee a sample size that will provide a K representative of the macroscopic structures of the tested material.
- None of the test methods are particularly suited for testing field-saturated K of relatively anisotropic material such as bedrock.
- The interviews indicated that preference for various methods is in part geographically, socially, politically, and marketing based.

5.0 HISTORICAL UMTRA TESTING TO DETERMINE FIELD-SATURATED HYDRAULIC CONDUCTIVITY

In the selection of optimum testing methods to determine field-saturated K of covers, liners, and foundation materials at UMTRA disposal sites, it is advantageous to look back and assess past *in situ* K testing experiences. We should assess past testing to determine if there is anything that should or should not be done in the future. Assessments such as this should help save money and time in planning future testing programs.

Two testing programs will be compared and contrasted in order to gather data to improve the overall efficiency and quality of future testing programs. These testing programs include those for the Cheney disposal site near Grand Junction, Colorado, and most recently, the Rifle, Colorado, disposal site investigation. Although there have reportedly been other SDRI testing programs conducted on the UMTRA Project, these two investigations appear to be the most detailed and well documented and are therefore easiest to evaluate. Both these investigations were fueled by the potential for bathtubbing of tailings seepage within the completed disposal cells.

5.1 CHENEY DISPOSAL SITE

5.1.1 Testing background

A records inspection of the 1989 SDRI testing at Cheney revealed that field activities were well documented. Records and interviews with MK-ES and TAC personnel indicate that SDRI tests were conducted in two separate phases at Cheney. The initial phase of SDRI testing was conducted by the TAC. This testing was conducted over a four month period from June through September of 1989. The initial phase of testing was conducted in the near surface Mancos Shale. The second phase of SDRI testing was conducted by MK-ES with support by Daniel B. Stephens & Associates. This second phase of testing was conducted from September to late November 1989 on exposed Mancos at the base of the disposal cell.

5.1.2 Testing evaluation

The first phase involved installation of four SDRI tests at different depths (approximately 10, 20, and 30 feet (3, 6, and 9 m) from the ground surface) in moderately to partially weathered Mancos Shale. In one of the SDRIs, an alum solution ($0.05M Al_2(SO_4)_3$) was used instead of water to simulate the salt concentration of tailings seepage. In all other SDRIs, water of drinking quality was used. A fifth SDRI was installed in alluvial material.

During testing, direct measurement of suction potential was not attempted. Due to the brittle, friable nature of the Mancos Shale, it was not considered possible to install tensiometers or any other instrument capable of reading the average suction potential. Instead, values of suction potential were determined from the literature. Furthermore, it was determined that the actual gradient on the saturated front was highly variable and therefore could not be determined accurately. Without wetting

front data, these tests resulted in infiltration rate values rather than field-saturated K values.

Also, during the first phase of testing, it was noted by field personnel involved in the testing that water bags used in the SDRI testing were not weighed on an appropriate scale.

A geometric mean of 3.9×10^{-7} cm/s was calculated without the use of suction potentials. This is considered an acceptable practice by some experienced individuals, as they feel that suction is usually so small in low-K materials that its omission will cause insignificant error. However, members of the Technical Assistance Contractor (TAC) team found that if they used typical suction potentials for shale obtained from literature, that K was rather sensitive to the inclusion of this term. Including literature-derived values of suction potential in their analyses resulted in a geometric mean of 7.6×10^{-8} cm/s. The difference in values was significant when trying to determine the potential for bathtubbing. Records indicate these initial infiltration rates were not heavily relied upon for design purposes. In addition, results of the water quality experiment involving $(\text{Al}_2(\text{SO}_4)_3)$ were not clearly presented in the available records.

Although a thorough job of documentation and test setup was performed by personnel who conducted the initial phase of SDRI testing at the Cheney disposal cell, they were largely inexperienced in the installation, operation, and analysis of the SDRI test.

Based on reports from personnel involved in the testing, the second phase of SDRI tests at the Cheney disposal cell, conducted on cell foundation materials, provided a lower K range. Reasons for this lower K range include the possibility that lines that lead into the SDRI had frozen and thus caused the determination of an unrepresentatively low K. Another reason includes the possibility that the second phase test locations did not intersect fractures which control the macro-K of the Mancos Shale. Selected results from the second phase of SDRI testing were used to show bathtubbing was not a problem at Cheney.

According to field personnel involved in the testing, several of the second-phase SDRI tests experienced high rates of infiltration and were not used in the final analysis. It was concluded that results of these SDRI tests were not representative of the Mancos Shale K. Many of the SDRI testing problems at the Cheney disposal site are directly related to volume change (swelling) properties of Mancos Shale, and macrostructure (weathering and jointing) of the Mancos Shale. Experience at the Cheney site indicates that use of the SDRI test on shale deposits can involve significant problems. Since the SDRI test required long testing times to achieve steady state, the clays have more time to swell and affect testing results.

5.2 RIFLE DISPOSAL SITE

5.2.1 Testing background

The Rifle disposal cell investigation has been conducted from 1988 to present. With more than 60 boreholes, 26 test pits, and considerable laboratory test data, the Rifle disposal cell investigation presents an excellent opportunity to evaluate an UMTRA Project *in situ* foundation material testing program.

Several phases of permeability testing of the bedrock at the Estes Gulch disposal site have been conducted. These include field studies by TAC, MK-ES with support by Morrison Knudsen-Ferguson, and Daniel B. Stephens & Associates. Laboratory permeability testing was conducted by the University of Arizona, Lambert and Associates, and Herzog Associates.

After several phases of characterization of deep and shallow Wasatch Formation siltstones, sandstones and shales, MK-ES and Daniel B. Stephens & Associates conducted long-term infiltrometer tests using the SDRI method, and intermediate and short-term permeability tests adjacent to the SDRI infiltrometer sites. The SDRI testing was conducted from October 1992 to March 1993 (see Appendix C, photographs 1 to 20). The intermediate and short-term testing which used the AEP, guelph permeameter, and disk/tension infiltrometer took approximately 1.5 months to complete (see Appendix C, photographs 21 to 34.)

This testing was done to improve the estimates of permeability of the sandstones and siltstones at the bottom of the excavation for the disposal cell. Determination of the range of *in situ* K is required for evaluation of the possibility of long-term ponding of tailings leachate at the bottom of the disposal cell (i.e., the bathtub effect). Such leachate ponding would likely cause a seep on the sideslope of the disposal cell.

Table 5.1 indicates that evaluation of results from the Rifle testing program showed relatively good agreement between the SDRI and AEP methods. Figure 5.1 is a semilogarithmic plot of hydraulic conductivity results from AEP and SDRI testing at seven of the nine Estes Gulch test sites. The geometric mean of SDRI results is 9×10^{-7} cm/s. The geometric mean of AEP results is 7×10^{-7} cm/s. The guelph permeameter and the disk permeameter produced results which were less useful.

5.2.2 Testing evaluation

Initial phases of K testing failed to conclusively define the K range of the foundation materials underlying the Rifle disposal cell. In late 1991, several samples were submitted to two testing laboratories for determination of saturated K. It was discovered at completion of testing that the laboratories were not using the same test methods. Lambert and Associates used a method known as the Holtz method and Herzog and Associates used ASTM method D5084. The laboratories also used different consolidation stresses to simulate overburden pressures. Samples that

**Table 5.1 K_{fs} testing results at Estes Gulch disposal cell (cm/s)
(October 1992 - February 1993)**

Test site no.	Unit	Lithologic description	Test methods			
			SDRI	AEP	Disc	Guelph
1	D	Sandstone	5×10^{-7}	1×10^{-7}	a	9.9×10^{-3}
2	E-F	Siltstone	3×10^{-5}	a	6.8×10^{-6}	2.1×10^{-6}
3	D	Sandstone	5×10^{-5}	6×10^{-6}	a	1.9×10^{-5}
4	D	Sandstone	1×10^{-7}	4×10^{-6}	a	a
5	D	Sandstone	1×10^{-4}	a	2.8×10^{-5}	9.8×10^{-7}
6	E	Sandstone	1×10^{-6}	5×10^{-7}	a	2.1×10^{-6}
7	E	Sandstone	9×10^{-8}	3×10^{-7}	8.7×10^{-6}	1.1×10^{-6}
8	F	Siltstone/sandstone	1×10^{-6}	4×10^{-7}	2.1×10^{-6}	2.8×10^{-7}
9	F	Sandstone	2×10^{-6}	4×10^{-7}	6.4×10^{-6}	1.1×10^{-6}

^aFailed test.

Notes:

AEP and SDRI methods test vertical K_{fs} .

Disc and guelph methods test three-dimensional K_{fs} .

Results of AEP tests from Daniel B. Stephens & Associates (1993) were rounded to one significant digit.

were tested for confirmatory reasons from the same interval were characterized differently (i.e., sandstone versus siltstone).

Looking back at the situation, it appears that use of the second laboratory for verification of K may not have been justified. Natural heterogeneity is more than enough reason for variation in K. Different testing methods, different tested intervals, and variable confining stresses indicate inadequate planning.

Laboratory test results were eventually discounted because they were considered to be unrepresentatively low. Field measurements of K from various packer tests, although they were considered to have low reliability, were chosen over the laboratory data to establish ranges of K for various rock types in the disposal cell. Uncertainty associated with field K values made it difficult to determine with certainty that bathtubbing would not occur. The SDRI and short-term tests of foundation materials were proposed to provide K values that could be used with certainty in the bathtub analysis of the Rifle cell.

After deciding that the SDRI method would be used, there were concerns of completing the testing before winter because extreme temperature fluctuations can affect SDRI test results.

NOTE: CONDUCTED 10/92 - 2/93

FIGURE 5.1
SDRI AND AEP K_{fs} TESTING RESULTS AT RIFLE, COLORADO (ESTES GULCH)
DISPOSAL CELL SITE

The Rifle site SDRI tests were not started until October 1992 and they were run well into the coldest 4-month period of the year. (Photographs 1 and 2, Appendix C, show site conditions during January 1993.) The AEP, guelph, and disc permeameter tests were also subjected to these cold-weather conditions.

5.3 SUMMARY OF OBSERVATIONS UPON REVIEW OF HISTORICAL UMTRA PROJECT TESTING TO DETERMINE FIELD-SATURATED HYDRAULIC CONDUCTIVITY

Following review of existing records and interviews with the TAC and MK-ES personnel regarding foundation testing at the Cheney and Rifle disposal cells, the following observations were made:

- Recent *in situ* K_{fs} testing at the Rifle disposal site indicates good agreement between AEP and SDRI results. Use of the AEP instead of the SDRI would allow for more efficient use of budget and time.
- Both testing programs were conducted under adverse weather conditions.
- Both testing programs indicate some lack of planning. Mistakes were made regarding QA.
- None of the available testing methods for determination of field-saturated K are easily applied to testing bedrock foundation materials.
- Future improved planning of testing programs should provide adequate data and save money.

6.0 *IN SITU* TESTING OF CELL COVERS, LINERS, AND FOUNDATIONS AT TITLE II SITES

6.1 TECHNICAL DIFFERENCES BETWEEN TITLE I AND TITLE II DISPOSAL SITES

Subparts D and E of 40 CFR Part 192 (1993) provide the EPA standards for managing wastes at active uranium and thorium processing sites (Title II sites). Technical criteria pertaining to tailings disposal were established by the NRC in Appendix A of 10 CFR Part 40 (1993). The NRC perspective on *in situ* testing of cell covers, liners, and foundation materials was gained through discussion with NRC personnel at the Uranium Recovery Field Office in Denver.

The primary technical difference (relative to application of *in situ* K_{fs} testing methods) between Title I and Title II sites is that Title II sites are stabilized in place. Therefore, detailed foundation testing is not as feasible and liner construction/testing is not practical.

6.2 TITLE II PERSPECTIVE REGARDING *IN SITU* TESTING AT URANIUM MILL TAILINGS DISPOSAL SITE

The NRC stated that *in situ* testing has not been performed on Title II sites. Although a clay cap is constructed over the Title II tailings piles, testing of the cap is limited to laboratory testing to ensure that compliance (i.e., $K = 10^{-7}$ cm/s) is achieved.

The primary reason for not performing *in situ* testing is that the NRC has many sites, called living models, for which they have 40 to 50 years of data. Title II experience indicates that after constructing a cap, water levels in the cells diminish and contaminant levels in surrounding monitor wells drop steadily with time. The NRC believes these living models show results so consistently in a qualitative way that they do not have to be concerned with detailed quantitative testing programs to determine precise ranges of K .

The NRC indicated that in the near future *in situ* testing and other types of detailed quantitative analysis may become part of Title II site investigations. However, they feel that their practical approach has worked and that detailed investigations such as field-saturated K testing would be a misuse of financial resources.

7.0 PRACTICAL GUIDELINES FOR *IN SITU* TEST SELECTION IN THE DETERMINATION OF FIELD-SATURATED HYDRAULIC CONDUCTIVITY OF NEAR-SURFACE MATERIALS ON THE UMTRA PROJECT

Through the detailed analysis of potential methods for determination of *in situ* field-saturated K, a more planned approach can be taken for selecting future test methods on the UMTRA Project. The key technical findings of this special study, which will aid in decision-making regarding test selection, are summarized in Table 7.1.

From a cost and efficiency perspective, Table 7.1 indicates that there are several methods for determining near-surface vertical field-saturated K (i.e., the AEP and potentially the constant head pressure infiltrometer) that are highly competitive with the SDRI method. Costs shown in the table assume that only one test is conducted. The cost per test would generally decrease for a program requiring multiple tests. Assuming an average of the costs per test presented in Table 7.1, for a program requiring ten tests, a potential savings of \$100,000 could be realized by using the AEP method instead of the SDRI method. Perhaps the biggest obstacles to overcome in achieving wider acceptance of methods such as the AEP is obtaining technically approved ASTM standards and educating regulators regarding the use of alternative methods.

Table 7.1 Practical guidelines for *in situ* K_{fs} test selection for near-surface materials on the UMTRA Project

Test method	Dimension of K determined from test	Primary advantages	Primary disadvantages	Approximate cost of testing per test	Lower limit of K testing	Degree of acceptance by regulating community	Application for cover and liner or foundation material
SDRI	Vertical, 1-dimensional	Large sample tested; ASTM standard	Relatively expensive; long testing times; only provides infiltration rate; relatively difficult to replicate	\$10,000-\$20,000	10^{-8} cm/s	High	Covers and liners
AEP	Vertical, 1-dimensional	Easy to replicate; short testing times	Shallow wetting front; highly dependent on suction term	\$4000-\$7000	10^{-9} cm/s	Medium	Covers, liners, and foundation materials
Guelph permeameter	3-dimensional	Facilitates testing at depth	Sidewall smear	\$3000-\$4500	10^{-6} cm/s	Medium	Foundation materials
TSB technique	Determination of K_h and K_v	Provides K_h and K_v	Sidewall smear; may neglect effects of unsaturated flow	\$3000-\$5000	10^{-9} cm/s	Medium	Applicable for testing cover and liner test pads when unsaturated conditions are accounted for
Constant head pressure infiltrometer	Vertical, 1-dimensional	Short testing times; easy to replicate; accounts for divergence of flow and capillarity	Shallow wetting front	\$4000-\$7000	10^{-7} cm/s (may be lower)	Low	Covers, liners, and foundation materials. High potential for UMTRA use. Method should be tested.
Disc permeameter	3-dimensional	Easy setup; relatively inexpensive	Fragile instrumentation	\$2500-\$4000	10^{-6} cm/s	Low	Not applicable for UMTRA testing

8.0 SUMMARY AND CONCLUSIONS

The conclusions of this special study are summarized below:

- The results of any attempt at measurement of K_{fs} is highly dependent on the methodology employed. To improve the utility of measurement values, it is imperative that methodological protocol be clearly identified and strictly adhered to. It is also advisable that some measurement redundancy be built into the sampling plan when the K measurement is of a highly critical nature.
- The lack of approved *in situ* testing standards and acceptance by the regulating community influences the degree of use of particular test methods. Interviews with experts in this field indicate that preference for various methods is, at least in part, geographically, socially, politically, and marketing based.
- Although no method has been invented that is well suited for *in situ* determination of field-saturated K in heterogeneous and anisotropic near-surface materials such as bedrock foundations, the SDRI, AEP, guelph permeameter, TSB, and pressure infiltrometer are all potentially applicable methods for near-surface *in situ* testing on the UMTRA Project.
- The TSB method, the only method presented which allows for determination of K_v and K_h , should be used only to test clay covers and liners. If this method is used, care should be taken to properly account for unsaturated conditions.
- Based on information gathered during this special study, the SDRI and AEP are currently best suited for determination of vertical K of low-K, near-surface materials.
- Methods that require short test times and are capable of providing high quality data, such as the AEP, are recommended over the SDRI when testing heterogeneous materials.
- Use of the AEP is supported by results obtained during recent Rifle testing. Rifle testing indicated that the SDRI and AEP are capable of providing results in close agreement in heterogeneous low-K materials.
- Due to heterogeneity of bedrock materials and associated uncertainty, it is not practical to spend larger amounts of time and money necessitated by use of the SDRI method.
- The pressure infiltrometer, which is similar to the AEP but also accounts for effects of flow divergence and capillarity, should be tested for use at UMTRA Project disposal sites.
- Representatives of the Title II program have stated that based on their living models (Title II sites for which they have 40 to 50 years of data), *in situ* testing of cell covers and foundation materials is not required. A special study should be conducted of the Title II ground water quality data trends. If data were compiled and analyzed in an

organized manner, perhaps information could be obtained which would reduce UMTRA Project remedial costs.

- If detailed *in situ* K investigations are to continue on the UMTRA Project, observations from examination of historical *in situ* testing suggest that increased planning regarding *in situ* test program design should be performed. Increased planning efforts will allow for selection of optimum *in situ* test methods and test conditions, and optimum laboratory testing procedures to bound field results.
- Planning procedures or data collection objectives regarding *in situ* testing should be outlined formally in order to better achieve data quality objectives without impacting UMTRA Project schedules and budgets.
- Of the available *in situ* test methods for moderate to deep testing to determine K_{fs} , the BAT probe and the constant head borehole permeameter have the highest potential for use on the UMTRA Project. Where numerous tests are required in a very short period of time and a less rigorous mathematical theoretical foundation is required, the BAT probe is recommended. However, if deep test results are of a very critical nature, the constant head borehole permeameter methods which account for unsaturated conditions should be used.

9.0 LIST OF CONTRIBUTORS

The following individuals contributed to the preparation of this audit report.

Name	Contributors
T. Monks	Document responsibility; primary author
J. Lommler	Document responsibility; author
WordCenter Inc., C. Slosberg	Text processing
J. Torline	Technical editing, document publication coordination

10.0 REFERENCES

- Ankeny, M. D., 1992. "Methods and Theory for Unconfined Infiltration Measurements. Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice," Soil Science Society of America Special Publication No. 30, pp. 123-141.
- Ankeny et al. (M. D. Ankeny, T. C. Kaspar, and A. Horton), 1988. "Design for an Automated Tension Infiltrometer," in *Soil Science Society of America Journal*, Vol. 52, pp. 893-896.
- ASTM (American Society for Testing and Materials), 1990. Standard Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer With a Sealed Inner Ring, Method D-5093, 6 pp.
- ASTM (American Society for Testing and Materials), 1988. Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometers, Method D-3385, 7 pp.
- Benson et al. (C. H. Benson, F. S. Hardianto, and E. S. Motan), 1993. "Representative Sample Size for Hydraulic Conductivity Assessment of Compacted Soil Liners," Hydraulic Conductivity and Waste Contaminant Transport in Soils, American Society for Testing and Materials STP 1142.
- Boutwell, G. P., 1993. Soil Testing Engineers, Inc, personal communication with Tod Monks and John Lommler, Jacobs Engineering Group Inc., UPDCC file location no. 0.2.2.38.79, Albuquerque, New Mexico.
- Boutwell, G. P., 1992. STEI Two-Stage Borehole Field Permeability Test, *Proceedings of the Containment Liner Technology and Subtitle D Seminar*, sponsored by Geotechnical Committee, Houston Branch, ASCE, Houston, Texas.
- Bouwer, H., 1986. *Methods of Soil Analysis*, Part I: Physical and Mineralogical Methods, Agronomy Monograph No. 9 (second edition), Chapter 32, "Intake Rate: Cylinder Infiltrometer," American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin.
- Bouwer, H., 1978. *Groundwater Hydrology*, McGraw-Hill, New York, NY.
- Bouwer, H., 1966. "Rapid Field Measurement of Air-Entry Value and Hydraulic Conductivity of Soils as Significant Parameters in Flow Systems Analysis," in *Water Resources Research*, Vol. 2(4), pp. 729-738.
- Daniel B. Stephens & Associates, 1993. "In Situ Permeability Testing at the UMTRAP Estes Gulch Disposal Cell, UMTRA Project, Rifle, Colorado," prepared for MK-Ferguson, Albuquerque, New Mexico and MK Environmental Services, San Francisco, California.

- Swartzendrucker, P., and T. C. Olson, 1961. "Model Study of the Double-Ring Infiltrometer as Affected by Depth of Wetting and Particle Size," *Proceedings, Soil Science Society of America*, Vol. 92, pp. 219-225.
- Torstensson, B. A., 1984. "A New System for Ground Water Monitoring," in *Ground Water Monitoring Review*, Vol. 4(4), pp. 131-138.
- Trautwein, S. J., and G. P. Boutwell, 1993. "In Situ Hydraulic Conductivity Tests for Compacted Soil Liners and Caps," Conference on Hydraulic Conductivity and Waste Containment Transport on Soils, American Society for Testing and Materials, San Antonio, Texas.
- Trautwein, S. J., and C. E. Williams, 1990. "Performance Evaluation of Earthen Liners," in *Waste Containment Systems*, Geotechnical Special Publication No. 26, American Society of Civil Engineers, November 1990, pp. 30-49.
- Williams, C. E., 1988. "Facts About the Design and Construction of Earthen Containment Structures," fall meeting, Texas Section of the American Society of Civil Engineers, College Station, Texas.

FEDERAL REGISTER

- 52 FR 36000, "Standards for Remedial Actions at Inactive Uranium Processing Sites; Proposed Rule," September 24, 1987.

CODE OF FEDERAL REGULATIONS

- 40 CFR Part 192, "Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings," U.S. Environmental Protection Agency (1993).
- 10 CFR Part 40, "Domestic Licensing of Source Material," U.S. Nuclear Regulatory Commission (1993).

UNITED STATES CODES

- 42 USC §7901 *et seq.*, *Uranium Mill Tailings Radiation Control Act*, November 8, 1978.

APPENDIX A

**LIST OF AVAILABLE REFERENCES IN DOCUMENT CONTROL
UMTRA PROJECT OFFICE
ALBUQUERQUE, NEW MEXICO**

***IN SITU* TESTING TO DETERMINE FIELD-SATURATED
HYDRAULIC CONDUCTIVITY OF UMTRA PROJECT
DISPOSAL CELL COVERS, LINERS, AND
FOUNDATION AREAS**

SPECIAL STUDY

All documents included in this reference list are on file in the UMTRA Project Document Control Center (UPDCC), UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.

- Ahuja, L. R., 1982. "Determining Unsaturated Hydraulic Conductivity of Soil During Drainage Under a Small Ring Infiltrometer," in *Journal of Hydrology*, Vol. 58, pp. 167-173.
- Aiken, M. D., 1993. Daniel B. Stephens & Associates, personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Amoozegar, A., 1989. "A Compact Constant-Head Permeameter for Measuring Saturated Hydraulic Conductivity of the Vadose Zone," in *Soil Science Society of America Journal*, Vol. 53, pp. 1356-1361.
- Amoozegar, A., 1989. "Comparison of the Glover Solution with the Simultaneous-Equations Approach for Measuring Hydraulic Conductivity," in *Soil Science Society of America Journal*, Vol. 53, pp. 1362-1367.
- Ankeny, M. D., 1993. Daniel B. Stephens & Associates, personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Ankeny, M. D., 1992. "Methods and Theory for Unconfined Infiltration Measurements, Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice," Soil Science of America Special Publication No. 30.
- Ankeny, M. D., M. Ahmed, T. C. Kaspar, and R. Horton, 1991. "Simple Field Method for Determining Unsaturated Hydraulic Conductivity," in *Soil Science Society of America Journal*, Vol. 55, pp. 467-470.
- Baehr, A. L., and M. F. Hult, 1991. "Evaluation of Unsaturated Zone Air Permeability Through Pneumatic Tests," in *Water Resources Research*, Vol. 27, No. 10, pp. 2605-2617.
- Baker, F. G., P. L. M. Veneman, and J. Bouma, 1974. "Limitations of the Instantaneous Profile Method for Field Measurement of Unsaturated Hydraulic Conductivity," in *Soil Science Society of America*, Vol. 38, pp. 885-888.
- Bedinger, M. S., and P. R. Stevens, 1988. "Safe Disposal of Radionuclides in Low-Level Radioactive-Waste Repository Sites," in *Proceedings of the Low-Level Radioactive-Waste Disposal Workshop*, U.S. Geological Survey, Department of the Interior, July 11-16, 1987, Big Bear Lake, California.

- Cercone, J., 1993. Morrison Knudsen-Environmental Services, personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Chandler, M. A., D. J. Goggin, and L. W. Lake, 1989. "A Mechanical Field Permeameter for Making Rapid, Non-Destructive, Permeability Measurements," in *Journal of Sedimentary Petrology*, Vol. 59, No. 4, pp. 613-635.
- Chandler, R. J., S. Leroueil, and N. A. Trenter, 1990. "Measurements of the Permeability of London Clay Using a Self-Boring Permeameter," in *Geotechnique*, Vol. 40, No. 1, pp. 113-124.
- Chapuis, R. P., K. Baass, and L. Davenne, 1989. "Granular Soils in Rigid-Wall Permeameters: Method for Determining the Degree of Saturation," in *Can. Geotech. J.*, Vol. 26, pp. 71-79.
- Chen (Chen and Associates Laboratories), 1987. "Particle Size Distribution for Belfield and Bowman UMTRA Project Sites," unpublished geotechnical data prepared in June 1987, available at the U.S. Department of Energy, UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico.
- Clothier, B. E., and I. White, 1981. "Measurement of Sorptivity and Soil Water Diffusivity in the Field," in *Soil Science Society of America Journal*, Vol. 45, pp. 241-245.
- Clothier, B. E., and K. R. J. Smettem, 1990. "Combining Laboratory and Field Measurements to Define the Hydraulic Properties of Soil," in *Soil Science Society of America Journal*, Vol. 54, pp. 299-304.
- Coen, G. M., and C. Wang, 1989. "Estimating Vertical Saturated Hydraulic Conductivity From Soil Morphology in Alberta," in *Canadian Journal of Soil Science*, Vol. 69, No. 1.
- Cook, F. J., 1991. "Calculation of Hydraulic Conductivity From Suction Permeameter Measurements," in *Soil Science*, Vol. 152, No. 5.
- Cullen, S., 1993. Geraghty & Miller, Inc., personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Dane, J. H., and A. Klute, 1977. "Salt Effects on the Hydraulic Properties of a Swelling Soil," in *Soil Science Society of America Journal*, Vol. 41, pp. 1043-1049.
- Daniel B. Stephens & Associates, 1993. "In Situ Permeability Testing at the UMTRAP Estes Gulch Disposal Cell, UMTRA Project, Rifle, Colorado," prepared for Morrison Knudsen-Ferguson.

- Fadl, A. E., 1979. "A Modified Permeameter for Measuring Hydraulic Conductivity of Soils," in *Soil Science*, Vol. 128, No. 2, pp. 126-128.
- Fernuik, N., and M. Haug, 1990. "Evaluation of In Situ Permeability Testing Methods," *Journal of Geotechnical Engineering*, Vol. 116, No. 2.
- Foreman, D. E., and D. E. Daniel, 1986. "Permeation of Compacted Clay with Organic Chemicals," in *Journal of Geotechnical Engineering*, Vol. 112, No. 7.
- Goldman, L. J., R. S. Truesdale, G. L. Kingsbury, C. M. Northeim, and A. S. Damle, 1986. "Design, Construction and Evaluation of Clay Liners for Waste Management Facilities Draft Technical Resource Document for Public Comment," U.S. Department of Commerce, National Technical Information Service.
- Gordon, M. E., P. M. Huebner, and T. J. Miazga, 1989. "Hydraulic Conductivity of Three Landfill Clay Liners," in *Journal of Geotechnical Engineering*, Vol. 115, No. 8.
- Hansen, L. A., R. D. Booth, and G. H. Beckwith, 1989. "Characterization of a Site Underlain by Deep Collapsing Soils," *Foundation Engineering: Current Principles and Practices*, Vol. 1.
- Havlena, J. A., 1993. Daniel B. Stephens & Associates, personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Healy, R. W., M. P. deVries, and R. G. Striegl, 1986. "Concepts and Data-Collection Techniques Used in a Study of the Unsaturated Zone at a Low-Level Radioactive-Waste Disposal Site Near Sheffield, Illinois," U.S. Geological Survey, Water-Resources Investigations Report 85-4226.
- Heinen, M., and P. A. C. Raats, 1990. "Evaluation of Two Models Describing the Steady Discharge From a Constant Head Well Permeameter Into Unsaturated Soil," in *Soil Science*, Vol. 150, No. 1.
- Hill, R. L., and L. D. King, 1982. "A Permeameter Which Eliminates Boundary Flow Errors in Saturated Hydraulic Conductivity Measurements," in *Soil Science Society of America Journal*, Vol. 46, pp. 877-880.
- Jabro, J. D., and D. D. Fritton, 1990. "Simulation of Water Flow from a Percolation Test Hole in Layered Soil," in *Soil Science Society of America Journal*, Vol. 54, pp. 1214-1218.
- Jennings, A. A., and V. Ravi, 1990. "Analytical Extensions of the Discrete Interface Penetration Model for Dynamic Permeability Analysis," in *Soil Science Society of America Journal*, Vol. 54, pp. 7-12.

- Michiels, P., R. Hartmann, and E. De Strooper, 1989. "Comparisons of the Unsaturated Hydraulic Conductivity of a Coarse-Textured Soil and Determined in the Field, in the Laboratory, and With Mathematical Models," in *Soil Science*, Vol. 147, No. 4.
- Morrison Knudson Corporation, 1992. "Evaluation of Surficial Soil and Rock Foundation Conditions Estes Gulch Disposal Cell, UMTRA Project, Rifle Colorado."
- Paillet, F. L., 1988. "Fracture Characterization and Fracture-Permeability Estimation at the Underground Research Laboratory in Southeastern Manitoba, Canada," U.S. Geological Survey, Water-Resources Investigations Report 88-4009.
- Paillet, F. L., A. E. Hess, and R. H. Morin, 1990. "Estimation of the Relative Permeability Distribution in Fractured Granitic Rocks by Means of Vertical Flow Measurements in the Siblingen Borehole, Switzerland," U.S. Geological Survey, Water-Resources Investigations Report 90-4034.
- Papusch, R., 1993. Jacobs Engineering Group Inc., personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Parlange, J. Y., M. Vauclin, R. Haverkanp, and I. Lisle, 1985. "Note: The Relation Between Desorptivity and Soil-Water Diffusivity," in *Soil Science*, Vol. 139, No. 5.
- Parlange, J. Y., R. Haverkanp, and C. Fuentes, 1988. "A Note on Linearized Infiltration," in *Soil Science*, Vol. 145, No. 4.
- Petsonk, A. M., 1988. "Hydraulic Conductivity Measurements in Unsaturated Materials-Field vs. Lab Methods," *Ground Water Monitoring Review*, Spring.
- Philip, J. R., 1985. "Approximate Analysis of the Borehole Permeameter in Unsaturated Soil," in *Water Resources Research*, Vol. 21, No. 7, pp. 1025-1033.
- Philip, J. R., 1986. "Steady Infiltration From Spheroidal Cavities in Isotropic and Anisotropic Soils," in *Water Resources Research*, Vol. 22, No. 13, pp. 1874-1880.
- Pierce, J. J., G. Salfors, and L. Murray, 1986. "Overburden Pressures Exerted on Clay Liners," in *Journal of Environmental Engineering*, Vol. 112, No. 2.
- Rayment, S. W., and J. L. Moruzzi, 1978. "Electron Detachment Studies Between O⁻ Ions and Nitrogen," in *International Journal of Mass Spectrometry and Ion Physics*, Vol. 26, pp. 321-326.
- Reynolds, W. D., 1993. Agriculture Canada, Research Branch, personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.

- Stephens, D. B., 1985. "A Field Method to Determine Unsaturated Hydraulic Conductivity Using Flow Nets," in *Water Resources Research*, Vol. 21, No. 1, pp. 45-50.
- Stephens, D. B., K. Lambert, and D. Watson, 1987. "Regression Models for Hydraulic Conductivity and Field Test of the Borehole Permeameter," in *Water Resources Research*, Vol. 23, No. 12, pp. 2207-2214.
- Stephens, D. B., and S. P. Neuman, 1982. "Vadose Zone Permeability Tests: Unsteady Flow," in *Journal of Hydraulics Division*, Proceedings of the American Society of Civil Engineers, Vol. 108, No. HY5.
- Stephens et al. (D. B. Stephens, M. Unruh, J. A. Havlena, R. G. Knowlton, Jr., E. Mattson, and W. Cox), 1988. "Vadose Zone Characterization of Low-Permeability Sediments Using Field Permeameters," in *Ground Water Monitoring Review*, Spring, pp. 59-66.
- Stonestrom, D. A., and J. Rubin, 1989. "Air Permeability and Trapped-Air Content in Two Soils," in *Water Resources Research*, Vol. 25, No. 9, pp. 1959-1969.
- Tolikas, P. K., D. K. Tolikas, and C. D. Tzimopoulos, 1983. "Vertical Infiltration of Water Into Unsaturated Soils With Variable Diffusivity and Conductivity," in *Journal of Hydrology*, Vol. 62, pp. 321-332.
- Trautwein, S., 1993. Soil Testing Equipment Company, personal communication with Tod Monks, Jacobs Engineering Group Inc., UPDCC File Location No. 0.2.2.38.79, Albuquerque, New Mexico.
- Trautwein, S. J., and G. P. Boutwell, 1993. "In Situ Hydraulic Conducting Tests for Compacted Soil Liners and Caps," in *Conference on Hydraulic Conductivity and Waste, Containment Transport in Soils*, American Society for Testing and Materials, San Antonio, Texas.
- Uppot, J. O., and R. W. Stephenson, 1989. "Permeability of Clays Under Organic Permeants," in *Journal of Geotechnical Engineering*, Vol. 115, No. 1.
- Vepraskas, M. J., A. G. Jongmans, M. T. Hoover, and J. Bouma, 1991. "Hydraulic Conductivity of Saprolite as Determined by Channels and Porous Groundmass," in *Soil Science Society of America Journal*, Vol. 55, pp. 932-938.
- Water Resources Research Investigation No. 180, "In Situ Determination of Hydraulic Conductivity in the Vadose Zone Using Borehole Infiltration Tests," New Mexico Water Resources Research Institute, 1983, Technical Completion Report, Project No. 1423648, New Mexico State University, Las Cruces, New Mexico, p. 140.
- Wei, K. K., 1983. "Effect of Confining Pressure and Temperature on Low Permeability Sandstone," masters thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico, September.

APPENDIX B

AMERICAN SOCIETY FOR TESTING AND MATERIALS METHODS

***IN SITU* TESTING TO DETERMINE FIELD-SATURATED
HYDRAULIC CONDUCTIVITY OF UMTRA PROJECT
DISPOSAL CELL COVERS, LINERS, AND
FOUNDATION AREAS**

SPECIAL STUDY

APPENDIX D

INTERVIEWS

***IN SITU* TESTING TO DETERMINE FIELD-SATURATED HYDRAULIC
CONDUCTIVITY OF UMTRA PROJECT DISPOSAL CELL COVERS, LINERS, AND
FOUNDATION AREAS**

SPECIAL STUDY

Herman Bouwer, Chief Engineer/U.S. Department of Agriculture, Phoenix, Arizona
Interview Date: July 1, 1993
Subject: Determination of Field-Saturated Hydraulic Conductivity

Profile on Herman Bouwer:

Herman Bouwer first proposed the air-entry permeameter (AEP) in the mid-1960s as a means to determine the vertical, field-saturated hydraulic conductivity (K) of geologic materials above the water table. Herman Bouwer has published numerous papers dealing with determination of *in situ* K.

Question 1:

Do you consider the AEP to be the most suitable instrument with which to determine field-saturated K in the vadose zone?

Answer:

Yes I do. The AEP was originally developed to measure K of agricultural soils. These relatively permeable soils have suction terms which are usually in the range of 10-20 centimeters. With these small suctions, errors introduced from estimating this term are not very significant. However, suctions in fine grained soils can be as great as 200 centimeters. It is possible that with a 1.0 meter standpipe, the total head estimated could be off by as much as 100 cm if suction at the wet front is estimated instead of measured. This can introduce a significant amount of error into the analysis.

The AEP allows for fairly rapid measurement of field-saturated K. Results can be obtained within about 1/2 hour, longer in soils with very low permeability.

Question 2:

In general, on the Uranium Mill Tailings Remedial Action (UMTRA) Project we are primarily concerned with determination of vertical K of covers, liners, and foundation material. Vertical heterogeneity and anisotropy are generally difficult to assess from testing relatively small, surficial sample volumes. How can the AEP be used to account for these factors?

Answer:

The AEP can be used at different depths to establish changes in vertical hydraulic conductivity. I have tested vertical profiles at intervals of 1 foot for depths extending up to 8 feet. In addition, since results can be obtained rather quickly, samples can be obtained from numerous locations thereby increasing the sampling frequency. If I can come within 50 and 100 percent of the mean hydraulic conductivity when testing naturally occurring materials, this is acceptable to me. Natural formations are inherently heterogeneous.

Question 6:

Do you consider the quality of water used during this type of testing to be an important consideration in obtaining a representative K (a K which will be representative of Kv after being saturated with tailings leachate and equilibrating with the surrounding foundation or liner material)?

Answer:

Yes, there are many studies which have shown that changes in ionic composition of water change clay structure and cause increases in permeability. Permeability can increase as a result of contact with leachate having an elevated TDS. Calcium adsorption can also lead to coagulation in clays and increases in permeability. Water quality used in testing should approximate the potentially contaminating leachate which will come in contact with the soil materials.

Answer:

Problems with the use of an SDRI include typically uneven wetting front on the tested materials, difficulty in determination of the hydraulic gradient and long testing times.

Question 5:

Do you think that methods currently in use for the determination of field-saturated K, many of which were designed for agricultural soils, have serious flaws in their assumptions and therefore we should be striving for something more accurate? Or do you think that our estimates of field-saturated K are close enough considering all of the uncertainty due to natural heterogeneity and anisotropy as well as imperfections such as cracking introduced during clay compaction. Do you think it matters if the techniques are further perfected?

Answer:

I believe we are pushing the limits on accuracy considering all uncertainties associated with K determination. I see few modifications occurring which will significantly alter equipment design.

Question 6:

I have noticed from the literature review which is part of this special study that several authors feel that laboratory results tend to underestimate actual *in situ* K. Do you feel this way?

Answer:

Field tests generally yield larger values of K.

Question 7:

In your opinion, what are the biggest limitations with respect to using the guelph permeameter, AEP, disc permeameter, and the SDRI?

Answer:

Guelph permeameter - Smearing of material over soil or rock pores during borehole preparation.

AEP - Edge effects, determination of the air entry value and accurate determination of the wetting front.

Disc permeameter - Only applicable for materials having a $K > 10^{-6}$ centimeters per second (cm/s).

SDRI - Determination of accurate gradient is difficult. Costs can be excessive. Because of time demand and details of testing, there is a lack of ability to replicate tests.

Answer:

I question whether you can obtain reliable results with borehole permeameters at such depths.

before the AEP was properly installed. At measurement sites #2 and #5, the numerous fractures within the sandstone made installation impossible.

In addition, the fracturing and variable lithology/cementation resulted in a variable wetting front depth for the vast majority of AEP tests. Due to the wetting front variability, two methods were utilized to determine its depth. First, a steel rod was driven through the wetted zone at several locations until firm resistance was encountered, and the depth of firm resistance recorded. Then, the wetted zone was excavated and the wetting front determined visually and depth recorded. Both methods showed good agreement as to wetting front depth. An average wetting front depth was then calculated and later used in the calculations of saturated hydraulic conductivity.

The Guelph Permeameter was generally easy to install and conduct measurements with at all the measurement sites. The main difficulties experienced resulted from the low temperatures causing freezing of water within the apparatus, and the inability to determine, a priori, a fracture free measurement location. The hydraulic conductivity calculated from the Guelph permeameter data at site #1, in my opinion, reflect such a hidden fracture.

Difficulties with the disc infiltrometer were discussed in question #1.

With regard to the different values of hydraulic conductivity calculated by the three methods at even a particular site the difference in theory between the methods should be considered as well as the heterogenous and anisotropic measurement materials. In addition, the AEP is a 1-dimensional flow measurement while both other methods assume 3-dimensional flow fields. In further applications, the use of a conservative tracer or dye is advisable to better determine the depth and extent of wetting caused by a test.

Question 3:

Explain why you support the use of the TSB technique.

Answer:

The TSB technique is applicable to natural and compacted materials because it allows for determination of both vertical hydraulic conductivity (K_v) and horizontal hydraulic conductivity (K_h). It is equivalent to running two slug tests at the same location. Although sidewall smear can be a problem as with any borehole method, it is possible to determine K_h and K_v to a depth of 30 feet. We can obtain a representative K on a material having K as low as 10^{-9} cm/s in about 1 week. If materials have a $K > 10^{-7}$ cm/s, results can be obtained within 48 hours. A greater volume of material is tested with the TSB method than some of the other methods. In addition you don't have to estimate how far the flow field extends as you do with the AEP.

At deeper intervals (> 10 feet) I recommend hollow stem augering to the desired testing depth.

Question 4:

How important do you think the use of representative water quality (i.e., water quality which approximates that of acid leachate) would be in determining representative K values when testing to determine field-saturated K ?

Answer:

I think the impact of water quality can be a significant factor when attempting to determine representative values for field-saturated hydraulic conductivity, but primarily with very high concentration leachates. I recommend the performance of a separate laboratory study to determine any compatibility effect. We don't want to pollute the natural ground by our test itself! I would first run natural water through the material and then conduct other tests running the anticipated quality of leachate through the material. Impacts on the materials can then be studied.

Question 5:

Do you feel that there is too much emphasis on achieving a certain K instead of realizing that K will almost always be a distribution in naturally occurring materials?

Answer:

Yes, I believe there is too much emphasis on obtaining one number. In general, I believe a mean and a deviation should be determined as well as a statistical probability of that mean being bad or good. Many people who are in positions of making decisions regarding whether a certain value of K is acceptable, are relatively uneducated when it comes to the physical understanding of hydraulic conductivity.

Steve Trautwein, President, Trautwein Soil Testing Equipment Co., Houston, Texas

Interview Date: June 14, 1993

Subject: Determination of Field-Saturated Hydraulic Conductivity

Profile on Steve Trautwein:

Steve Trautwein has been extensively involved in field testing and has had the unique experience of "hands on" involvement with a wide variety of testing methods on projects throughout the country. Steve Trautwein is very supportive of the SDRI method of testing to obtain field-saturated K. He is recognized as an expert regarding the SDRI method.

Question 1:

What is your opinion regarding the AEP method of determination of field-saturated K for low-K materials?

Answer:

It is my opinion that the AEP is not suitable for field measurements of saturated K for fine-grain soils ($K < 1 \times 10^{-6}$ cm/s). The AEP test consists of two stages. The first stage requires that a steady-state infiltration rate be measured. The second stage involves the determination of the air-entry suction. Fine-grain soils present serious problems for both stages.

During the first stage, sealed single-ring infiltrometers (SSRI) are used to measure infiltration rate. While these devices may work well in coarse-grain soils where infiltration rates are high, accuracy is a problem in fine-grain soils where infiltration rates are low. While SSRIs offer high resolution, many users do not appreciate the difference between resolution and accuracy. Accuracy is compromised due to leakage, temperature changes, expansion and contraction of the ring due to head changes, vertical movement of the ring, and soil swell. Flow in or out of the measurement standpipe due to any of these factors can be significantly greater than flow due to infiltration. For example, if a 24-inch-diameter ring is used, the amount of flow measured per day for an infiltration rate of 1×10^{-7} cm/s is approximately 25 ml. Vertical movement of the ring of 0.001 inch produces a flow of 7 ml. A typical head of 2 to 3 feet of water from the height of the standpipe generates 400 to 600 pounds of uplift. Under these circumstances, it is doubtful that vertical movement of the ring can be restricted to less than 0.1 inch of movement.

Another problem associated with the first stage is obtaining a steady-state infiltration rate. For fine-grain soils, quasisteady state is not achieved until the saturation front penetrates the test zone at least 6 to 12 inches. This typically takes several days to several weeks. However, for most of the AEP testing that I am familiar with, the first stage is terminated within 12 to 48 hours. Not only is steady state not achieved, but the thickness of the saturated zone at this time is typically less than 0.25 inches. The practical significance of a K calculated for a zone this thin is minimal. In addition, calculation of K for such a shallow saturation depth results in a value that is 5 to 10 times less than that calculated for deeper penetrations (6 to 12 inches).

Question 5:

Do you ever use water quality which is typical of leachate in your field testing programs in order to determine its impact on K?

Answer:

No, we use potable water in most cases. Most projects I have been involved with perform these studies in the lab. I have never seen water quality experiments conducted in the field.

Question 6:

What is your opinion of the guelph permeameter as a device for measuring field-saturated K of low-K materials?

Answer:

The Guelph permeameter appears to be well built but is only useful for materials possessing a $K > 10^{-7}$ cm/s. As with any borehole method, smearing can be a problem. The method is well supported mathematically but the equations are complex.

Question 7:

What is your opinion of the disc permeameter as a device for measuring field-saturated K?

Answer:

The disc permeameter is not useful for low-K soils. It is difficult to constrain the instrument from vertical movement. If it moves as little as 1/1000 of an inch, results of the test can be affected. Whatever would be gained in terms of time and cost using this method is lost on accuracy. Also, the volume of material tested is very small.

Question 8:

What is your opinion on where a laboratory program should fit into the overall testing program?

Answer:

Laboratory testing is useful for qualifying materials for clay liners and for establishing an acceptance zone. Laboratory testing is also useful for compatibility testing (using permeants other than water) and for comparative tests when the influence of such factors as stress, void ratio, water content, etc., are to be studied. It is much easier to do this type of testing in the laboratory than in the field.

The practice of extrapolating the results of laboratory testing on small-diameter specimens to determine field values of hydraulic conductivity must be used with extreme caution.

W. D. Reynolds, Soil Physicist, Agriculture Canada, Research Branch, Ottawa, Canada

Interview Date: June 8, 1993

Subject: Determination of Field-Saturated Hydraulic Conductivity

Profile on W. D. Reynolds:

Dr. Reynolds developed, in collaboration with Prof. D. E. Elrick, the theory and apparatus that comprises the guelph permeameter and pressure infiltrometer methods for *in situ* measurement of field-saturated K. He has also published many scientific and engineering articles that relate to the *in situ* measurement of field-saturated K.

Question 1:

In your opinion, what is the most accurate method or methods to determine field-saturated K of low-K materials?

Answer:

I consider the pressure infiltrometer, a single ponded ring infiltrometer method, to be currently the most appropriate. It appears to be accurate, well based on the physics of water flow in porous materials, easily replicated, and does not require extensive equipment, large amounts of water or several operators. Important theoretical advantages of the method over other ring infiltrometer methods are that it accounts for the capillarity of the porous material, and the divergence of water flow caused by the ponding and the ring wall. Theoretical aspects of the pressure infiltrometer method appear in Reynolds and Elrick (1991) and in Youngs et al. (1992) (see Appendix A).

In my opinion the second most appropriate method of testing for determining field-saturated hydraulic conductivity is the AEP. However, this ponded single ring infiltrometer method neglects the affects of porous medium capillarity (which can be very important), and the precise position of the wetting front (required for the calculations) is often difficult to detect in low-K materials.

I also recommend the use of borehole permeameters, but with caution. The UMTRA Project seems to be concerned primarily with Kv. Borehole permeameters usually provide a 3-D K value that is weighted heavily toward Kh, rather than Kv. In addition, smearing and compaction of the borehole during the augering process can result in K values that are unrepresentatively low.

Question 2:

What is your opinion on where laboratory testing should fit in with an entire testing program?

Answer:

I prefer *in situ* results field measurements of K over laboratory core measurements. The process of core insertion can cause compression if the material is wet, and shattering if

Answer:

I am not sufficiently familiar with the Boutwell TSB method to comment.

Question 7:

Do you think that the existence of an ASTM standard is adequate reason for assuming that a test method is appropriate?

Answer:

A standard is at least evidence that substantial work was done to prove that a technique has some validity. However, regulating agencies must also be flexible enough to recognize and adopt/allow the use of new techniques as they are developed and validated. Recent advances in the theory of water flow have shown that some standard ASTM methods can yield misleading results.

Question 8:

If you were asked to characterize a disposal cell foundation area similar to the one I have described in Rifle, Colorado, what would be your approach?

Answer:

I would choose a method that could provide a lot of replication. I would use the infiltrometer or AEP (or possibly the borehole permeameter if the material and application are amenable to its use) and run multiple tests. The tests would be conducted on a regularly spaced (square) grid. I would then develop a feeling for the precision and accuracy of the data from factors such as instrument range and reliability, operator error, apparent porous medium heterogeneity, etc. I would then give a mean K value (using appropriate statistics), the range of K values obtained, and a contour map of the area that shows clearly where the high and low-K values are located.

hydraulic gradient and hydraulic conductivity. Air-entry pressure is in itself an important parameter, frequently used in analysis and numerical models for simulating unsaturated flow. Other test methods (e.g., SDRI) typically assume that the air-entry pressure and the wetting front pressure head are zero. This typically leads to overly conservative values of hydraulic conductivity. Consequently, the AEP provides better estimates for saturated hydraulic conductivity than those methods which do not measure this parameter. This is especially true in dry fine-grained materials where the wetting front pressure head can be quite large. The AEP is the only field instrument capable of providing reliable estimates of wetting front pressure head.

- The most commonly used alternative method, the SDRI, is an infiltrometer which can only provide measurement of the infiltration rate—not saturated hydraulic conductivity. The AEP is a true permeameter in that it provides values for permeability (hydraulic conductivity). The ASTM Method for the SDRI acknowledges this.
- The AEP also has advantages over laboratory analysis of cores in that it provides results at a larger scale than the small diameter core samples that are typically used for laboratory analysis. There is commonly an order of magnitude difference between AEP field measurements and laboratory derived values.

If there is one advantage the SDRI method has over the AEP method, it is probably the size of the specimen being tested. However, this can be overcome using the AEP by conducting multiple tests and looking at the geostatistical distribution of the results. This approach offers a distinct advantage owing to the portability and short testing times for the AEP compared to the SDRI; usually a number of AEP tests can be conducted within the same time and budget for a single SDRI test. For applications where hydraulic conductivity varies geographically across the site (this is true for virtually everywhere), it is especially important to conduct a number of tests at different locations to assess the spatial variability of hydraulic conductivity. AEP tests are well suited to this. Additionally, various size permeameter rings can be used for the AEP. There is no limit other than practical installation and logistical issues. A two-foot diameter AEP for use in clays and low permeability materials was recently constructed at Sandia based on a design I prepared for them several years ago. Larger diameter rings are possible for certain applications.

Question 2:

If the AEP method is so much more appropriate than other methods for the determination of field-saturated K in low-K materials, why isn't there an approved ASTM method?

Answer:

Actually the AEP is covered briefly in ASTM D-5126, which I co-authored. D-5126 is a guide for comparison of field methods for determining hydraulic conductivity in the vadose zone, and includes a brief discussion and comparison of the different methods currently available, including the AEP and double ring infiltrometers. There is an effort under way within ASTM Section D.18.21.02 to develop individual Standard Test Methods, including those for the AEP. However, the drafting and approval of Standard Test Methods is a

This precedence-setting requirement no doubt stems from the fact that Iowa is an agriculturally oriented state and the Guelph Permeameter was developed for agricultural applications. Iowa probably has some soil scientists on the payroll.

Regarding the Guelph Permeameter and the other alternate test methods (AEP and disc), I think that we will see greater acceptance of these methods by the EPA state regulators once they become aware of their existence. For the most part, the SDRI has received most of the attention to date. Consequently, SDRI is most often the method of choice for regulators and consultants alike. The alternate methods which are better, cheaper and faster, such as the AEP, disc permeameter and Guelph Permeameter, will need to become more familiar to both communities.

Question 5:

Are you aware of the Boutwell TSB method and what is your opinion regarding its validity and utility?

Answer:

From what I know about the method, I do not believe that the mathematical foundation for the solution is appropriate; the solution for the TSB method appears to be a misapplication of the Hvorslev equation in unsaturated materials, and the validity of the assignment of boundary conditions is questionable. Furthermore, this method ignores capillarity. I have a number of concerns and see no clear advantage for near-surface testing offered by this method.

Question 6:

Do you think that there is any validity to the assumption that the outer ring of an SDRI constrains flow to vertical in the inner ring?

Answer:

The effectiveness of the outer ring to constrain flow from the inner ring to one dimension is only an assumption which could be achieved with the proper ring geometry in homogeneous materials. It is unlikely that this could be accomplished using the typical ring design and in typical layered heterogeneous materials. The 'f' factor for lateral spreading used in the solution for the SDRI admits this.

Question 7:

In general terms, what type of cost savings can be experienced from use of the AEP over the SDRI?

Answer:

We have done a general cost analysis and we estimate that on the average, AEP testing costs approximately 1/5 of what the SDRI tests cost. The savings could be more or less,

another project. They were shown only a small exposure of the bedrock on site and brought back a sample of the rock that was very soft and easily worked. I designed the project based on the ease with which the one sample could be worked back at our lab in Albuquerque. When I finally got to the Rifle site and started testing, it became apparent that most of the material was far harder, more brittle and difficult to work than the sample was. I would like have visited the site beforehand to look at both fresh and weathered exposures of the Wasatch.

Question 10:

In your opinion, what measures can be taken to gain increased certainty in the determination of field-saturated K?

Answer:

First, identify the objectives of the testing program. Ideally this should be done through a formal data quality objectives (DQO) process which addresses the end uses and users of the data. Use the appropriate test methods and number of individual tests and locations to meet these objectives; a single measurement in the middle of a several acre plot is not sufficient, nor is the use of a three-dimensional test method where one-dimensional results are required. Identify and address uncertainty and error in the test methods and resulting measurements. The DQO process is well developed for analytical chemistry and similar applications, but is virtually never rigorously applied to vadose zone testing. Without some type of DQO approach, most of the common errors and mistakes will unfortunately be repeated again and again. Secondly, use the appropriate test equipment and method for the materials. Know the range of applications and limitations of the equipment, and assess the validity of the assumptions used for the solutions. For example, do not attempt to use the disc permeameter in materials with moisture content near saturation. Thirdly, know the equipment and methodology thoroughly; be proficient in their use and ready to adapt to changing conditions. Lastly, anticipate problems. They will occur.

Answer:

It is too early to tell.

Question 4:

When it comes to testing of this importance, do you think it may be a good idea to streamline an approach to ensure as much consistency as possible from site to site?

Answer:

Yes, the institutional memory on this project has to improve. This would allow us to avoid time and weather problems.

Answer:

No, I wouldn't automatically recommend any one method. I would assess the testing conditions requirements and choose the appropriate method or methods. I would not automatically select the SDRI method over the AEP method. I may recommend use of the two-stage borehole technique at a number of test locations (it provides an estimate of both K_h and K_v) in combination with either the AEP or the SDRI. The two-stage borehole technique is easily replicated and can measure K 's as low as 10^{-9} cm/s. However, the two-stage borehole method is not very applicable to fractured bedrock.

Question 4:

Do you know of any methods for which there is currently an effort to pass an ASTM standard?

Answer:

Yes, there is currently an effort to pass an ASTM standard for the Two-Stage Borehole technique. It should be passed within a year or two.

Question 5:

What is your opinion of the theoretical validity of the TSB technique? Do you have concerns over the fact that the theory behind the method does not address the affects of unsaturated flow?

Answer:

I do have concerns about its theoretical validity. The theory does not properly address boundary affects, swelling of clays or account for unsaturated flow conditions.

Question 6:

What is your opinion of the guelph permeameter method?

Answer:

I think the Guelph permeameter method is applicable for conditions where K is greater than 10^{-7} cm/s.

Question 7:

Do you think quality of water used during *in situ* testing is an important consideration determining representative values of K ? Assume that the potential contaminants are primarily inorganics and radionuclides.

Question 12:

If you were asked to design a testing program for a project which required determination of the range of vertical field-saturated K for exposed foundation (bedrock having low-K) over a relatively large area of a disposal cell, how would you specify the testing?

Answer:

This is tough question because I really need more information but I probably would specify use of the SDRI method in conjunction with multiple two-stage borehole tests. The SDRI would be used over the AEP to obtain more representative K (SDRI tests larger area). The two-stage borehole technique would allow for relatively easy replication across the site to account for spatial variation.

Question 13:

Are you currently involved in active research associated with design of testing equipment or theory associated with the determination of field-saturated K? Do you know of any recent research by others?

Answer:

No, I am currently not involved with research in this area. Actually I anticipate seeing very few changes in testing equipment directly related to field-saturated K testing. There are a number of issues related to the theory of testing (i.e., better understanding of unsaturated flow, influence of swelling and the influence of temperature) which require further research. However, advances in these areas will come very slowly.

Question 14:

Are there any methods of testing which are applicable to determination of field-saturated K in low-K materials which I have not mentioned?

Answer:

Yes, there is one method worthy of discussion. There is a single ring method which involves the use of multiple single rings of large (20-30 feet) diameter. One of the primary limitations of this method is that evaporation must be accounted for. An exact evaporation volume can be difficult to determine, especially for very low K materials. This method may be suitable to determine compliance.

Answer:

I believe that a large tested sample means a couple of large tests that typically would provide the best measurement for that particular location. However, we have noted that the variability of hydraulic conductivities in a large heterogeneous area can result in variations in K which are very large in comparison with measurements associated with only a couple of sites. Therefore, a testing program which understands the heterogeneous nature of an area though a large number of samples is preferred.

Question 5:

What involvement have you had in the development of equipment or theory for any of the following test methods:

- Single or double-ring infiltrometer (RI)
- Air-entry permeameter (AEP)
- Guelph permeameter (GP)
- Disc permeameter (DP)
- TBS test (2BII)

Answer:

We have had extensive involvement in developing instrumentation associated with the use of the above techniques. Substantial research has been provided relative to developing the use of tensiometers, neutron moderation, time domain reflectometry (TDR), frequency domain capacitance (FDC) probes, etc., relative to the instrumentation for measuring the above activities. Innovative new techniques which complement the above list are in development and will be discussed as a part of future professional papers. My colleague, Stephen Cullen, was personally involved in the development of the application of the GP and DP for field measurement of K_{fs} .

Question 6:

What are the primary limitations for the guelph permeameter?

Answer:

The primary limitations of the Guelph permeameter are related to the hydraulic conductivity (10^{-2} to 10^{-6} cm/sec) range, the depth, condition of the sidewall, and air temperature effects on the Mariotte constant head device.

Question 7:

What depth limits exist for use of the borehole permeameters?

Answer:

All of the above mentioned tests for measuring K_{fs} are in consideration for ASTM method approval. Each method is being considered since each method has a particular applicability and no one method is applicable at all sites.

Question 12:

Do you think there may be too much confidence placed in the use in certain test methods just because they have an ASTM approved method?

Answer:

I do not think that too much confidence is placed in certain test methods because they have an ASTM approval. I do believe that the ASTM approval identifies clearly the detail of the test method, the accuracy, precision and the bias associated with the test method. I also believe that the consensus approach used by ASTM indicates that when 33,000 of our peers approve of the standard, the standard probably is defensible in a court of law. Since I am chairing ASTM D18-21-02 entitled, "Vadose Zone Hydrology," I am aware that numerous techniques such as the use of the BAT infiltrometer are not included in as yet within the ASTM review process. Since I believe that the BAT system has substantial applicability in low K heterogeneous environments, I am pushing the development of an ASTM standard covering this technology. Therefore, the value of the ASTM approach only covers those technologies which have been evaluated.

Question 13:

Are there any other researchers than those I mentioned which you feel could contribute substantially to this special study? Please list them and state their involvement in developing theory or equipment associated with K_{fs} determination.

Answer:

There are numerous scientists throughout America and the world who are constantly making contributions to the above subject. Three notables include Dr. M. van Genuchten at the U.S. Riverside Salinity Laboratory, Dr. Don Neilson at U.C. Davis, and Dr. George Vachaud, Director of the Institute for the Environment at the POLE European University of Science in Grenoble, France. Also please recognize that Dr. Boris Fabyshenko, formerly with the Russian National Academy of Sciences and now visiting in the United States has worked extensively in measuring field saturated hydraulic conductivities in the vadose zone.

END

DATE
FILMED

3 / 16 1944