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July 16, 1998

Mr. Bill Tans
Wisconsin Department of Natural Resources
Bureau of Integrated Science Services
P.O. Box 7921
Madison, WI 53707

Mr. David Ballman, Ecologist
U.S. Army Corps of Engineers
St. Paul District
190 Fifth Street East
St. Paul, MN 55101

Dear Mr. Tans and Mr. Ballman:

Re: Crandon Project - *Addendum No. 4 to the Tailings Management Area Feasibility Report/Plan of Operation*

Nicolet Minerals Company (NMC) is pleased to submit the enclosed update to *Addendum No. 4 to the Tailings Management Area Feasibility Report/Plan of Operation* (Addendum No. 4).

The update has been prepared on behalf of NMC by Foth & Van Dyke and Associates, Inc. NMC has distributed the information to appropriate state and federal agencies, to local officials, and to various interested parties according to the current distribution list for Addendum No. 4. It is our understanding that the Wisconsin Department of Natural Resources (WDNR) and the U.S. Army Corps of Engineers (USCOE) will be responsible for distribution of the document to their appropriate staff members.

The pages contained in this update need to be inserted into Addendum No. 4 according to Items 1 through 3 on the attached reference list. This list will serve as a log and reference identifying changes made to Addendum No. 4 by NMC throughout the permitting process. If additional revisions are made, they will be added to the attached list in sequential order and the list will be forwarded with the changes.

If you or your staff have any questions regarding Addendum No. 4, please call me at (715) 478-3393.

Sincerely,

Gordon Reid
Manager of Engineering
Nicolet Minerals Company

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Addendum No. 4 to the May 1995 Crandon Project Tailings Management Area Feasibility Report/Plan of Operation

Scope ID: 93C049

Prepared for
Nicolet Minerals Company
7 North Brown Street, 3rd Floor
Rhinelander, Wisconsin 54501-3161

Prepared by
Foth & Van Dyke and Associates Inc.

June 1998

Foth & Van Dyke 1998
2737 S. Ridge Road, P.O. Box 19012, Green Bay, Wisconsin 54304, 414/497-2500, FAX: 414/497-8516

Addendum No. 4 to the May 1995 Crandon Project Tailings Management Area Feasibility Report/Plan of Operation

Contents

Tables

Page

Page

Figures

(Note: Figures for Addendum No. 4 to the May 1995 Tailings Management Area Feasibility Report/Plan of Operation are located at the end of the text, following page 62.)

Appendices

1 Introduction

The WDNR issued a Completeness Determination dated September 26, 1997, pertaining to the Feasibility Report for the proposed Crandon Project Tailings Management Area (TMA) requesting additional information. NMC issued a December 12, 1997, response addressing this request. As part of the December 12, 1997, response, NMC agreed to perform additional testing in two areas: (1) geosynthetic clay liner (GCL) compatibility tests to document the effect of simulated process water and leachate on the hydraulic conductivity of the GCL; and (2) filter tests to document that the calculated filter criteria are applicable to the design of a filter layer over the leachate collection system which will function to prevent clogging of the system. The results of the GCL compatibility testing are presented in Appendix A. The results of the filter tests will be submitted as a separate document.

This document, titled *Addendum No. 4 to the May 1995 Crandon Project Tailings Management Area Feasibility Report/Plan of Operation* (Addendum No. 4), has been prepared to describe TMA design changes made as a result of the GCL compatibility tests. This document also updates the previously submitted estimates of percolation through the liner and cover systems during the TMA operation, closure, and post-closure periods due to the proposed design changes. The revisions are necessary due to modifications made to the TMA design which primarily include the addition of a of drainage sidewall layer on the upper stages of the TMA cells.

The remainder of this report is divided into the following sections:

- Section 2 - TMA Design Modifications
- Section 3 - HELP Model Update
- Section 4 - Sensitivity Analysis

2 TMA Design Modifications

2.1 Liner System

2.1.1 Background

Addendum No. 3, (Foth & Van Dyke, 1997) to the May 1995 Crandon Project Tailings Management Area Feasibility Report/Plan of Operation, included modifications to the TMA liner which resulted in the following liner configurations (listed from the top to the bottom).

Base Liner

- 18-inch riprap;
- 6-inch till fines (P40);
- 12-inch glacial till;
- geotextile;
- 24-inch granular soil drainage layer;
- geotextile;
- 60 mil high density polyethylene (HDPE) geomembrane;
- GCL; and
- 12-inch low permeability soil (P40).

First Stage (Lower) Sideslope

- 18-inch glacial till;
- geocomposite drainage layer;
- HDPE textured (both sides) 60 mil geomembrane;
- GCL; and
- 12-inch low permeability soil (P40).

Second Stage (Upper) Sideslope

- 18-inch riprap (only on the interior slopes where required during final tailings deposition);
- 18-inch glacial till;
- geotextile;
- 60 mil HDPE geomembrane;
- GCL; and
- 12-inch low permeability soil (P40).

In response to Comment 12 of the WDNR's September 26, 1997 TMA Completeness Determination (WDNR, 1997), NMC completed GCL compatibility testing using synthetic process water and a synthetic acidic leachate as permeants. The results of these tests (Shackelford, 1998) indicated hydraulic conductivities for installed GCL's could be greater than the manufacturers' reported values used in the design presented in Addendum No. 3. Subsequently, NMC determined that the potential increase in the percolation from the site as a result of an increased GCL hydraulic conductivity could be offset by modifying the design of the liner system to improve collection efficiency. Such improvements include use of lateral drainage on the sideslopes of the second stage of the TMA, the use of geocomposites, and improved construction quality assurance as discussed in Section 3.2.2 below. The proposed liner system modifications are are discussed in Section 2.1.2 below.

2.1.2 Liner Design Modifications

Hydraulic conductivities as reported by GCL manufacturers of $3x10^{-9}$ cm/sec were used in the HELP model analyses presented in Addendum No. 3 for both the TMA liner and final cover systems. Compatibility testing of both prehydrated and non-prehydrated GCL's with synthetic leachates (Shackelford, 1998) showed that in field GCL hydraulic conductivities can range from a low of $6.9x10^{-9}$ cm/sec to a high of $8.8x10^{-6}$ cm/sec depending on the permeant and the degree of pre-hydration achieved. Experts in the field expect that some degree of pre-hydration of installed GCL's will take place, but physical data quantifying the degree to which it will occur is not available. Rather than developing and conducting a test program addressing pre-hydration, NMC has opted to conservatively assume the GCL used in the TMA liner system will function with a hydraulic conductivity of $8.8x10^{-6}$ cm/sec. Since the GCL in the final cover system will not be exposed to leachates, its hydraulic conductivity was established at the manufacturer's reported value of $3x10^{-9}$ cm/sec for the HELP model runs presented below, even though laboratory testing (Shackelford, 1998) showed a value closer to $1.3x10^{-9}$ cm/sec would be reasonable. To compensate for the higher GCL hydraulic conductivity, the TMA liner design has been modified to extend the geocomposite drainage layer up the second stage (upper) sideslope. In addition, the protective layer of till on the sideslopes has been modified to perform the function of a transition zone between the tailings and the drainage medium. The modified liner configuration is as follows (listed from the top to the bottom):

<u>Base Liner</u>

- 18-inch riprap;
- 6-inch till fines (P40);
- 12-inch glacial till;
- 24-inch drainage layer;
- geotextile;
- 60 mil HDPE geomembrane;
- GCL; and
- 12-inch low permeability soil (P 40).

<u>First and Second Stage Sideslope</u>

- 6-inch till fines (P40);
- 12-inch glacial till;
- geocomposite drainage layer;
- textured (both sides) 60 mil HDPE geomembrane;
- GCL; and
- 12-inch low permeability soil (P 40).

In addition, an 18-inch riprap layer will be placed over the 6-inch till fines layer on the interior slopes as required during final tailings deposition. The proposed modifications are shown on Figure 2-1. Figure 2-2 depicts a typical detail of the transition berm between Stage I and Stage II. The TMA final cover system has not been modified from the design presented in Figure 13 of NMC's December 12, 1997 response (NMC, 1997) to WDNR's September 26, 1997 Completeness Determination Letter (WDNR, 1997), and therefore design features for this project component are not repeated in this document.

2.2 Oxygen Intrusion

Controlling the amount of oxygen which is allowed to come into contact with the sulfide wastes is important for controlling the production of acid leachates in the TMA. The design originally submitted (Foth & Van Dyke, 1995) sought to reduce intrusion of oxygen into the TMA by: a) use of a water trap at the end of the sideslope riser, and b) not extending the sidewall drainage layer into the upper stage of the TMA cells. Based on the comments received from the WDNR, the water trap was eliminated when Addendum No. 3 was submitted. Based on a re-evaluation of the issue of oxygen intrusion, an alternative water trap design located at the end of the sideslope riser is proposed as part of this addendum. In addition, the sideslope drainage includes a design provision to isolate the sideslope drainage layer in the upper 5 feet of the tailings. These two design features are discussed below.

Figure 2-3 presents a proposed modified sideslope riser detail to prevent oxygen intrusion. Perforations in the riser will be limited to the area beyond the far bend just below the terminus of the riser pipe. The pump will be located in the portion of the riser pipe before the first bend entering the sump area. Therefore, in the event of failure of the pump-off relay, the liquid in the bend will not be evacuated. A water trap will thus be maintained at all times, which will prevent oxygen entry into the sump via the sideslope riser.

Figure 2-4 shows a typical detail of the top of the second stage berm. As shown in the figure, a geomembrane flap will be installed from the anchor trench and placed over the geocomposite drainage medium extending downslope to a vertical depth in the tailings of 5 feet. The geomembrane flap is designed to limit oxygen intrusion into the tailings via the geocomposite and to conform with the assumptions made in the geochemical modeling (SRK, 1998).

2.3 Soil Volumes

The modifications to the liner system also include a redesign of the protective cover over the geomembrane for the sideslopes. Instead of an 18-inch layer of unprocessed till, the current proposal is to use a 12-inch layer of unprocessed till over the geocomposite overlying the geomembrane and a 6-inch layer of P40 till over the unprocessed till. This design is identical to that proposed for the base liner system. The design will provide the necessary protection to the geomembrane and the geocomposite and function as a filter between the tailings and the drainage system. Table 2-1 is an updated version of Table 2 in NMC's December 12, 1997 response letter

(NMC, 1997), which accounts for the changes in the required soil volumes due to the described design modification. The analysis shows that for both the case of average gradation curve and the case of fine gradation curve, sufficient quantities of P40 till material are available from on-site soils. Enough fines will be produced during the production of the drainage layer using the coarse LWT gradation curve to supply 67% of the P40 till layer. Processing additional LWT would provide the remaining 33%. Therefore, there is sufficient LWT onsite to manufacture the drainage layers, fine till layer, and the P40 till layer regardless of which gradation curve (fine, average, or coarse) predominates at the site.

Table 2-1

Till Soil Volume Availability

Layer	Required Volume	Available Using Average LWT Gradation Curve	Available Using Coarse LWT Gradation Curve	Available Using Fine LWT Gradation Curve
Drainage Layer (½-in to #40 sieve)	675,000	675,000	675,000	675,000
P40 - Filter Layer (finer than #40 sieve)	179,000	179,000	179,000	179,000
P40 - Bedding Layer (finer than #40 sieve)	746,000	920,300	496,200	2,858,500

Note: All values in cubic yards.

Prepared by: MRS
Checked by: NXP

3 HELP Model Update

3.1 Background

Section 6.7 of the Feasibility Report (Foth & Van Dyke, 1995) explains how the HELP model analyses were used to estimate the quantity of percolation through the liner and cover systems during the TMA operation, closure, and post-closure periods. Section 6.7.2 of that document included a HELP model program overview discussing the rationale for selecting model input data for evapotranspiration, precipitation, temperature, and solar radiation. Section 6.7.3 provided the rationale for selection of the various soil and geosynthetic material properties and the tailings properties which were estimated taking into account the depth at which each tailings layer was located.

The HELP models presented in the Feasibility Report (Foth & Van Dyke, 1995) were updated in Addendum No. 3 to the TMA Feasibility Report/Plan of Operation (Foth & Van Dyke, 1997). Addendum No. 3 reflected the modifications made to the TMA's composite liner, leachate collection system, and final cover in response to regulatory agency review comments. Addendum No. 4 updates the HELP model analysis to reflect the addition of a geocomposite drainage layer on the upper sideslope and a GCL with a higher hydraulic conductivity.

3.2 Design Data

3.2.1 Primary Models

Two primary models were used for the water balance of the selected TMA design. These two primary HELP model designs are hence referred to as Sideslope and Base Models. Sideslope refers to the case where a geocomposite drainage layer is placed over the liner on the sideslope. The sideslope bottom liner layer is sloped at 33%. The Base Model has a granular drainage layer over the base liner and is sloped at two percent. Both the Sideslope and Base HELP Models have the same final cover configuration, as was previously modeled.

3.2.2 Submodels

In order to estimate the water balance at different time periods of operation and post-closure of the TMA, the primary models have been subdivided into submodels. As in Addendum No. 3, the Sideslope and Base HELP Models have been subdivided into several models to represent filling, closure, and post-closure scenarios. The submodels are listed below.

1. Stages I, III, V, and VII [first (lower) stage of TMA cell filling, referred to as initial stage];

2. Stages II, IV, VI, and VIII [second (upper) stage of TMA cell filling] referred to as second stages;

3. Post-Closure Period With Lateral Drainage on the Sideslopes and Base (represents the case with active leachate removal);

4. Post-Closure Period With Lateral Drainage on the Sideslope and No Lateral Drainage on the Base (represents the case when leachate removal is discontinued); and

5. Post-Closure Period With Lateral Drainage on the Sideslope and No Lateral Drainage on Base, and the GCL and P40 till portion of the liner (represents an assumed case in which the geomembrane may no longer be functional after a very long period).

The first four scenarios listed above represent the TMA defined by construction, operation, and post-closure conditions. The fifth scenario represents a postulated condition where the geomembrane in the composite liner is assumed to degrade after 150 years. The postulated degradation scenario is very conservative and is included in the analysis to assess the performance of the TMA if such an unlikely condition were to occur. In fact, based on the December 1996 report prepared by GeoSyntec Consultants of Boca Raton, Florida, titled *Assessment of Long-Term Performance of the Proposed HDPE Geomembrane Liner and Cap at the Crandon Project TMA Facility* (GeoSyntec, 1996) which is provided in Appendix F of Addendum No. 3 to the TMA Feasibility Report, ". . . the HDPE geomembrane liner and cap at the TMA facility should function as designed for a very long time (e.g., hundreds of years) without deterioration in performance."

The Sideslope and Base HELP Models for the initial stages have been assembled based on the following generalized design specifications and soil characteristic input parameters:

<u>Sideslope HELP Model: Initial Stages</u>

- no cover;
- no surface water runoff;
- 22.5-foot thickness of tailings (half of maximum tailings depth);
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite above the liner;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-1.

Table 3.2-1

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model
Sideslope - Initial Stages (I, III, V, VII)

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Tailings	30	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5803
2	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5529
3	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5445
4	Till/ Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
5	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100
6	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
7	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
8	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Base HELP Model: Initial Stages

- no cover;
- no surface water runoff;
- 45-foot thickness of tailings;
- 970-foot length of base drainage at two percent slope;
- lateral drainage above the liner;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-2.

The 4-inch diameter leachate collection system laterals with a typical 260-foot spacing at the cell base were not considered in the base second stages analyses. The more conservative 970-foot leachate collection system spacing was used in the Base HELP model's second stage.

The Sideslope and Base HELP Models for the second stages have been assembled based on the following design specifications and soil input parameters:

Sideslope HELP Model: Second Stages (Lower Sideslope)

- no cover;
- no surface water runoff;
- 67.5-foot thickness of tailings (average of tailings depth at ends);
- 135-foot length of drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-3.

Sideslope HELP Model: Second Stages (Upper Sideslope)

- no cover;
- no surface water runoff;
- 22.5-foot thickness of tailings (average of tailings depth at ends);
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-4.

Table 3.2-2

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model
Base - Initial Stages (I, III, V, VII)

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Tailings	60	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5803
2	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5529
3	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5445
4	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.5385
5	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.5338
6	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
7	Granular Soil/ Lateral Drainage	24	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0320
8	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
9	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
10	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Table 3.2-3

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model
Lower Sideslope - Second Stages (II, IV, VI, VIII)

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Tailings	90	0	—	—	0.5803	0.5100	0.3400	4×10^{-6}	0.5803
2	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5529
3	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5445
4	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.5385
5	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.5338
6	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.5297
7	Tailings	120	0	—	—	0.5259	0.4915	0.3215	2.0×10^{-6}	0.5259
8	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
9	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100
10	Geomembrane	0.06	35	—	—	—	—	—	2×10^{-13}	—
11	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
12	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Table 3.2-4

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Upper Sideslope - Second Stages (II, IV, VI, VIII)

Layer #	General Description	Thickness (Inches)	Classification HELP	Classification USDA	Classification USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Tailings	30	0	—	—	0.5803	0.5100	0.3400	4×10^{-6}	0.5803
2	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5529
3	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5445
4	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
5	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100
6	Geomembrane	0.06	35	—	—	—	—	—	2×10^{-13}	—
7	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
8	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Base HELP Model: Second Stages

- no cover;
- no surface water runoff;
- 90-foot thickness of tailings;
- 970-foot length of base drainage at 2% slope;
- lateral drainage above the liner;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-5.

The Sideslope and Base HELP Models for Post-Closure Period with lateral drainage on the base have been assembled based on the following design specifications and soil input parameters:

Sideslope (lower) HELP Model: Post-Closure Period With Lateral Drainage on the Base

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 67.5-foot thickness of tailings (average of tailings depths at the end);
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-6.

Table 3.2-5

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model
Base - Second Stages (II, IV, VI, VIII)

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Tailings	120	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5803
2	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5529
3	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5445
4	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.5385
5	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.5338
6	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.5297
7	Tailings	120	0	—	—	0.5259	0.4915	0.3215	2.0×10^{-6}	0.5259
8	Tailings	120	0	—	—	0.5226	0.4905	0.3205	1.5×10^{-6}	0.5226
9	Tailings	120	0	—	—	0.5195	0.4900	0.3200	1.0×10^{-6}	0.5195
10	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
11	Granular Soil/ Lateral Drainage	24	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0320
12	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
13	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
14	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Table 3.2-6

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Sideslope (lower) - Post-Closure Period With Lateral Drainage on the Base

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3231
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2443
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0320
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	90	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5129
9	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5200
10	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5216
11	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.5292
12	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.5124
13	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.4978

Table 3.2-6 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification HELP	Classification USDA	Classification USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
14	Tailings	120	0	—	—	0.5226	0.4905	0.3205	2.0×10^{-6}	0.5022
15	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2929
16	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0595
17	Geomembrane	0.06	35	—	—	—	—	—	2×10^{-13}	—
18	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
19	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2248

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Sideslope (upper) HELP Model: Post-Closure Period With Lateral Drainage on the Base

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 22.5-foot thickness of tailings (average of tailings depths at ends);
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-7.

Base HELP Model: Post-Closure Period With Lateral Drainage on the Base

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 90-foot thickness of tailings;
- 970-foot length of base drainage at 2% slope ;
- lateral drainage above the liner;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-8.

Table 3.2-7

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Sideslope (upper) - Post-Closure Period With Lateral Drainage on the Base

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3231
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2443
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0320
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	30	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5086
9	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.5066
10	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5156
11	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.3013
12	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.01	0.005	33.0	0.0100

Table 3.2-7 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
13	Geomembrane	0.06	35	—	—	—	—	—	2×10^{-13}	—
14	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
15	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2250

[1]Geosynthetic Clay Liner.

Prepared by: MRS
Checked by: NXP

Table 3.2-8

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Base - Post-Closure Period With Lateral Drainage on the Base

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3231
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2443
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0320
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.5010
7	Till/Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	240	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5239
9	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.5238
10	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.5269
11	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.5024
12	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.4994
13	Tailings	120	0	—	—	0.5259	0.4915	0.3215	2.0×10^{-6}	0.5084

Table 3.2-8 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
14	Tailings	120	0	—	—	0.5226	0.4905	0.3205	1.5×10^{-6}	0.5218
15	Tailings	120	0	—	—	0.5195	0.4900	0.3200	1.0×10^{-6}	0.5194
16	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2959
17	Granular Soil/ Lateral Drainage	24	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0835
18	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
19	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
20	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2278

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

The Sideslope and Base HELP Models for the Post-Closure Period with lateral drainage on the sideslope and no lateral drainage on the base have been assembled based on the following design specifications and soil input parameters:

<u>Sideslope (Lower) HELP Model: Post-Closure Period With No Lateral Drainage on the Base</u>

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 67.5 foot thickness of tailings (average of tailings depths at the ends);
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-9.

<u>Sideslope (Upper) HELP Model: Post-Closure Period With No Lateral Drainage on the Base</u>

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 22.5-foot thickness of tailings (average of the depths at the ends);
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through the till layer;
- lateral drainage through geocomposite;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-10.

Table 3.2-9

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Sideslope (lower) - Post-Closure Period With No Lateral Drainage on the Base

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3813
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2561
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0329
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2840
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	90	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5055
9	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.4817
10	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.4739
11	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.4682
12	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.4636
13	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.4594

Table 3.2-9 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
14	Tailings	120	0	—	—	0.5226	0.4905	0.3205	2.0×10^{-6}	0.4530
15	Till/ Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
16	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100
17	Geomembrane	0.06	35	—	—	—	—	—	2×10^{-13}	—
18	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
19	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.1973

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Table 3.2-10

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Sideslope (upper) - Post-Closure Period With No Lateral Drainage on the Base

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3813
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2561
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0329
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2840
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	30	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5055
9	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.4817
10	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.4739
11	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
12	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100

Table 3.2-10 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
13	Geomembrane	0.06	35	—	—	—	—	—	2×10^{-13}	—
14	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
15	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.1974

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Base HELP Model: Post-Closure Period With No Lateral Drainage

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 90-foot thickness of tailings;
- till and granular soil layer as vertical percolation layers;
- geomembrane;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-11.

The Sideslope and Base HELP Models for Post-Closure Period have been assembled with lateral drainage on the sideslope and no lateral drainage on base and a hypothesized lack of a geomembrane layer in the base after 150 years. The following design specifications and soil input parameters represent this case:

Sideslope (Lower) HELP Model: Post-Closure Period With No Lateral Drainage on the Base and No Geomembrane in the Liner

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 67.5-foot thickness of tailings;
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through till layer;
- lateral drainage through geocomposite;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-12.

Table 3.2-11

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Base - Post-Closure Period With No Lateral Drainage

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3813
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2561
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0329
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2840
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	240	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5055
9	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.4739
10	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.4682
11	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.4636
12	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.4594
13	Tailings	120	0	—	—	0.5259	0.4915	0.3215	2.0×10^{-6}	0.4559

Table 3.2-11 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
14	Tailings	120	0	—	—	0.5226	0.4905	0.3205	1.5×10^{-6}	0.4530
15	Tailings	120	0	—	—	0.5195	0.4900	0.3200	1.0×10^{-6}	0.4503
16	Till	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
17	Granular Soil/ Vertical Percolation	24	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0320
18	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
19	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
20	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.1984

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Table 3.2-12

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Sideslope (lower) - Post-Closure Period With No Lateral Drainage on the Base and No Geomembrane in the Liner

Layer #	General Description	Thickness (Inches)	Classification HELP	Classification USDA	Classification USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3328
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2469
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0399
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2840
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	90	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5055
9	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.4817
10	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.4739
11	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.4682
12	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.4636
13	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.4594

Table 3.2-12 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
14	Tailings	120	0	—	—	0.5226	0.4905	0.3205	2.0×10^{-6}	0.4530
15	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
16	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100
17	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
18	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.1973

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Sideslope (Upper) HELP Model: Post-Closure Period With No Lateral Drainage on the Base and No Geomembrane in the Liner

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 22.5-foot thickness of tailings;
- 135-foot length of base drainage at 3H:1V slope;
- lateral drainage through the till layer;
- lateral drainage through geocomposite;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-13.

Base HELP Model: Post-Closure Period With No Lateral Drainage and No Geomembrane in the Liner

- final cover soils;
- 1,500-foot length of cover drainage at 2% slope;
- geomembrane;
- GCL;
- P40 till layer;
- 90-foot thickness of tailings;
- till and granular soil layer as vertical percolation layers;
- GCL;
- P40 till layer; and
- soil and tailing layer data as provided in Table 3.2-14.

Tables 3.2-1 through 3.2-5 show that the models do not include the ponding of the slurry water on the tailings. This is a reasonable assumption since the purpose of the water balance is primarily to determine leachate generation rates during post-closure monitoring and the percolation from the site. Since the simulation starts with the case of initial saturation of all tailings layers, the effect of ponding (which is to keep the tailings layers saturated) will be indirectly accounted for if percolation through the liner for the first year of simulation is assumed to be prevailing throughout the operation period of a cell. After conducting the HELP model runs in this fashion for the initial simulations described in the Feasibility Report (Foth & Van Dyke, 1995), Dr. Paul Schroeder of the USCOE, Waterways Experiment Station, who is the primary author of HELP, was contacted for his comments on this approach. He suggested that the model may be operated to mimic the presence of ponding on the surface if the precipitation values were increased and surface runoff prevented. Accordingly, in the Feasibility Report (Foth & Van Dyke, 1995), the submodels during the initial simulations for the open conditions were rerun with the precipitation values increased by a factor of two. The values

Table 3.2-13

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Sideslope (upper) - Post-Closure Period With No Lateral Drainage on the Base and No Geomembrane in the Liner

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3328
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2469
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0399
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2840
7	Till/ Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	30	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5055
9	Tailings	120	0	—	—	0.5529	0.5066	0.3366	3.66×10^{-6}	0.4817
10	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.4739
11	Till/Lateral Drainage	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440

Table 3.2-13 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
12	Geocomposite/ Lateral Drainage	0.24	34	—	—	0.8500	0.0100	0.0050	33.0	0.0100
13	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
14	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.1871

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

Table 3.2-14

Soil, Waste and Geosynthetic Characteristics Used for Water Balance Model Base - Post-Closure Period With No Lateral Drainage and No Geomembrane in the Liner

Layer #	General Description	Thickness (Inches)	Classification HELP	USDA	USCS	Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
1	Topsoil	6	8	L	ML	0.4630	0.2320	0.1160	3.7×10^{-4}	0.3328
2	Till/ Rooting Zone	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2469
3	Granular Soil/ Lateral Drainage	12	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0399
4	Geomembrane	0.06	35	—	—	—	—	—	2.0×10^{-13}	—
5	GCL[1]	0.24	17	—	—	0.7500	0.7470	0.4000	3×10^{-9}	0.7500
6	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.2840
7	Till/Grading Layer	36	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
8	Tailings	240	0	—	—	0.5803	0.5100	0.3400	4.0×10^{-6}	0.5055
9	Tailings	120	0	—	—	0.5445	0.5033	0.3333	3.33×10^{-6}	0.4739
10	Tailings	120	0	—	—	0.5385	0.5000	0.3300	3.0×10^{-6}	0.4682
11	Tailings	120	0	—	—	0.5338	0.4965	0.3265	2.66×10^{-6}	0.4636
12	Tailings	120	0	—	—	0.5297	0.4930	0.3230	2.33×10^{-6}	0.4594
13	Tailings	120	0	—	—	0.5259	0.4915	0.3215	2.0×10^{-6}	0.4559

Table 3.2-14 *(Continued)*

Layer #	General Description	Thickness (Inches)	Classification			Total Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)	Initial Soil Water Content (vol/vol)
			HELP	USDA	USCS					
14	Tailings	120	0	—	—	0.5226	0.4905	0.3205	1.5×10^{-6}	0.4530
15	Tailings	120	0	—	—	0.5195	0.4900	0.3200	1.0×10^{-6}	0.4503
16	Till	18	10	SCL	SC	0.3980	0.2440	0.1360	1.2×10^{-4}	0.2440
17	Granular Soil/ Vertical Percolation	24	21	Gravel		0.3970	0.0320	0.0130	3.0×10^{-1}	0.0321
18	GCL[1]	0.24	0	—	—	0.7500	0.7470	0.4000	8.8×10^{-6}	0.7500
19	P40 Till	12	0	SiL	ML	0.5010	0.2840	0.1350	2×10^{-5}	0.1818

[1]Geosynthetic Clay Liner

Prepared by: MRS
Checked by: NXP

obtained for leachate generation and percolation from the site for this case were found to be very similar to those obtained for the first year using actual precipitation values. This provided an interesting aspect of the simulation; that is, the percolation through the base liner was impacted more by the saturation and hence the head on the liner rather than the rainfall intensity during any year. For ponded conditions, since the rainfall variation will be neutralized by the relatively constant pond depths on the tailings surface, this result was not unexpected. Therefore, for the present analyses (included in Addendum No. 4) with the modified liner and sideslope drain systems, only the runs with the precipitation increased by a factor of two were performed.

For all analyses, the geomembrane included in the final cover and the base liner was considered to have one pinhole per acre due to manufacturing defects and one hole per acre due to installation defects. The contact between the membrane and the GCL component of the composite liner was assigned as "excellent". The above parameters are direct functions of the construction quality assurance (CQA) program, and are readily achievable. For example, a leak location survey and repair of the located leaks is part of the CQA program. With the GCL as the soil component of the composite liner, excellent contact can be achieved in the field between the geomembrane and the soil component. Thus, by considering different geometries, appropriate material properties, and techniques for simulating operation scenarios, the HELP model should provide conservative values of leachate quantities and percolation from the site. These results are discussed in Section 3.3.

3.3 Summary of Results

3.3.1 Percolation Through the Liner and Leachate Generation

A summary of the results from the water balance study using the HELP models is shown in Table 3.3-1. The results shown pertain to the different submodels of both the sideslope HELP models and base HELP model. Thus different operation scenarios are covered; such as open case with doubled precipitation, closed case during the initial post-closure period, closed case after the discontinuation of leachate removal and closed case after a very long time period when the geomembrane in the base liner is hypothetically assumed to be no longer effective. The percolation and leachate generation are given in terms of annual averages for the duration of the simulation period.

For illustrative purposes, the yearly variation of percolation through the liner during the operation period for two cases, i.e., Sideslope Initial Stage, and Base Initial Stage are shown in Table 3.3-2 from the HELP model runs for the original design included in the May 1995 Feasibility Report (Foth & Van Dyke, 1995). The percolation through the liner for Second Stage of the sideslope and base cases from the May 1995 Feasibility Report are shown in Table 3.3-3. Tables 3.3-2 and 3.3-3 show that the percolation quantities diminish through the initial years of operation. This is indicative of the gradual draining of the tailings and therefore does not account for the ponding on top of the cell. As described earlier in Section 3.2, one way to approximate the effects of ponding is to assume that the results for the first year (the maximum value) will continue to prevail throughout the time of ponding.

Table 3.3-1

Results of HELP Model Water Balance Analyses

HELP Model ID	Average Annual Totals for the Simulation Period					Peak Daily Values for Simulation Period			
	Water Balance Simulation Period Years	Percolation Through Cover[1] in/yr; (Percent)	Lateral Drainage/Leachate Collected[1] in/yr; (Percent)	Percolation Through Liner[1] in/yr; (Percent)	Average Head Across Liner (in)	Percolation Through Cover (in/day)	Lateral Drainage/Leachate Collected (in/day)	Percolation through Liner (in/day)	Average Head Across Liner (in)
Sideslope - Initial Stage (Table 3.2-1)	10	NA	14.71430 (23.37829)	0 (0)	0.006	NA	0.12100	0	0.018
Base - Initial Stage (Table 3.2-2)	10	NA	15.10799 (24.0038)	0.00570 (0.00905)	1.182	NA	0.09160	0.00004	2.613
Sideslope (lower) - Second Stage (Table 3.2-3)	10	NA	16.13836 (25.64087)	0 (0)	0.007	NA	0.12241	0	0.022
Sideslope (upper) - Second Stage (Table 3.2-4)	10	NA	14.71430 (23.37829)	0 (0)	0.006	NA	0.12100	0.00004	0.018
Base - Second Stage (Table 3.2-5)	10	NA	16.19932 (25.73772)	0.00571 (0.00907)	1.266	NA	0.09084	0	2.592
Sideslope (lower) - Final Cover (Table 3.2-6)	40	0.00003 (0.0001)	0.95430 (3.10264)	0 (0)	0	0.000001	0.09158	0	0.014
Sideslope (upper) - Final Cover (Table 3.2-7)	40	0.00003 (0.00010)	0.29308 (0.95296)	0 (0)	0	0.000001	0.09223	0	0.014
Base - Final Cover (Table 3.2-8)	40	0.00003 (0.00010)	1.36278 (4.43072)	0.00036 (0.00116)	0.107	0.000001	0.06492	0.000024	1.852
Sideslope (lower) - Final Cover (Table 3.2-9)	100	0.00003 (0.00010)	0.00007 (0.00023)	0 (0)	0	0.000001	0.00296	0	0.001
Sideslope (upper) - Final Cover (Table 3.2-10)	100	0.00003 (0.00010)	0.00004 (0.00014)	0 (0)	0	0.000001	0.00236	0	0

Table 3.3-1 *(Continued)*

HELP Model ID	Average Annual Totals for the Simulation Period					Peak Daily Values for Simulation Period			
	Water Balance Simulation Period Years	Percolation Through Cover[1] in/yr; (Percent)	Lateral Drainage/Leachate Collected[1] in/yr; (Percent)	Percolation Through Liner[1] in/yr; (Percent)	Average Head Across Liner (in)	Percolation Through Cover (in/day)	Lateral Drainage/Leachate Collected (in/day)	Percolation through Liner (in/day)	Average Head Across Liner (in)
Base - No Drainage (Table 3.2-11)	100	0.00003 (0.00010)	NA	0.00003 (0.00011)	0.012	0.000001	NA	0	0.017
Sideslope (lower) - No Geomembrane in the Liner (Table 3.2-12)	100	0.00003 (0.00010)	0.00003 (0.00010)	0.00004 (0.00013)	0	0.000001	0.00171	0.001256	0.001
Sideslope (upper) - No Geomembrane in the Liner (Table 3.2-13)	100	0.00003 (0.00010)	0.00002 (0.00005)	0.00003 (0.00010)	0	0.000001	0.00131	0.001051	0
Base - No Geomembrane in the Liner (Table 3.2-14)	100	0.00003 (0.00010)	NA	0.00009 (0.00028)	0	0.000001	NA	0.001200	0.001

[1]These values are given in inches/year as well as a percentage of precipitation, the latter within parentheses.

Notes:
- HELP Model ID - Soil properties are provided in respective table listed under the HELP Model ID.
- NA - Not applicable.
- Zero (0) represents values less than 0.0000005.

Prepared by: MRS
Checked by: NXP

Table 3.3-2

Maximum Average Annual Percolation Through Liner During Operation Years of Initial Stages

Year	Sideslope (in/yr)	Base (in/yr)
1	0.187326	0.002003
2	0.149477	0.000396
3	0.112421	0.000441
4	0.044193	0.000342
5	0.005470	0.000290
6	0.013519	0.000327
7	0.006639	0.000404
8	0.012266	0.000315
9	0.017525	0.000489
10	0.005306	0.000491

Note: The data in this table do not pertain to the modified liner, LCS, and cover configurations described in Section 2 of Addendum No. 4. These data are from the initial HELP model runs presented in the May 1995 Feasibility Report and are presented here for illustrative purposes only. (Ref. Table 6.7-14 of the Feasibility Report.)

Prepared by: JBK
Checked by: MDF

Table 3.3-3

Maximum Average Annual Percolation Through Liner During Operation Years of Second Stages

Year	Sideslope (in/yr)	Base (in/yr)
1	0.817797	0.000816
2	0.844675	0.000956
3	0.788535	0.000956
4	0.683487	0.000959
5	0.554911	0.000751
6	0.687312	0.000356
7	0.666802	0.000505
8	0.659438	0.000288
9	0.818071	0.000356
10	0.731234	0.000604

Note: The data in this table do not pertain to the modified liner, LCS, and cover configurations described in Section 2 of Addendum No. 4. These data are from the initial HELP model runs presented in the May 1995 Feasibility Report and are presented here for illustrative purposes only. (Ref. Table 6.7-15 of the Feasibility Report.)

Prepared by: JBK
Checked by: MDF

A second, perhaps more appropriate method is to increase the rainfall data by a factor of two and thus create excess water on the top tailings layer [as described in Section 6.7.4.2 of the Feasibility Report (Foth & Van Dyke, 1995)]. The results of these analyses for the revised TMA design addressed in Addendum No. 4 in terms of averages through the simulation period as shown in Table 3.3-1 are reproduced in Table 3.3-4. Yearly values of percolation through the liner during the operation period based on doubled precipitation for the initial stages and second stages are shown on Tables 3.3-5 and 3.3-6, respectively. These results do not show a diminishing trend of percolation through the liner with time during the operation period. Also, average head on the liner (Table 3.3-4) is similar to peak daily head. It can therefore be concluded that the effects of ponding can be approximated by the technique used, i.e., increased rainfall.

Based on the above results, it has been concluded that for the period when the TMA remains open and ponding takes place on top of the tailings, the leachate generation and percolation through the liner should be represented by HELP models using two times the average rainfall data (Tables 3.3-4, 3.3-5 and 3.3-6). After closure of each TMA cell when there will be no ponding and draining of the tailings is occurring, the results from the analyses with normal rainfall are appropriate (Table 3.3-1).

3.3.2 Total Percolation from the TMA

The results of HELP model studies show that the rate of percolation varies with time due to varying operation conditions (i.e. open, closed, geomembrane assumptions, etc.). Also, the rate of percolation varies due to changes in geometry (i.e., sideslope profile, base profile, tailing thickness, etc.). Therefore, in order to estimate the percolation rate through the liner with time, these conditions need to be considered.

Table 3.3-7 shows the estimated rates of percolation assuming the initial stage of a TMA cell will be operative for 4 years and the second stage for 6 years, including the consolidation period, before the cell is closed. The values in the table represent the average values from Tables 3.3-5 and 3.3-6 for 0 to 4 years and 5 to 10 years, respectively. For the remaining periods the estimated percolation rates following placement of the cell final cover are as shown in Table 3.3-8.

Percolation rates summarized in Tables 3.3-7 and 3.3-8 are based on a GCL hydraulic conductivity in the liner system of 8.8×10^{-6} cm/sec. Based on the hydraulic conductivity tests using simulated process water and leachate, this is a worst-case value which occurs when there is no prehydration of the GCL. Laboratory results indicate a prehydrated GCL can have a hydraulic conductivity as low as 6.9×10^{-9} cm/sec in the TMA liner system. Therefore, the actual percolation will be determined by a GCL hydraulic conductivity which falls somewhere between these two values. Table 3.3-9 compares percolation quantities for upper and lower bound conditions for TMA cell 1. The comparison shows that the already low percolation rates diminish with decreasing GCL hydraulic conductivity.

Table 3.3-4

HELP Model Results: Simulation of Ponding

	Average Annual Totals for Model Duration				Peak Daily Values		
HELP Model ID	Water Balance Duration Years	Lateral Drainage/ Leachate Collected (in/yr)	Percolation Through Liner (in/yr)	Average Head Across Liner (in)	Lateral Drainage/ Leachate Collected (in/day)	Percolation Through Liner (in/day)	Average Head Across Liner (in)
Sideslope - Initial Stage (Table 3.2-1)	10	14.71430	0	0.006	0.12100	0	0.018
Base - Initial Stage (Table 3.2-2)	10	15.10799	0.00570	1.182	0.09160	0.00004	2.613
Sideslope (lower) - Second Stage (Table 3.2-3)	10	16.13836	0	0.007	0.12241	0	0.022
Sideslope (upper) - Second Stage (Table 3.2-4)	10	14.71430	0	0.006	0.12100	0.00004	0.018
Base - Second Stage (Table 3.2-5)	10	16.19932	0.00571	1.266	0.09084	0	2.592

Notes:
- Since HELP model output gives only six digits, values less than 0.0000005 are shown as 0.
- HELP Model ID - Soil properties are provided in the respective table listed under the HELP Model ID.

Prepared by: MRS
Checked by: NXP

Table 3.3-5

Percolation from TMA Based on Doubled Precipitation Values During Operation of Initial Stages

Year	Sideslope (in/yr)	Base (in/yr)
1	0	0.010461
2	0	0.004917
3	0	0.003490
4	0	0.008997
5	0	0.005416
6	0	0.004207
7	0	0.006230
8	0	0.003004
9	0	0.001347
10	0	0.008891

Note: Since HELP model output gives only six digits, values less than 0.0000005 are shown as 0.

Prepared by: MRS
Checked by: NXP

Table 3.3-6

Percolation from TMA Based on Doubled Precipitation Values During Operation of Second Stages

Year	Lower Sideslope (in/yr)	Upper Sideslope (in/yr)	Base (in/yr)
1	0	0	0.012519
2	0	0	0.006330
3	0	0	0.004707
4	0	0	0.007421
5	0	0	0.004741
6	0	0	0.004464
7	0	0	0.005390
8	0	0	0.003720
9	0	0	0.002812
10	0	0	0.004966

Note: Since HELP model output gives only six digits, values less than 0.0000005 are shown as 0.

Prepared by: MRS
Checked by: NXP

Table 3.3-7

Percolation During Cell Filling

	Rate of Percolation (in/yr)	
	0-4 yrs	5-10 yrs
Sideslopes	0	0
Base Area	0.005696	0.005707

Note: Since HELP model output gives only six digits, values less than 0.0000005 are shown as 0.

Prepared by: MRS
Checked by: NXP

Table 3.3-8

Post-Closure Percolation

Year from Placement of Cover	Lower Sideslope	Upper Sideslope	Base (in/yr)
1	<0.0000005	<0.0000005	0.004681
2	<0.0000005	<0.0000005	0.003328
3	<0.0000005	<0.0000005	0.000607
4	<0.0000005	<0.0000005	0.000512
5	<0.0000005	<0.0000005	0.000453
6	<0.0000005	<0.0000005	0.000406
7	<0.0000005	<0.0000005	0.000368
8-15	<0.0000005	<0.0000005	0.000264
16-25	<0.0000005	<0.0000005	0.000162
26-35	<0.0000005	<0.0000005	0.000012
36-40	<0.0000005	<0.0000005	0.000002
41-50	<0.0000005	<0.0000005	0.000044
51-60	0	<0.0000005	0.000042
61-70	0	<0.0000005	0.000039
71-80	0	<0.0000005	0.000036
81-90	0	<0.0000005	0.000033
91-115	0	<0.0000005	0.000030
116-140	0	<0.0000005	0.000025
141	0.03876	0.001376	0.008757
142-165	0	0	0
166-175	0	0	0
176-185	0	0	0
186-195	0	0.000021[1]	0

Table 3.3-8 *(Continued)*

Year from Placement of Cover	Lower Sideslope	Upper Sideslope	Base (in/yr)
196-205	0	0.000029[1]	0
206-215	0	0.000026[1]	0
216-220	0	0.000039[1]	0
221-230	0	0.000031[1]	0
231-240	0	0.000030[1]	0

[1]Percolation equal to infiltration through cover.

Prepared by: NXP
Checked by: SVD1

Table 3.3-9

Summary of Percolation Through TMA 1 During Operations and Post-Closure Monitoring Period

	Percolation (gallons) for Given GCL Hydraulic Conductivity (cm/s)	
	8.8×10^{-6} (upper bound)	6.9×10^{-9} (lower bound)
Operation (years 1-10)	34,500*	400*
Post-Closure (years 11-80)	8,600	200

*Based on average percolation over the 10-year operation period.

Prepared by: MRS
Checked by: NXP

3.3.3 Leachate Generated

Tables 3.3-10 and 3.3-11 show leachate quantities for initial and second stage filling of a TMA cell, respectively. The results are shown for the case where ponding is simulated (i.e., two times precipitation). After closure of the unit, the estimated leachate quantities can be obtained from Table 3.3-1.

The estimated leachate production rates for the initial and second stages shown in Tables 3.3-10 and 3.3-11 are not uniform, indicating that equilibrium has not been reached. To be conservative, the highest values should be used to estimate leachate quantities for sump and pump sizing. Accordingly, for the initial stage use 18.9 in/yr for sideslope areas and 25.1 in/yr for the base. For the second stage use 30.8 in/yr for lower sideslopes, 18.9 in/yr for upper sideslopes, and 29.3 in/yr for the base.

3.4 HELP Model Input Parameters

As described in Section 6.7.2 of the Feasibility Report (Foth & Van Dyke 1995), HELP model inputs can be grouped into the following three categories:

- Weather data;
- Soil data; and
- Design data.

Table 3.3-10

Lateral Drainage/Leachate Collected[1]
Initial Stages

Year	Sideslope (in/yr)	Base (in/yr)
1	18.9155	25.1401
2	14.8534	13.8489
3	18.4409	10.8807
4	13.3399	21.9714
5	13.9858	14.7060
6	16.5791	11.9078
7	9.2730	16.4138
8	7.8941	9.0487
9	17.6025	5.2698
10	16.2588	21.8927

[1]Table based on results from HELP model runs with twice the normal mean monthly precipitation values.

Prepared by: MRS
Checked by: NXP

Table 3.3-11

Lateral Drainage/Leachate Collected[1]
Second Stages

Year	Sideslope (in/yr) Lower	Sideslope (in/yr) Upper	Base (in/yr)
1	30.7917	18.9155	29.2921
2	17.2987	14.8534	18.1804
3	11.7304	18.4409	14.5182
4	22.0388	13.3399	20.0855
5	14.3597	13.9858	14.4773
6	13.2745	16.5791	13.9069
7	16.1276	9.2730	16.0181
8	9.3330	7.8941	12.0622
9	5.3602	17.6025	9.7716
10	21.0690	16.2588	13.6811

[1]Table based on results from HELP model runs with twice the normal mean monthly precipitation values.

Prepared by: MRS
Checked by: NXP

Section 6.7.3 and subsections 6.7.3.1 through 6.7.3.2.3 of the Feasibility Report (Foth & Van Dyke, 1995) describe how the soil data inputs were obtained. The properties of the tailings, which may impact the rate at which leachate is collected and may also impact the estimated site percolation rates, have been obtained from laboratory tests.

The sensitivity analyses completed by Peyton and Schroeder (1990) and Helmy Emam (1995) suggest that the quantity of percolation from a site will be impacted most by the hydraulic conductivities of the barrier layer (composite liner) and the drainage layer above it. For the Crandon Project, both of these items are "specified parameters". In other words, the values used in the HELP model runs are those which are specified in the design process and which will be verified in the field during construction. It should also be noted that NMC is proposing to perform post-installation leak testing of the geomembrane. This step, not a customary part of containment facility construction, has been proposed as a result of NMC's recognition of the importance of achieving the effective hydraulic conductivity of the composite liner as part of the construction process. Post-installation leak testing will help in identifying leaks in need of repair prior to placing the barrier layer into service. The model runs, however, use one manufacturing defect and one installation defect.

In view of the above discussion, NMC believes that the HELP model analyses completed for the TMA have been performed using scientifically supportable input data resulting in defensible output.

3.5 Verification of Percolation Through the TMA Liner

3.5.1 Background

During a review meeting, WDNR requested that NMC submit a comparison between the estimated percolation from the site using HELP model runs and those obtained using the Giroud-Bonaparte equations. Since the HELP model uses the Giroud-Bonaparte equations to characterize the flow through a small, albeit important, part of the material profile, the two methods are not entirely independent. The two methods are different in that while the Giroud-Bonaparte equations provide an estimated percolation rate for a given head on the liner for one set of values (i.e., sizes and distribution of defects of the geomembrane, membrane-substrate contact conditions, hydraulic conductivity and thickness of the underlying soil), the HELP model computes the head on the liner, percolation through the liner and lateral drainage simultaneously on a daily basis based on a water budget analysis. The output from the HELP model run shows the annual/monthly average head on the liner as well as annual/monthly percolation from the site. The output also gives the peak daily average head on the liner and peak percolation rate from the site. Thus, to compare the two methods, either the peak daily or the annual average percolation rates should be used.

3.5.2 Comparison of Average Annual Percolation

The percolation from the site is used as input into the project's solute transport model to evaluate compliance. Since the average annual values are used for this purpose, NMC believes the comparison of the estimated annual average percolation from the site using the HELP model and

Giroud-Bonaparte equations is appropriate. For the comparison, the previously reported results (FVD, 1997) obtained for the design proposed in TMA Addendum No. 3 are reproduced here. Since the evaluation discussed in this section of Addendum No. 4 compares the average annual percolation computed by two separate methods, the previously completed analysis as presented in Addendum No. 3 is appropriate, even though the HELP model data presented in Addenda No. 3 and No. 4 vary.

To complete the comparison, the average annual head on the liner as computed by the HELP model was used in the calculations. Also, consistency regarding the sizes and distribution of defects of the geomembrane, membrane-substrate contact conditions, hydraulic conductivity, and thickness of the soil component as presented in Addendum No. 3 have been maintained.

For the analysis, the properties of the liner system were fixed, making the "head on the liner" the only variable in the analysis. Different stages of the TMA construction and operation lead to different values of average annual heads, providing the basis for a good comparison of the two methods. The calculations performed are provided in Appendix G of Addendum No. 3 and are reproduced in Appendix B of Addendum No. 4. The results of the calculations are summarized in Table 3.5-1 and show the following:

- For the eight cases of construction and operation considered, the range of annual average head was 0.000152 meters (0.006 inches) to 4.051 meters (159.5 inches), thus providing a comparison of calculated percolation rates over an extremely large range of heads.

- In general, the differences between the rates of percolation calculated using the two methods are very small.

- Except under two scenarios where the heads on the liner are very small, the HELP model predicts higher percolation through the liner than those predicted by the Giroud-Bonaparte equations.

- In the two cases where the HELP model predicts smaller percolation rates, the quantity of percolation is extremely small (less than $7.3x10^{-7}$ in/yr). This translates to less than 0.3 gallons per year from the area of the TMA where these conditions will prevail at any time during the construction and operation of the TMA.

In conclusion, the comparison shows that the results from the two methods are similar and that in all cases, with the exception of very low head conditions, the HELP model estimates are more conservative when compared to the Giroud-Bonaparte equations. For the very low head conditions the difference in the predictions of the two methods is insignificant.

3.6 Leachate Volume

Leachate generation volume estimates have been recalculated using the modified TMA liner and GCL hydraulic conductivity. The results are summarized in Table 3.6-1.

Table 3.5-1

Comparison of HELP Model and Giroud-Bonaparte Equation Results

Case[1]	Head (inches)	Percolation Using Giroud-Bonaparte Equation (in/yr)	Percolation from HELP Model (in/yr)
1. Sideslope with geocomposite; initial stage	0.006	6.33×10^{-7}	3.8×10^{-8}
2. Base; initial stage	1.18	1.14×10^{-4}	1.9×10^{-4}
3. Sideslope with geocomposite; second stage	0.007	7.29×10^{-7}	4.6×10^{-8}
4. Sideslope without geocomposite; second stage	159.5	0.308	0.399
5. Base; second stage	1.27	1.23×10^{-4}	1.9×10^{-4}
6. Base; early post-closure period	0.64	5.57×10^{-5}	1×10^{-4}
7. Base; leachate system shutoff	0.64	5.52×10^{-5}	1×10^{-4}
8. Sideslope without geocomposite; early post-closure period	3.27	4.37×10^{-4}	5.5×10^{-3}

1 The first item designates location for which the percolation calculation is done. The second item designates the time period in which the calculation is performed. For example, "sideslope without geocomposite; second stage" references that the percolation calculation was completed for the sideslope that by design does not have a drainage layer (geocomposite) and the period when the second stage has been filled with tailings but before the cover is placed.

Prepared by: NXP
Checked by: PAE

Table 3.6-1

TMA Post-Closure Leachate Volumes

Year After Total TMA Closure	Estimate Total Gallons Per Year	Estimated Total Gallons Per Day
1	20,387,000	55,900
2	10,910,000	29,900
3	6,118,000	16,800
4	5,171,000	14,200
5	4,107,000	11,300
6	3,521,000	9,600
7	3,216,000	8,800
8	2,972,000	8,100
9	2,354,000	6,400
10	2,159,000	5,900
11	2,034,000	5,600
12	1,930,000	5,300
13	1,382,000	3,800
14	1,272,000	3,500
15	1,074,000	2,900
16	792,000	2,200
17	741,000	2,000
18	698,000	1,900
19	672,000	1,800
20	650,000	1,800
21	629,000	1,700
22	517,000	1,400
23	346,000	900

Table 3.6-1 *(Continued)*

Year After Total TMA Closure	Estimate Total Gallons Per Year	Estimated Total Gallons Per Day
24	325,000	900
25	306,000	800
26	197,000	500
27	23,000	60
28	10,000	30
29	<100	<1
30	<100	<1
31	<100	<1
32	<100	<1
33	<100	<1
34	<100	<1
35	<100	<1
36	<100	<1
37	<100	<1
38	<100	<1
39	<100	<1
40	<100	<1

Prepared by: NXP
Checked by: MRS

4 Sensitivity Analysis

Comment 27 of the September 26, 1997, WDNR Completeness Determination requested a sensitivity analysis be performed on varying parameters used as inputs to the HELP model. The sensitivity analysis was presented in Tables 4 through 7 of the NMC response dated December 12, 1997. The tables have been revised to reflect the modifications presented in Section 2. Tables 4-1 through 4-4 summarize the revised sensitivity analysis.

Table 4-1

Sensitivity Analyses
Effect of Geomembrane in Reducing Percolation Under Operations Conditions

Case	Year	Percolation with GCL Only in Liner[1]	Percolation with Geomembrane and GCL in Liner[1]	Percent Percolation Reduction with Geomembrane
Lower Sideslope Stage II Twice Precipitation[2]	1	0.967638	<0.000005	>99.99
	2	1.085111	<0.000005	>99.99
	3	0.840738	<0.000005	>99.99
	4	0.978535	<0.000005	>99.99
	5	0.891592	<0.000005	>99.99
	6	0.815633	<0.000005	>99.99
	7	0.843704	<0.000005	>99.99
	8	0.807758	<0.000005	>99.99
	9	0.782062	<0.000005	>99.99
	10	0.984448	<0.000005	>99.99
Base Stage II Twice Precipitation[2]	1	29.793777	0.012519	>99.96
	2	18.008127	0.006330	>99.96
	3	14.176351	0.004707	>99.97
	4	20.397226	0.007421	>99.96
	5	14.355091	0.004741	>99.97
	6	13.688351	0.004464	>99.97
	7	16.152657	0.005390	>99.97
	8	11.574838	0.003720	>99.97
	9	9.759223	0.002812	>99.97
	10	14.203776	0.004966	>99.97

[1]Inches per year.
[2]Simulates ponding.

Prepared by: MRS
Checked by: NXP

Table 4-2

Sensitivity Analyses
Effect of Geomembrane in Reducing Percolation
Under Post-Closure Conditions - Base Stage II

Year	Percolation with GCL Only in Liner[1]	Percolation with Geomembrane and GCL in Liner[1]	Percent Percolation Reduction with Geomembrane
1	14.292581	0.004681	>99.97
2	10.418475	0.003328	>99.97
3	2.733410	0.000607	>99.98
4	2.354346	0.000512	>99.98
5	2.106809	0.000453	>99.98
6-10	1.649599	0.000342	>99.98
11-20	1.048967	0.000206	>99.98
21-40	0.409776	0.000043	>99.99
41-50	0.124710	0.000044	>99.96
51-60	0.124265	0.000042	>99.97
61-100	0.129278	0.000035	>99.97
101-140	0.12867	0.000027	>99.98

[1]Inches per year.

Prepared by: MRS
Checked by: NXP

Table 4-3

Sensitivity Analyses
Effect of Geomembrane in Reducing Cover Infiltration
Post-Closure Condition

Year	Infiltration with GCL Only in Cap[1]	Infiltration with Geomembrane and GCL in Cap[1]	Percent Infiltration Reduction with Geomembrane
1	0.082450	0.000017	99.98
2	0.141240	0.000034	99.98
3	0.117199	0.000027	99.98
4	0.103825	0.000023	99.98
5	0.168445	0.000041	99.98
6-10	0.130276	0.000030	99.98
11-20	0.126124	0.000029	99.98
21-40	0.134972	0.000032	99.98
41-50	0.124078	0.000028	99.98
51-60	0.125824	0.000029	99.98
61-100	0.129426	0.000031	99.98
101-140	0.1279465	0.000030	99.98

[1]Inches per year.

Prepared by: MRS
Checked by: NXP

Table 4-4

Sensitivity Analyses
Effect of Drainage Layer and GCL Hydraulic Conductivities

Year	Percolation with Varying Drainage Layer Hydraulic Conductivity (k); $k_{GCL} = 8.8x10^{-6}$ cm/s				Percolation with Varying GCL Hydraulic Conductivity (k); $k_{drain} = 0.3$ cm/sec		
	Run with k=0.3 cm/sec	Run with k=0.1 cm/sec	Run with k=0.03 cm/sec	Run with k=0.01 cm/sec	$k=3x10^{-9}$ cm/sec	$k=1x10^{-7}$ cm/sec	$k=1x10^{-6}$ cm/sec
1	0.012519	0.065382	0.386850	10.390356	0.000105	0.000328	0.001897
2	0.006330	0.034425	0.311020	7.096852	0.000064	0.000177	0.000971
3	0.004707	0.024009	0.182136	4.258595	0.000051	0.000135	0.000725
4	0.007421	0.036214	0.232328	8.594913	0.000071	0.000204	0.001134
5	0.004741	0.024583	0.210871	3.841426	0.000051	0.000136	0.000730
6	0.004464	0.022459	0.160512	3.860054	0.000049	0.000129	0.000688
7	0.005390	0.024315	0.155206	4.592669	0.000056	0.000153	0.000828
8	0.003720	0.019808	0.158174	2.863430	0.000042	0.000109	0.000575
9	0.002812	0.012517	0.081221	0.721456	0.000034	0.000084	0.000437
10	0.004966	0.022445	0.119552	2.677093	0.000048	0.000137	0.000760

Prepared by: MRS
Checked by: NXP

5 References

Foth & Van Dyke, 1995. *Tailings Management Area Feasibility Report/Plan of Operation for the Crandon Project.*

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Helmy Emam, Ahmed, M.S., 1995. "Sensitivity Analysis of HELP Model Version 3.04a for Landfill Cover Designs". MS Project Report, University of Mississippi.

Nicolet Minerals Company (formerly Crandon Mining Company), 1997. Letter dated December 12, 1997, from Don Moe to W. Tans, C. Carlson, and R. Grefe, Wisconsin Department of Natural Resources Re: Crandon Project - Reponse to WDNR September 26, 1997, Completeness Determination on the Feasibility Report for the Proposed Crandon Mine Tailings Management Area.

Peyton, R.L. and P.R. Schroeder, 1990. "Evaluation of Landfill-Liner Designs". *Journal of Environmental Engineering.* ASCE Vol. 116, No. 3, May/June.

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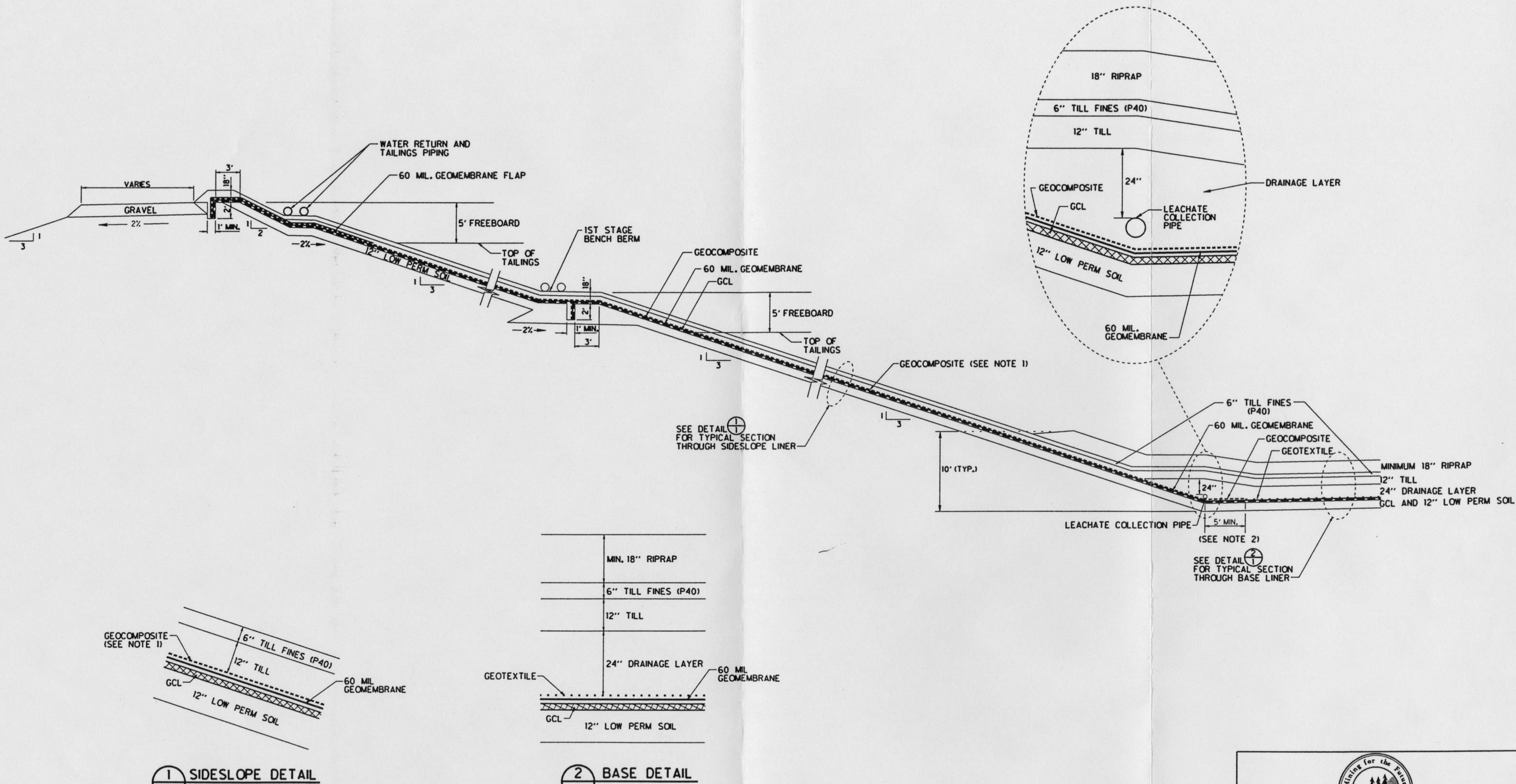
Steffen Robertson and Kirsten Inc., April, 1998. *TMA Source Term Geochemical Equilibrium Modeling Final.*

Wisconsin Department of Natural Resources, 1997. Letter dated September 26, 1997, from W. Tans, C. Carlson, and R. Grefe to Don Moe, Nicolet Minerals Company (formerly Crandon Mining Company) Re: Completeness Determination on the Feasibility Report for the Proposed Crandon Mine Tailings Management Area, Town of Lincoln, Forest County.

FIGURES FOR ADDENDUM NO. 4 TO THE MAY 1995 TAILINGS MANAGEMENT AREA FEASIBILITY REPORT/PLAN OF OPERATION



NOTES:

1. GEOCOMPOSITE CONSISTS OF A GEONET WITH A NON-WOVEN GEOTEXTILE HEAT BONDED TO ITS TOP AND BOTTOM.
2. GEOCOMPOSITE EXTENDED A MINIMUM OF FIVE FEET HORIZONTALLY INTO SAND DRAINAGE LAYER AT THE CELL BASE.

Foth & Van Dyke			
REVISED	DATE	BY	DESCRIPTION
CHECKED BY:	MRS	DATE: MAY '98	
APPROVED BY:	NXP	DATE: MAY '98	
APPROVED BY:	SAD2	DATE: MAY '98	

Nicolet Minerals COMPANY

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FIGURE 2-1

TYPICAL SIDESLOPE WITH GEOCOMPOSITE DRAINAGE LAYER DETAIL

Scale: NOT TO SCALE	Date: MAY, 1998	
Prepared By: Foth & Van Dyke	By: JRB2	93C049

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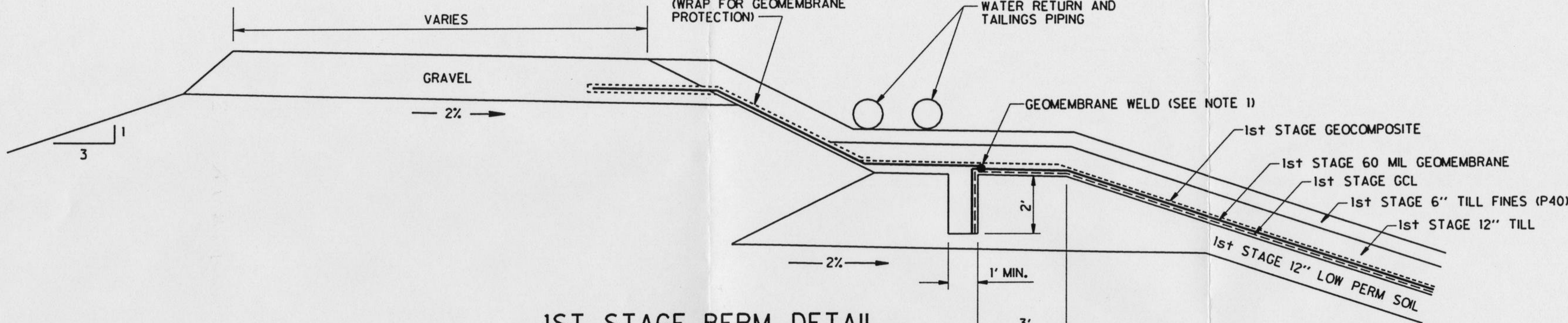
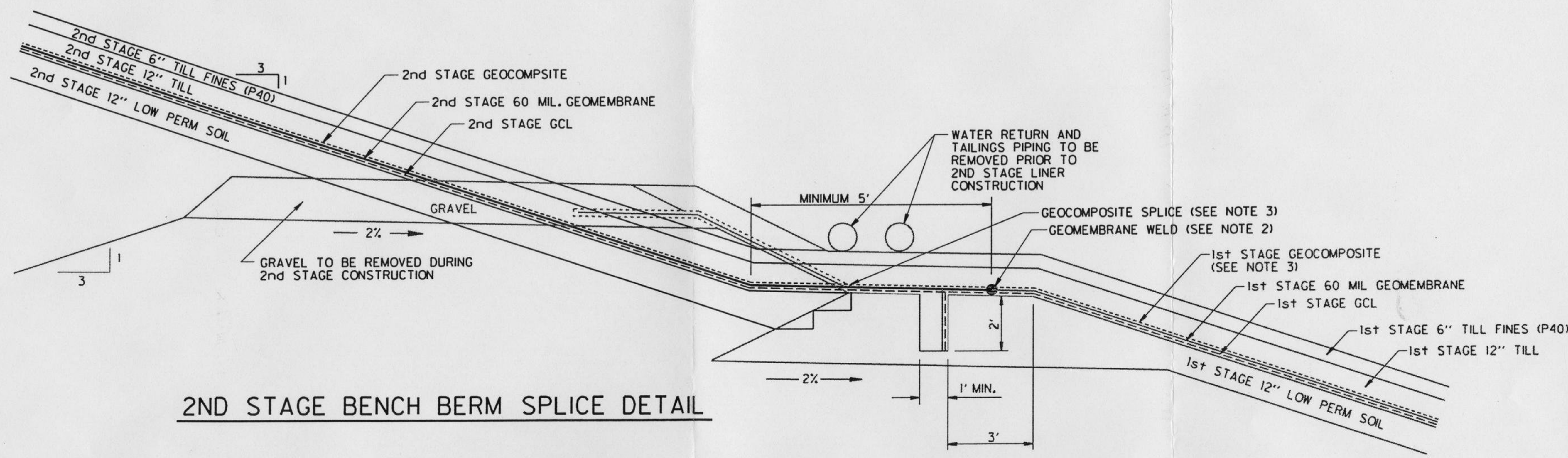


1ST STAGE BERM DETAIL



2ND STAGE BENCH BERM SPLICE DETAIL

NOTES:

1. GEOMEMBRANE WELD OF SACRIFICIAL PIECE OF GEOMEMBRANE TO IST STAGE PRIMARY LINER TO BE REMOVED JUST PRIOR TO SPLICING OF 2ND STAGE LINER.
2. GEOMEMBRANE WELD OF IST STAGE PRIMARY LINER TO SECOND STAGE PRIMARY LINER.
3. GEOCOMPOSITE SPLICING SHOULD NOT CAUSE LOSS OF TRANSMISSIVITY ACROSS SPLICE.

Foth & Van Dyke

REVISED	DATE	BY	DESCRIPTION

CHECKED BY:	MRS	DATE: MAY '98
APPROVED BY:	NXP	DATE: MAY '98
APPROVED BY:	SAD2	DATE: MAY '98

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FIGURE 2-2

TYPICAL STAGE I/STAGE II TRANSITION BENCH DETAIL

Scale: NOT TO SCALE	Date: MAY, 1998		
Prepared By: Foth & Van Dyke	By: JRB2	93C049	

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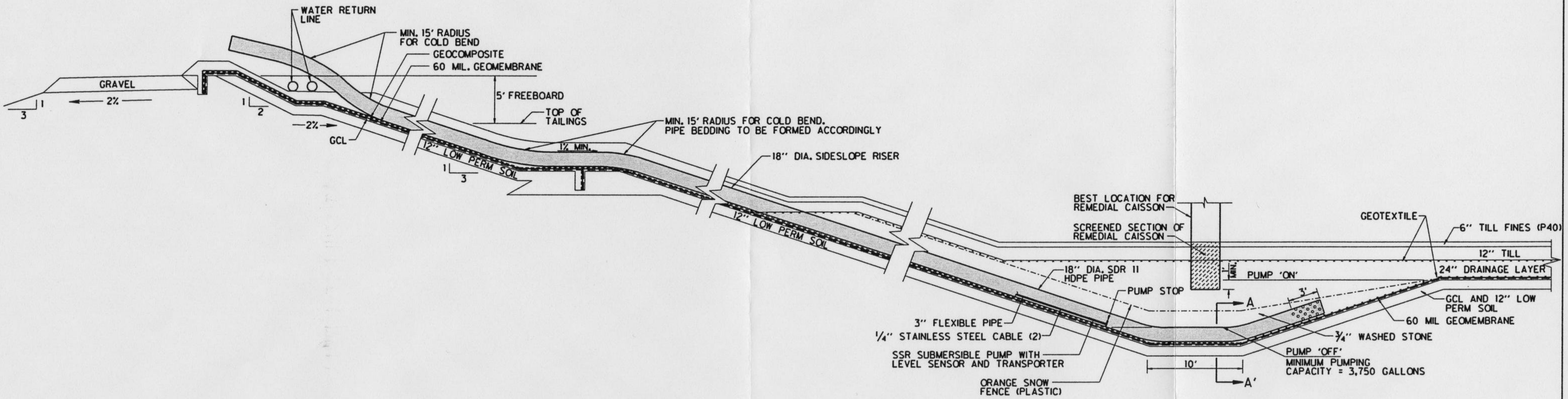

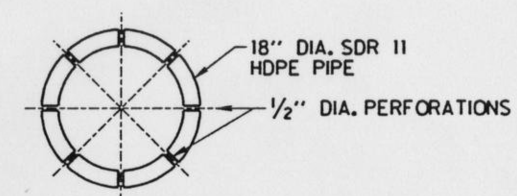

SECTION A-A' PIPE PERFORATION DETAIL

NOT TO SCALE

Foth & Van Dyke

REVISED	DATE	BY	DESCRIPTION

CHECKED BY:	MRS	DATE: MAY '98
APPROVED BY:	NXP	DATE: MAY '98
APPROVED BY:	SAD2	DATE: MAY '98

Nicolet Minerals COMPANY

FIGURE 2-3

SIDESLOPE RISER DETAIL WITH REMEDIAL CAISSON

Scale: NOT TO SCALE		Date:	MAY, 1998
Prepared By: Foth & Van Dyke		By: JRB2	93C049

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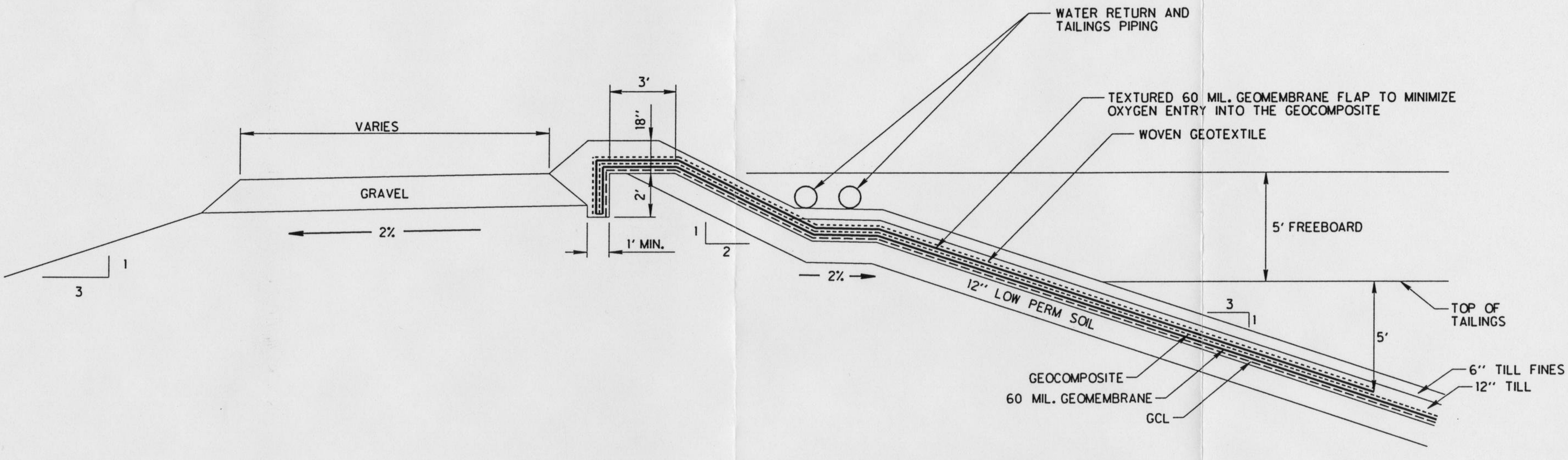

Foth & Van Dyke			
REVISED	DATE	BY	DESCRIPTION

CHECKED BY:	MRS	DATE: MAY '98
APPROVED BY:	NXP	DATE: MAY '98
APPROVED BY:	SAD2	DATE: MAY '98

Nicolet Minerals COMPANY

FIGURE 2-4

TYPICAL TOP OF SECOND STAGE BERM DETAIL

Scale: NOT TO SCALE	Date: MAY, 1998		
Prepared By: Foth & Van Dyke	By: JRB2	93C049	

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Appendix A

GCL Compatibility Test Report

Final Report

on

GCL Compatibility Testing for Base Liner at the Tailings Management Area for the Proposed Nicolet Minerals Company Zinc/Copper Mine, Near Crandon, Wisconsin

by

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April 22, 1998

Table of Contents

Introduction

This report presents the results of tests performed to assess the performance of two types of geosynthetic clay liners (GCLs). Both types of GCLs are under consideration for use as the soil component of the basal liner for the tailings management area (TMA) for the proposed Nicolet Minerals Company (NMC) zinc/copper mine located near Crandon, Wisconsin. The assessment of the performance of the GCLs reported herein is based on the measurement of the hydraulic conductivity of the GCLs in accordance with the Work Plan for GCL Compatibility Tests (Appendix A). This final report contains the results of a total of twelve tests in the work plan, the six tests in the original scope of work and the additional six tests described in the Addendum dated January 23, 1998.

Materials and Methods

Materials

The two GCLs tested in this study are *CETCO Bentomat DN GCL*, hereafter referred to as standard GCL, and *CETCO Bentomat DN CR GCL*, hereafter referred to as CR GCL. The CR GCL is a contaminant resistant GCL manufactured by CETCO. Both GCLs were shipped directly to Dr. Charles D. Shackelford from CETCO.

The three liquids used in the tests were an on-site ground water, a process water, and a simulated leachate. Sufficient quantities ($\geq \sim 20$ liters) of each of the three liquids were shipped directly to Dr. Shackelford from Foth & Van Dyke and Associates, Inc. to perform the required tests.

The on-site ground water (GW) was used in this study both as the prehydration water when the testing protocol required the GCL to be prehydrated before permeation with either the process water or the synthetic leachate and as a permeant liquid. The GW was collected from on-site well CMC-10P and is expected to have characteristics similar to the water that is expected to be placed in TMA cell 1 prior to commencement of tailings deposition. The measured chemical composition of the GW is shown in Appendix B as designation CMC-10P.

The process water (PW) was used in this study as a permeant liquid. The PW was prepared to have the expected process water characteristics for pH and selected parameters as shown in Table 1. The actual measured chemical composition of the process water is shown in Appendix B as designation CMC-SPW (NLS #157297 and NLS #163104).

The simulated leachate (SL) was used in this study as a permeant liquid. The SL was prepared to have the expected simulated leachate characteristics for pH and selected parameters as shown in Table 2. The actual measured chemical composition of the simulated leachate is shown in Appendix B as designation CMC-SAL (NLS #157296).

Table 1 - Process Water Characteristics(1).

Parameter	Target Value	Source Compound
pH	9 to 10	$Ca(OH)_2$
Calcium	330 mg/L	$CaSO_4 \cdot 2H_2O$
Potassium	10 mg/L	K_2SO_4
Sodium	110 mg/L	Na_2SO_4
Sulfate	1,200 to 1,500 mg/L	--------

(1) From Table 2, Target Process Water Permeant Characteristics of the *Work Plan for GCL Compatibility Tests (Appendix A)* provided by Foth & Van Dyke and Associates, Inc.

Table 2 - Simulated Leachate Characteristics(1).

Parameter	Target Value	Source Compound
pH	2.5	H_2SO_4
Al	30 mg/L	$Al_2(SO_4)_3 \cdot 18H_2O$
As	1.0 mg/L	As_2O_3
Cd	5.0 mg/L	$3CdSO_4 \cdot 8H_2O$
Ca	300 mg/L	$CaSO_4 \cdot 2H_2O$
Co	3.0 mg/L	$CoSO_4 \cdot xH_2O$ (x=6-7)
Cu	65 mg/L	$CuSO_4 \cdot 5H_2O$
Fe	450 mg/L	$FeSO_4 \cdot 7H_2O$
Pb	1.2 mg/L	$PbSO_4$
Mg	1,500 mg/L	$MgSO_4 \cdot 7H_2O$
Mn	180 mg/L	$MnSO_4 \cdot H_2O$
Ni	2.0 mg/L	$NiSO_4 \cdot 6H_2O$
SO_4^{2-}	12,000 mg/L	-----
Zn	2,400 mg/L	$ZnSO_4 \cdot 7H_2O$

(1) From Table 3, Target Process Water Permeant Characteristics of the *Work Plan for GCL Compatibility Tests (Appendix A)* provided by Foth & Van Dyke and Associates, Inc.

Methods

General Testing Considerations

The hydraulic conductivity tests generally were performed in accordance with ASTM D 5084 (*Standard Test Method for the Measurement of the Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*) and GRI-GCL2 (*Standard Test Method for Permeability of Geosynthetic Clay Liners (GCLs)*) with the following modifications.

(1) The test specimens were back-pressure saturated to an effective stress of 4±0.5 psi (instead of 10 psi as specified in GRI-GCL2) to simulate the initial TMA cell start-up conditions. The back-pressure stage of the test was performed using either the on-site GW when prehydration of the GCL before permeation was specified in the work plan, or the PW or SL when prehydration of the GCL was not specified in the work plan.

(2) The influent and effluent pH and electrical conductivity (EC) were measured to provide an indication of chemical equilibrium across the test specimen when the PW or SL were used as permeant liquids. The importance of considering chemical equilibrium in compatibility testing as well as the use of pH and EC as measures of chemical equilibrium are described in the literature review attached as Appendix E. The pH and EC of the effluent were not measured for the two tests involving GW as the permeant liquid because analysis of the GW indicated that the average EC of the GW (0.320 mS/cm as shown in Table 3) was less than the EC of 0.005N $CaSO_4$ (EC ≈ 0.769 mS/cm) solution recommended for use as "standard water" in ASTM D 5084. Thus, the two tests using GW as the permeant liquid are considered to provide baseline (lower limit) hydraulic conductivity values.

Table 3 - Electrical Conductivity (EC) and pH of Permeant Liquids.

Parameter	Electrical Conductivity at 25°C (mS/cm)			pH		
	Ground Water (GW)	Process Water (PW)	Simulated Leachate (SL)	Ground Water (GW)	Process Water (PW)	Simulated Leachate (SL)
No. of Measurements	6	123	86	6	123	86
Mean	0.320	3.99	27.4	6.71	8.58	2.47
Standard Deviation	0.021	0.239	0.583	0.12	0.84	0.10
Maximum	0.417	4.66	28.6	6.93	9.60	2.63
Minimum	0.267	3.38	26.4	6.62	6.24	2.31
Range	0.150	1.28	2.2	0.31	3.36	0.32
Standard Error	0.052	0.022	0.063	0.046	0.075	0.010

(3) Each test that indicated a steady-state hydraulic conductivity $\leq 3 \times 10^{-9}$ cm/s for the GCL based on permeation with either the PW or SL permeant liquids was to be continued until the ratios of the pH of the effluent relative to the pH of the influent, or pH_{out}/pH_{in}, and the EC of the effluent relative to the EC of the influent, or EC_{out}/EC_{in}, were at least 1±0.15, with one test being continued for a longer duration.

(4) Hydraulic gradients typically higher than those specified in ASTM D 5084 were used in this study in order to provide sufficient flow to establish chemical equilibrium across the GCL in a reasonable period. For example, the "recommended maximum hydraulic gradient" for specimens with hydraulic conductivity values < 1×10^{-7} cm/s is 30 based on ASTM D 5084. However, GRI-GCL2 allows for the establishment of a pressure loss corresponding to 5 psi for permeation of GCLs. This pressure loss corresponds to hydraulic gradients ranging from ~ 350 for a 10-mm-thick GCL to ~ 500 for a 7-mm-thick GCL. Since the pressure loss used in this study corresponded to 4 psi, the hydraulic gradients used in this study were expected to be greater than the recommended maximum values noted by ASTM D 5084 but less than the range of values based on GRI-GCL2. As indicated by the literature review (Appendix E), the use of relatively high hydraulic gradients is typical for hydraulic conductivity testing of GCLs, and generally does not have a significant effect on the hydraulic conductivity of GCLs.

Hydraulic Conductivity Test Procedures

Specimen Preparation

The GCL specimens were prepared in accordance with GRI-GCL2. After preparation of the GCL specimen, the specimen was placed in a flexible-wall (FW) permeameter, the permeameter was assembled, and the specimen was back pressured to achieve a high initial degree of saturation before permeation. As mentioned above, the "prehydrated" specimens were back pressured using the on-site ground water (GW), where the "non-prehydrated" specimens were back pressured with the permeant liquid to be used during the permeation stage.

The back-pressure saturation stage generally was performed in accordance with the guidelines established by either ASTM D 5084 or GRI-GCL2. The back-pressure saturation procedure consisted of initially applying a cell-water pressure of 5 psi and a pore-water pressure at both ends of the specimen (i.e., a back pressure) of 1 psi to establish the 4 psi difference required as the final initial effective stress at the end of the back-pressure saturation stage of the test (i.e., before permeation). Both the cell-water and back pressures were increased incrementally thereafter in either 5-psi or 10-psi increments until final cell-water and back pressures of 50 psi and 46 psi, respectively, were achieved. The 10-psi increments were used only after the cell-water pressure had reached 30 psi. The cell-water and back pressures resulting after each incremental increase in the pressures typically were maintained for a period of 3 to 4 hours. As a result, the entire procedure associated with increasing incrementally the cell-water and back pressures lasted from one to two days. The final cell-water and back pressures of 50 psi and 46 psi, respectively, were maintained for the duration of the back-pressure stage of the test. Two different target back-pressure durations were evaluated: (1) a short-term back-pressure duration of ~ 2 days, and (2) a long-term back-pressure duration of ~ 20 days.

Permeation

At the end of the back-pressure saturation stage of the test, the specimens were permeated with GW, PW, or SL. Permeation was established by increasing the pore-water pressure at the bottom or inflow end of the specimen from 46 psi to 48 psi, and decreasing the pore-water pressure at the top or outflow end of the specimen from 46 psi to 44 psi. As a result, an average effective stress of 4 (±0.5) psi was maintained in the specimen during permeation, with the nominal 4-psi difference between the headwater pressure and the tailwater pressure (= 48 psi minus 44 psi) establishing the pressure gradient for flow through the specimen.

Both the headwater and tailwater levels changed during the test, resulting in falling headwater - rising tailwater conditions as described in ASTM D 5084. However, the change in elevation head due to the difference in the liquid levels was always less than one percent of the change in pressure head. This percentage difference in elevation head is substantially less than the maximum difference of 10 percent recommended by GRI-GCL2 required to assume constant-head conditions. Nonetheless, the hydraulic conductivity, k, was calculated in accordance with both the falling headwater-rising tailwater equation and the constant-head equation presented in ASTM D 5084. As expected, both equations resulted in the same calculated hydraulic conductivity value to two significant digits due to the negligible effect of the difference in elevation head.

In addition to measurement of the hydraulic conductivity, influent and effluent samples were recovered for measurement of the pH and EC in the case of permeation with either PW or SL as previously described. The procedures for measuring the pH and EC are described in the *QA/QC Plan for Electrical Conductivity (EC) & pH Measurements for GCL Compatibility Test Program* included in Appendix A.

Testing Program

As shown in Table 4, the testing program consists of 12 tests. The first 4 tests (Test Nos. 1-4) were performed to evaluate the effect of prehydration on the hydraulic conductivity of the standard GCL permeated with either PW or SL under a relatively long-term back-pressure duration. Four additional tests (Test Nos. 5, 6, 11, and 12) were performed to evaluate the effect of prehydration on the hydraulic conductivity of the CR-GCL permeated with either PW or SL under a relatively long-term back-pressure duration. Two tests (Test Nos. 9 and 10) were performed to evaluate the effect of a shorter back-pressure duration relative to Test Nos. 11 and 12

Table 4 - Hydraulic Conductivity Testing Program.

Test No.	Test Material	Permeant Liquid	Prehydration w/Ground Water	Target Back-Pressure Duration (days)
1	GCL	Process Water	Yes	20
2	GCL	Process Water	No	20
3	GCL	Simulated Leachate	Yes	20
4	GCL	Simulated Leachate	No	20
5	CR-GCL	Process Water	No	20
6	CR-GCL	Simulated Leachate	No	20
7	GCL	Ground Water	Yes	2
8	CR-GCL	Ground Water	Yes	2
9	CR-GCL	Process Water	Yes	2
10	CR-GCL	Simulated Leachate	Yes	2
11	CR-GCL	Process Water	Yes	20
12	CR-GCL	Simulated Leachate	Yes	20

for prehydrated CR-GCL specimens permeated with either PW or SL. Finally, two tests (Test Nos. 7 and 8) were performed to establish the lower limit hydraulic conductivity values of each type of GCL based on permeation with GW.

Results and Discussion

Initial and Final Test Conditions

The initial and final test conditions for all twelve tests are summarized in Table 5. The initial (gravimetric) water contents (before specimen preparation) for all test specimens range from 14.1 percent for Test No. 12 to 37.5 percent for Test No. 7. The final water contents (after permeation) for all specimens completed to date are substantially higher than the initial water contents, with the values for the ratio of the final-to-initial water contents, w_f/w_i, for all tests. Higher final water contents relative to the initial water contents result from hydration of the bentonite during the back-pressure and/or permeation stages of the hydraulic conductivity test.

For the four tests involving the standard GCL permeated with either the process water or the simulated leachate (Test Nos. 1-4), the lower values of w_f/w_i for the two tests involving the simulated leachate (Test Nos. 3 and 4) relative to the two tests involving the process water (Test Nos. 1 and 2) are consistent with less swelling of the bentonite resulting from compression of the diffuse double layer of the bentonite particles due to the higher concentration of divalent metals in the simulated leachate. This observation also is supported by the values for the ratio of final-to-initial thickness, L_f/L_i, for Test Nos. 3 (L_f/L_i = 1.11) and 4 (L_f/L_i = 0.97) using the simulated leachate as the permeant liquid relative to the L_f/L_i values for Test Nos. 1 and 2 (L_f/L_i = 1.14) using the process water as the permeant liquid.

These trends in w_f/w_i and L_f/L_i values also are apparent for the four tests involving the CR-GCL permeated with either the process water or the simulated leachate for the long-term back-pressure duration (Test Nos. 5, 6, 11, and 12). However, in the case of these tests, the values of

Table 5 - Initial and Final Test Conditions.

Parameter	Test Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Test Material	GCL	GCL	GCL	GCL	CR-GCL	CR-GCL	GCL	CR-GCL	CR-GCL	CR-GCL	CR-GCL	CR-GCL
Permeant Liquid(1)	PW	PW	SL	SL	PW	SL	GW	GW	PW	SL	PW	SL
Prehydration	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Initial Thickness, L_i (mm)	7.2	6.6	6.5	6.6	6.9	7.5	6.8	6.5	7.4	7.4	7.1	7.3
Initial Water Content, w_i (%)	19.1	19.1	19.1	19.1	20.7	20.7	37.5	16.0	18.5	18.3	15.0	14.1
Back-pressure Duration (days)	23	23	28	21	23	21	3.8	3.8	2.0	2.0	27	29
Hydraulic Gradient(s), i	352 to 354	374 to 383	463 to 526	418	435 to 442	388 to 394	353 to 417	405 to 426	382 to 413	330 to 342	447 to 454	410 to 467
Final-to-Initial Thickness, L_f/L_i	1.14	1.14	1.11	0.97	1.10	1.02	1.30	1.26	1.01	1.01	1.13	1.03
Final Water Content, w_f (%)	111.9	118.5	92.9	86.2	122.1	95.6	130.0	124.4	116.0	112.7	125.9	111.4
Water Content Ratio, w_f/w_i	5.86	6.20	4.86	4.51	5.90	4.62	3.47	7.78	6.27	6.16	8.39	7.90

(1) GW = Ground Water; PW = Processed Water; SL = Simulated Leachate.

w_f/w_i for the two prehydrated CR-GCL specimens (Test Nos. 11 and 12) are significantly higher than the values of w_f/w_i for the two non-prehydrated CR-GCL specimens (Test Nos. 5 and 6).In addition, the values of w_f/w_i for all prehydrated CR-GCL specimens (Test Nos. 8, 11, and 12) generally are significantly greater than all other test specimens regardless of the permeant liquid used in the test. Thus, the greatest increase in water content relative to the initial water content is observed for the prehydrated CR-GCL specimens.

Hydraulic Conductivity Test Results

The test results are provided in Table 6 and plotted in Appendix C. The hydraulic conductivity values for each type of GCL based on specimens subjected to long-term back-pressure durations are summarized in Table 7 with respect to the permeant liquid used in the test and whether or not the specimen was prehydrated prior to permeation.

Effect of Prehydration

As indicated in Table 7, there is a significant effect on hydraulic conductivity due to prehydration. For example, the hydraulic conductivity values for the non-prehydrated specimens range from 3.8×10^{-6} cm/s to 2.5×10^{-5} cm/s, whereas the hydraulic conductivity values for the prehydrated specimens range from 1.3×10^{-9} cm/s to 4.7×10^{-6} cm/s. Thus, the lower limit of the range of hydraulic conductivity values for the non-prehydrated specimens is greater than the upper limit of the range of hydraulic conductivity values for the prehydrated specimens. This difference in hydraulic conductivity values due to prehydration is consistent with previously published results using different permeant liquids and GCLs (see Appendix E).

The effect of prehydration on the hydraulic conductivity of the GCLs for tests performed using long-term back-pressure durations also is summarized as a function of type of GCL and permeant liquid in Table 8. In the case of the standard GCL permeated with process water, the hydraulic conductivity of the non-prehydrated specimen is 1280 times, or 3.1 orders-of-

Table 6 - Results of Hydraulic Conductivity Tests.

Parameter	Test Number 1	2	3	4	5	6	7	8	9	10	11	12
Test Material	GCL	GCL	GCL	GCL	CR-GCL	CR-GCL	GCL	CR-GCL	CR-GCL	CR-GCL	CR-GCL	CR-GCL
Permeant Liquid(1)	PW	PW	SL	SL	PW	SL	GW	GW	PW	SL	PW	SL
Prehydration	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Duration of Back Pressure (days)	23	23	28	21	23	21	3.8	3.8	2.0	2.0	27	29
Duration of Permeation (days)	29.1	0.18	1.35	0.05	0.08	0.01	57.0	56.1	1.03	9.7	0.05	0.04
Pore Volumes of Flow	13.6	11.2	30.1	17.8	10.7	9.64	6.74	7.03	38.7	45.8	19.5	17.7
Hydraulic Conductivity, k(2) (cm/s)	6.9×10^{-9}	8.8×10^{-6}	9.5×10^{-7}	3.8×10^{-6}	1.0×10^{-5}	2.5×10^{-5}	1.3×10^{-9}	1.4×10^{-9}	3.8×10^{-6}	8.4×10^{-8}	4.7×10^{-6}	8.0×10^{-6}

(1) GW = Ground Water; PW = Processed Water; SL = Simulated Leachate; (2) k values reported are logarithmic averages of final three measured k values.

Table 7 - Hydraulic Conductivity as a Function of Prehydration, GCL Type, and Permeant Liquid for Long-Term, Back-Pressured Specimens.

Type of GCL	Permeant Liquid	Hydraulic Conductivity, k (cm/s)	
		Prehydrated	Non-Prehydrated
Standard GCL	Ground Water (GW)	1.3×10^{-9}	NA
	Process Water (PW)	6.9×10^{-9}	8.8×10^{-6}
	Simulated Leachate (SL)	9.5×10^{-7}	3.8×10^{-6}
CR GCL	Ground Water (GW)	1.4×10^{-9}	NA
	Process Water (PW)	4.7×10^{-6}	1.0×10^{-5}
	Simulated Leachate (SL)	8.0×10^{-6}	2.5×10^{-5}

NA = Not Applicable

Table 8 - Effect of Prehydration on Hydraulic Conductivity Results.

Permeant Liquid	Ratio of Hydraulic Conductivity of Non-Prehydrated Specimens to Hydraulic Conductivity of Prehydrated Specimens, k_{NP}/k_P	
	Standard GCL	CR-GCL
Process Water (PW)	1280	2.1
Simulated Leachate (SL)	4.0	3.1

magnitude, higher than the hydraulic conductivity of the prehydrated specimen, whereas the hydraulic conductivity of the non-prehydrated specimen for the case of permeation with the simulated leachate is only 4.0 times higher than the hydraulic conductivity of the prehydrated specimen. The difference between these two sets of results can be attributed to the significantly higher hydraulic conductivity of 9.8 x 10^{-7} cm/s for the prehydrated standard GCL permeated with the simulated leachate relative to the hydraulic conductivity of 6.2 x 10^{-9} cm/s for the prehydrated GCL permeated with the process water. Thus, although the effect of prehydration is noticeably less for the specimens permeated with the simulated leachate relative to the specimens permeated with process water, the effect of prehydration is insignificant with respect to establishing a relatively low hydraulic conductivity after permeation with the simulated leachate.

This prehydration effect also is apparent in the results for the tests involving the CR-GCL with long-term back-pressure durations. For example, the hydraulic conductivity for the non-prehydrated CR-GCL permeated with process water is 2.1 times higher than the hydraulic conductivity for the prehydrated CR-GCL permeated with process water, whereas the hydraulic conductivity for the non-prehydrated CR-GCL permeated with simulated leachate is 3.1 times higher than the hydraulic conductivity for the prehydrated CR-GCL permeated with simulated leachate. Thus, there is a greater prehydration effect on the CR-GCL when the simulated leachate is used relative to the process water, and the effect of prehydration on the CR-GCL tends to be less than the effect of prehydration on the standard GCL for a given permeant liquid (i.e., either PW or SL).

Effect of Type of GCL

The effect of type of GCL on the hydraulic conductivity of the GCLs for tests performed using long-term back-pressure durations is summarized as a function of prehydration and permeant liquid in Table 9. As indicated in Table 9, the CR-GCL actually performs worse than the standard GCL regardless of the prehydration effect or the permeant liquid. Explanation of the effect of type of GCL is difficult since the nature of the treatment process for the CR-GCL is proprietary.

Table 9 - Effect of Type of GCL on Hydraulic Conductivity Results.

Permeant Liquid	Ratio of Hydraulic Conductivity of CR-GCL to Hydraulic Conductivity of Standard GCL, k_{CR-GCL}/k_{GCL}	
	Prehydrated	Non-Prehydrated
Process Water (PW)	680	1.1
Simulated Leachate (SL)	8.4	26

Effect of Type of Permeant Liquid

The effect of type of permeant liquid on the hydraulic conductivity of the GCLs for tests performed using long-term back-pressure durations is summarized as a function of prehydration and type of GCL in Table 10. Except for the test involving the non-prehydrated, standard GCL, the hydraulic conductivity based on permeation with the simulated leachate is higher than the hydraulic conductivity based on permeation with the process water. This trend is consistent with the expected effect of the higher ionic strength simulated leachate solution on the hydraulic conductivity of the GCLs relative to the lower ionic strength process water solution. For the test involving the non-prehydrated, standard GCL, the slight decrease in hydraulic conductivity upon permeation with the simulated leachate may simply represent the potential scatter in the test results due to typical testing variations.

Table 10 - Effect of Type of Permeant Liquid on Hydraulic Conductivity Results.

Type of GCL	Ratio of Hydraulic Conductivity with Simulated Leachate to Hydraulic Conductivity with Process Water, k_{SL}/k_{PW}	
	Prehydrated	Non-Prehydrated
Standard GCL	140	0.43
CR-GCL	1.7	2.5

Effect of Back-Pressure Duration

A comparison of the hydraulic conductivity values of prehydrated CR-GCL specimens based on the two different back-pressure durations is provided in Table 11. As indicated in Table 11, very little difference in hydraulic conductivity values is observed when the process water is used as the permeant liquid indicating essentially no effect due to a difference in back-pressure duration. However, when the simulated leachate is used as the permeant liquid, the 2-day back-pressure duration results in a hydraulic conductivity value that is almost two orders-of-magnitude lower than the hydraulic conductivity value for the specimen back-pressure saturated for the longer duration. Explanation of this result is difficult since the nature of the treatment process for the CR-GCL is proprietary. Nonetheless, the results for the test using the simulated leachate indicate that there is a back-pressure duration effect with respect to the CR-GCL and the low pH (=2.5) simulated leachate used in this study.

Table 11 - Hydraulic Conductivity of Pre-Hydrated Contaminant Resistant Geosynthetic Clay Liner (CR-GCL) as a Function of Back-Pressured Duration.

Permeant Liquid	Hydraulic Conductivity, k (cm/s)	
	Long-term (20-30 days) Back-pressure Duration	Short-term (2 days) Back-pressure Duration
Process Water (PW)	4.7×10^{-6}	3.8×10^{-6}
Simulated Leachate (SL)	8.0×10^{-6}	8.4×10^{-8}

Appendix A -
Work Plan for GCL Compatibility Tests

Work Plan for GCL Compatibility Tests

Contents

Tables

Figures

1 Introduction

The tailings management area (TMA) for the proposed Crandon Mining Company (CMC) zinc/copper mine located near Crandon, Wisconsin, has been designed as a containment structure with base drainage. The base liner is a composite liner with a 60-mil HDPE geomembrane and a geosynthetic clay liner (GCL). The composite liner will overlie a prepared bed of native till fraction passing through U.S. Sieve No. 40, compacted in two lifts of 6 inches each. Figure 1 shows the base liner configuration. The purpose of this work plan is to identify and describe a series of hydraulic conductivity tests to be conducted to assess the performance of the GCL component of the base composite liner. These tests were requested by the Wisconsin Department of Natural Resources as part of their review of the TMA design.

2 Test Program Design

The base of the TMA will slope to two low points where leachate collection will occur. As part of the construction QA/QC program, the HDPE liner will be tested and defects repaired. Before the start of tailings placement into the cells, the cell bottom will be flooded with water. Therefore, remaining defects, if any, of the base liner geomembrane will result in the prehydration of the underlying GCL with water prior to potential exposure to leachate. On the upper portion of the sideslope liner the initial exposure of the GCL located below remaining geomembrane defects, if any, could be to leachate, since the cells will not be totally flooded with water. Therefore, it is desirable to investigate GCL compatibility with the expected leachate both under prehydrated and non-prehydrated conditions.

During the operation period of a given TMA cell, leachate will basically be process water which will be alkaline, having a pH above 7 SU. After closure of the facility there is a small potential that the tailings may be oxidized thereby causing the leachate to turn acidic. This potential change in leachate characteristics also make it desirable to investigate GCL compatibility with leachates representing basic and acidic characteristics.

Finally, a potential exists that the calcium in the process water may replace the sodium in the bentonite of the GCL and thus impact hydraulic conductivities. If these impacts are significant, contaminant resistant clay (CRC) or other treated bentonite may have to be specified for the GCL. Therefore, it is desirable to address the potential effects of the two leachates discussed above on CRC.

3 Tests to be Conducted

Table 1 specifies a series of hydraulic conductivity tests to be performed in general accordance with ASTM D 5084 and GRI-GCL2[1] to meet the program objectives discussed in Section 2 above. The modifications made for the test procedure in order to meet the program objectives shall be listed in the test report. One modification necessary is the test duration. Should the GCL be deemed compatible with the leachate (i.e., hydraulic conductivity of the GCL equal to or less than the design value of 3E-9 cm/sec at steady state conditions), the test shall be continued until such time that chemical equilibrium based on ratios of effluent to influent pH and conductivity of 1±0.15 have been achieved. However, one test will be continued for a longer duration. Hydraulic gradients greater than those recommended in ASTM D 5084 will be required to generate the number of pore volumes required to verify chemical equilibrium between the influent and effluent. Also, the average effective stress will not exceed a value of 4±0.5 psi during any stage of the test. This value will better simulate field conditions before tailings placement in a cell.

Process water for the above tests will be obtained from either the Inmet Mining Corporation's zinc/copper mine located in Winston Lake, Ontario, Canada, or it will be prepared based on the expected process water characteristics for pH and selected parameters as defined in Table 2-7 of the *Crandon Project Groundwater Quality Performance Evaluation* (Foth & Van Dyke, et al., 1997). The Inmet mine's ore and milling processes are similar to those proposed for the Crandon Project. Process water from the Inmet mine was also used during the Crandon Project treatability studies. The simulated leachate would consist of a synthetic acidified leachate of similar characteristics to that used in the project's supplementary waste characterization work. Tables 2 and 3 contain an approximate characterization of the two permeants. The water for prehydration will be collected from the on-site well WW-2 which is expected to have similar characteristics to that water expected to be placed in TMA cell 1 prior to commencement of tailings deposition.

[1]GRI-GCL2 was developed by Geosynthetic Research Institute (GRI) for geosynthetic clay liner (GCL) tests.

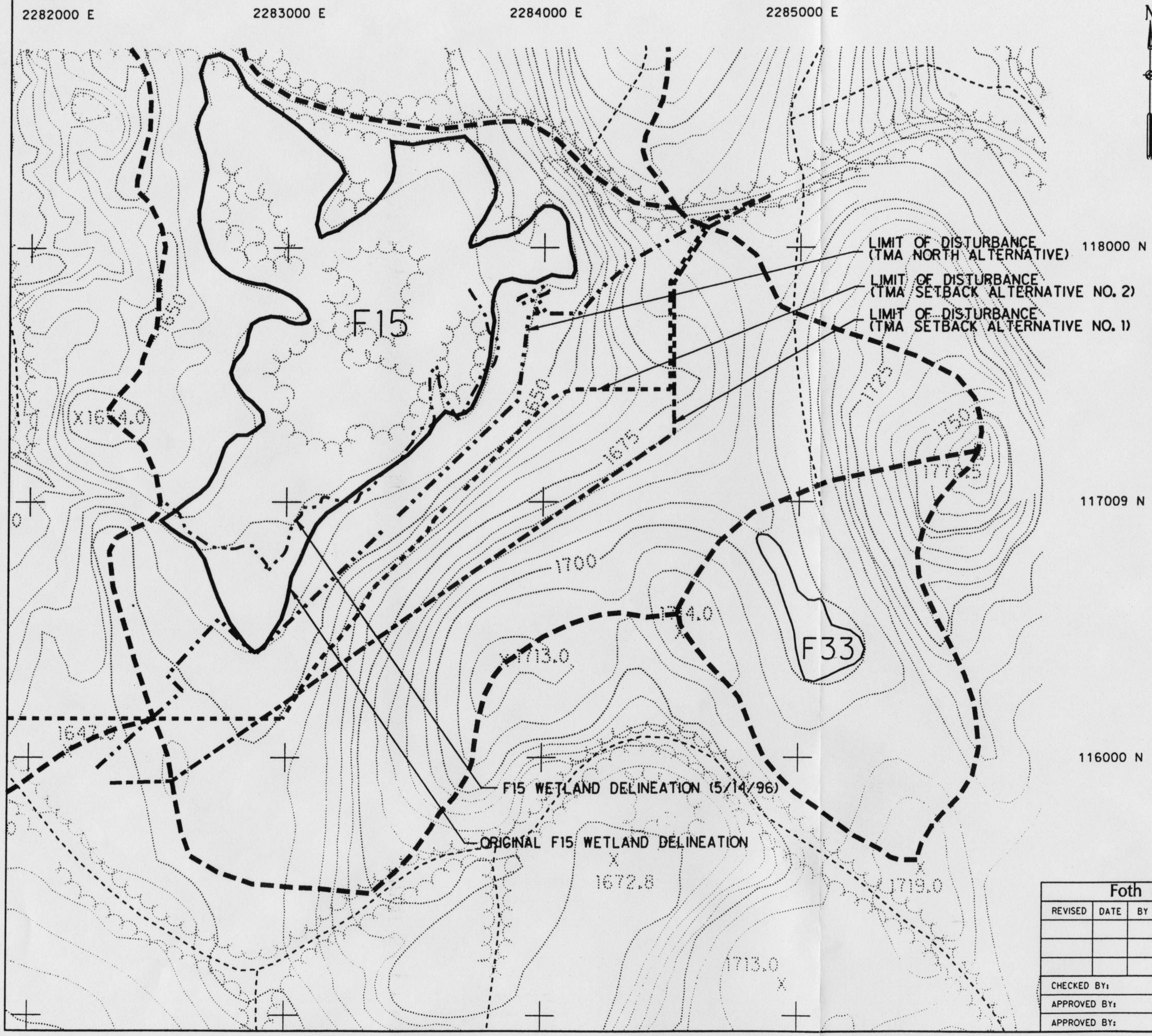
Table 1

Hydraulic Conductivity Tests

Test No.	Test Material	Permeant	Prehydration with Water	Remarks
1	GCL	Process Water[1]	Yes	GCL and process water to be provided by CMC.
2	GCL	Process Water[1]	No	GCL and process water to be provided by CMC.
3	GCL	Simulated Leachate	Yes	GCL and simulated leachate to be provided by CMC.
4	GCL	Simulated Leachate	No	GCL and simulated leachate to be provided by CMC.
5	GCL with CRC-treated bentonite	Process Water	No	GCL manufacturer and testing laboratory to work together and develop appropriate treated bentonite. CMC to provide process water.
6	GCL with CRC-treated bentonite	Simulated Leachate	No	GCL manufacturer and testing laboratory to work together and develop appropriate treated bentonite. CMC to provide simulated leachate.

[1]Source to be from a similar mine or simulated.

Prepared by: NXP
Checked by: JWS



LEGEND

- STREAMS
- EXISTING ROAD
- EXISTING CONTOUR
- SPOT ELEVATION
- F15 WETLAND DELINEATION (ORIGINAL)
- F15 WETLAND DELINEATION (5/14/96)
- WATERSHED DELINEATION

NOTES:

1. TOPOGRAPHIC BASE MAP DIGITIZED FROM 1"=1000' SCALE, 5' CONTOUR INTERVAL MAP PREPARED BY AERO-METRIC ENGINEERING, INC., SHEBOYGAN, WISCONSIN. DATE OF PHOTOGRAPHY APRIL 28, 1976.
2. HORIZONTAL DATUM BASED ON WISCONSIN STATE PLANE COORDINATE SYSTEM - NORTH ZONE.
3. VERTICAL DATUM BASED ON MEAN SEA LEVEL DATUM. CONTOUR INTERVAL IS FIVE FEET.
4. COUNTY AND TOWNSHIP LINES DIGITIZED FROM 7.5' SERIES USGS MAPS.

Foth & Van Dyke			
REVISED	DATE	BY	DESCRIPTION
CHECKED BY:	JKS1	DATE: JAN. '97	
APPROVED BY:	PAE	DATE: JAN. '97	
APPROVED BY:	GWS	DATE: JAN. '97	

Crandon Mining Company

FIGURE 3.1-1
TMA SETBACK ALTERNATIVES

Scale: 0 200' 400' | Date: JANUARY, 1997
Prepared By: Foth & Van Dyke | By: GAM

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93C049

Table 3[1]

Synthetic Leachate Composition as Used in the Supplemental Kinetic Test Program[2]

Parameter	Target (mg/l)	Source Compound
pH[3]	2.5	H_2SO_4
Al	30	$Al_2(SO_4)_3 \cdot 18H_2O$
As	1.0	As_2O_3
Cd	5.0	$3\ CdSO_4 \cdot 8H_2O$
Ca	300	$CaSO_4 \cdot 2H_2O$
Co	3.0	$CoSO_4 \cdot xH_2O$ (x=6 -7)
Cu	65	$CuSO_4 \cdot 5\ H_2O$
Fe	450	$FeSO_4 \cdot 7H_2O$
Pb	1.2	$PbSO_4$
Mg	1500	$MgSO_4 \cdot 7H_2O$
Mn	180	$MnSO_4 \cdot H_2O$
Ni	2.0	$NiSO_4 \cdot 6H_2O$
SO_4	12000	--
Zn	2400	$ZnSO_4 \cdot 7H_2O$

[1]From Table 2.4 of Appendix A to the *Crandon Project Tailings Management Area Groundwater Quality Performance Evaluation* (Foth & Van Dyke, et al., 1997).
[2]Trace metals are not relevant to the compatibility test because their concentrations in the process water are low and they are not expected to have a significant impact on the stability of bentonite.
[3]Given in SU.

Prepared by: JTC
Checked by: JWS

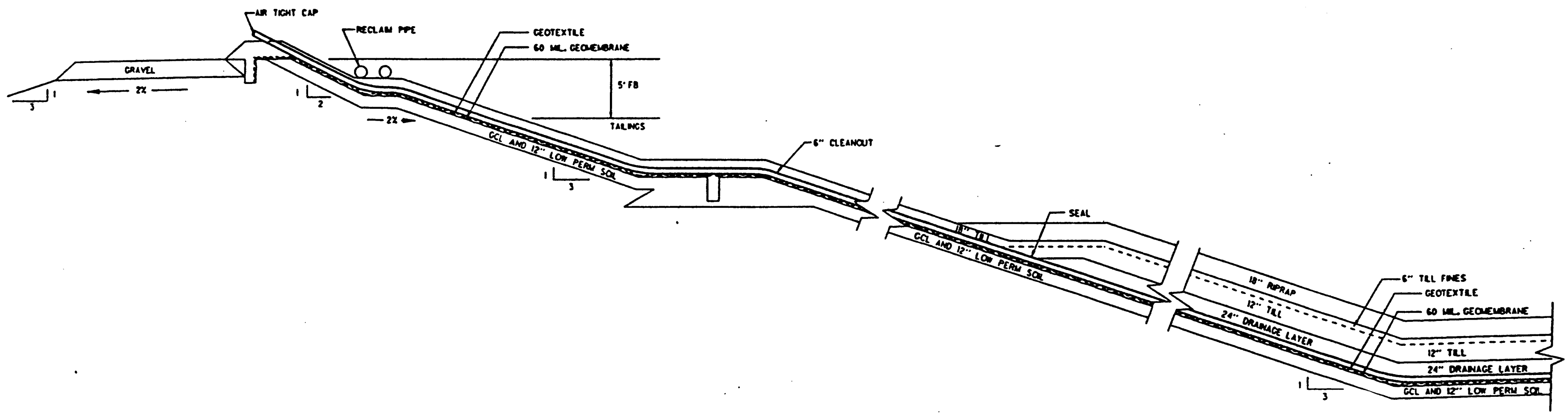
4 Results

The final (end of test) hydraulic conductivity of the GCL with sodium bentonite as well as with CRC or other treated bentonite using the process water and simulated leachate as permeants with and without prehydration will be used as the indicator of compatibility. A discussion of the test methods, including modifications made to ASTM D 5084 and GRI-GCL2; results; and recommendations will be presented in a project report.

5 References

Foth & Van Dyke; Steffen Robertson and Kirsten (Canada), Inc.; and HSI GeoTrans, Inc.; May 1997. *Crandon Project Tailings Management Area Groundwater Quality Performance Evaluation*.

A-35



TYPICAL REPRESENTATION: REFINEMENTS MAY BE MADE PRIOR TO CONSTRUCTION

Foth & Van Dyke

REVISED	DATE	BY	DESCRIPTION

CHECKED BY: NXP DATE: DEC. '97

APPROVED BY: TMS DATE: DEC. '97

APPROVED BY: DATE:

Crandon Mining Company

FIGURE 1

BASE LINER DETAIL

Scale: NOT TO SCALE Date: DECEMBER, 19

Prepared By: Foth & Van Dyke By:

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93C049

QA/QC Plan for
Electrical Conductivity (EC) & pH Measurements for GCL Compatibility Test Program
by
Charles D. Shackelford
(12/30/97)

- The pH and EC of liquid samples recovered from the influent and effluent accumulators of the permeability test apparatus will be measured using a Hach One Laboratory pH Meter (Model 44701) with a Hach Combination pH Electrode with Temperature (Model 50205), and EC will be measured using a Hach Conductivity/TDS Meter (Model 44600).
- Calibrations for pH and EC measurements based on specifications provided by Hach will be performed each day that either pH or EC measurements are made before any such measurements are made with respect to the compatibility tests. In addition, the calibration for EC will be repeated after the EC of all samples has been measured. Records of instrument calibrations will be maintained.
- The pH calibration will be performed using standard color-coded pH buffer solutions (pH = 4.01, 7.00, and 10.00) depending on the expected range in measured pH. For measured pH < 7, the pH = 4.01 and pH = 7.00 buffer solutions will be used for calibration, whereas for measured pH > 7, the pH = 7.00 and pH = 10.00 buffer solutions will be used for calibration.
- The pH electrode will be maintained in a standard pH = 7 buffer solution between measurements, and will be rinsed with distilled water both prior to and immediately after measurement of the pH of recovered liquid samples.
- The EC meter will be calibrated using Hach Co. Sodium Chloride Standard Solution for Conductivity or a commercially available equivalent solution.
- The EC probe will be rinsed with distilled water both prior to and immediately after each measurement of EC.
- The pH of influent and effluent liquid samples recovered from the permeability apparatus will be measured as soon as possible after sampling but always within 5 minutes of sampling to

minimize changes in pH. Aliquots of the effluent samples for EC measurement will be diluted using distilled water as necessary to insure readings within the linear portion of the EC calibration. As a result, EC generally will be measured within 10 minutes ± 5 minutes immediately after the pH measurement. The electrical conductivity of the dilution water as well as the amount of dilution water will be documented in accordance with standard practice for measuring and calibrating EC.

- In all cases, each liquid sample recovered from the influent and effluent accumulators of the permeability test apparatus will be split for separate pH and EC measurements.
- In all cases, an attempt will be made to collect influent and effluent samples from the respective accumulators of the permeability test apparatus for measurement of pH and EC at intervals approximating one pore volume of flow. However, this sample collection and measurement frequency may not be possible in cases where the flow rate is relatively high due to incompatibility between the permeant liquid and GCL. In such cases, influent and effluent samples will be collected from the respective accumulators of the permeability test apparatus in sufficient frequency and number to establish general trends in both pH and EC until such time as the termination criterion as established in Section 3 of the Work Plan for GCL Compatibility Tests has been achieved.

Appendix B - Chemical Compositions of Permeant Liquids

Crandon Project
Groundwater Results : CMC-10P
May 1994 - Jan 1995

Parameter		May-94	Jun-94	Jul-94	Aug-94	Sep-94	Oct-94	Dec-94	Jan-95
pH (Field)	S.U.	7.88	7.02	6.52	7.21	6.93	7.18	7.68	7.53
Conductivity (Field)	umhos	237	315	348	342	265	252	325	401
Temperature (Field)	Degrees C	9.5	10.1	8.8	10.9	10.2	9.2	8.4	7.5
Alkalinity	mg/L	152	155	142	160	150	150	150	160
Hardness	mg/L	137	154	135	150		36	150	160
Total Dissolved Solids	mg/L	181	176	164	169	180	220	170	200
Chemical Oxygen Demand	mg/L	< 10.0	< 10.0	< 10.0	< 10.0	< 20	< 20	< 10	< 10
Nitrate + Nitrite	mg/L	0.728	0.731	0.757	0.982	< 0.5	< 0.5	< 0.5	< 0.5
Nitrogen, Total Kjeldahl	mg/L	0.336	< 0.200	< 0.200	< 0.200	< 0.2	0.2	0.2	< 0.2
Chloride	mg/L	1	1	1	1	< 1	< 1	< 1	2
Fluoride	mg/L	< 0.100	0.105	0.102	0.109	0.1	0.1	< 0.1	0.1
Sulfate	mg/L	8.00	7.00	5.40	10.0	11	9.7	6.6	6.4
Cyanide, total	mg/L	< 0.020	< 0.020	< 0.020	< 0.020	< 0.02	< 0.020	< 0.020	< 0.020
Calcium, dissolved	mg/L	36.8	38.3	35.4	36.6	36	36	37	36
Calcium, total	mg/L		38.4				35		
Arsenic, dissolved	mg/L	< 0.005	< 0.005	< 0.005	< 0.005	< 0.0050	< 0.0050	< 0.0050	< 0.0050
Arsenic, total	mg/L		< 0.005				< 0.005		
Barium, dissolved	mg/L	0.032	0.032	0.030	0.030	0.030	0.027	0.032	0.031
Barium, total	mg/L		0.031				0.029		
Iron, dissolved	mg/L	< 0.100	< 0.100	< 0.100	< 0.100	< 0.050	< 0.050	< 0.050	< 0.050
Iron, total	mg/L		< 0.100				0.23		
Manganese, dissolved	mg/L	0.182	0.189	0.172	0.189	0.19	0.17	0.48	0.40
Manganese, total	mg/L		0.183				0.18		
Molybdenum, dissolved	mg/L	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020
Molybdenum, total	mg/L		< 0.020				< 0.020		
Selenium, dissolved	mg/L	< 0.005	< 0.005	< 0.005	< 0.005	< 0.0050	< 0.0050	< 0.0050	< 0.0050
Selenium, total	mg/L		< 0.005				< 0.0050		
Silver, dissolved	mg/L	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Silver, total	mg/L		< 0.010				< 0.010		
Chromium, dissolved	mg/L	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.0050	< 0.0050	< 0.0050
Chromium, total	mg/L		< 0.005				< 0.0050		
Cobalt, dissolved	mg/L	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010
Cobalt, total	mg/L		< 0.010				< 0.010		
Nickel, dissolved	mg/L	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030
Nickel, total	mg/L		< 0.030				< 0.030		
Antimony, dissolved	mg/L	< 0.050	< 0.050	< 0.050	< 0.050	< 0.20	< 0.20	< 0.0050	< 0.0050
Antimony, total	mg/L		< 0.050				< 0.20		
Magnesium, dissolved	mg/L	14.2	15.2	14.3	14.9	16	15	15	15
Magnesium, total	mg/L		15.3				14		
Aluminum, dissolved	mg/L	< 0.200	< 0.200	< 0.200	0.258	< 0.050	< 0.050	< 0.050	< 0.050
Aluminum, total	mg/L		< 0.200				0.10		
Cadmium, dissolved	mg/L	< 0.001	< 0.001	< 0.001	< 0.001	0.0003	< 0.0010	< 0.0001	< 0.0001
Cadmium, total	mg/L		< 0.001				< 0.0001		
Copper, dissolved	mg/L	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030	< 0.030
Copper, total	mg/L		< 0.030				< 0.030		
Lead, dissolved	mg/L	< 0.001	< 0.001	0.003	< 0.001	< 0.0020	< 0.0020	< 0.0020	< 0.0020
Lead, total	mg/L		0.006				< 0.0020		
Mercury, dissolved	mg/L	< 0.0002	0.0004	0.0004	< 0.0002	< 0.0002	< 0.0002	< 0.00020	< 0.00020
Mercury, total	mg/L		0.0005				< 0.00020		
Zinc, dissolved	mg/L	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	< 0.020	0.031
Zinc, total	mg/L		< 0.020				< 0.020		

25-Apr-95

Summary of Study Area
Groundwater Quality
CMC-10P

May 1994 - Jan. 1995
Crandon Project

Parameter	Units	Total Samples	Total Detections		Minimum		Maximum	Mean(1)	Standard Deviation(1)	Mean(2)	Standard Deviation(2)
pH (Field)	S.U.	8	8		6.52		7.88	7.244	0.440	7.244	0.440
Conductivity (Field)	umhos	8	8		237		548	335.6	101.2	335.6	101.2
Temperature (Field)	Degrees C	8	8		7.5		10.9	9.325	1.093	9.325	1.093
Alkalinity	mg/L	8	8		142		160	152.4	6.0	152.4	6.0
Hardness	mg/L	7	7		36		160	131.7	43.1	131.7	43.1
Total Dissolved Solids	mg/L	8	8		164		220	182.5	18.7	182.5	18.7
Chemical Oxygen Demand	mg/L	8	0	<	10	<	20	6.25	2.31	0.00	0.00
Nitrate + Nitrite	mg/L	8	4	<	0.5		0.982	0.525	0.304	0.400	0.435
Nitrogen, Total Kjeldahl	mg/L	8	3	<	0.2		0.336	0.155	0.086	0.092	0.134
Chloride	mg/L	8	5	<	1		2	0.938	0.496	0.750	0.707
Fluoride	mg/L	8	6	<	0.1		0.109	0.090	0.025	0.077	0.048
Sulfate	mg/L	8	8		5.4		11	8.01	2.01	8.01	2.01
Cyanide, total	mg/L	8	0	<	0.02	<	0.02	0.010	0.000	0	0
Calcium, dissolved	mg/L	8	8		35.4		38.3	36.51	0.89	36.51	0.89
Calcium, total	mg/L	2	2		35		38.4	36.70	2.40	36.70	2.40
Arsenic, dissolved	mg/L	8	0	<	0.005	<	0.005	0.0025	0.0000	0.0000	0.0000
Arsenic, total	mg/L	2	0	<	0.005	<	0.005	0.0025	0.0000	0.0000	0.0000
Barium, dissolved	mg/L	8	8		0.027		0.032	0.031	0.002	0.031	0.002
Barium, total	mg/L	2	2		0.029		0.031	0.030	0.001	0.030	0.001
Iron, dissolved	mg/L	8	0	<	0.05	<	0.1	0.038	0.013	0.000	0.000
Iron, total	mg/L	2	1	<	0.1		0.23	0.140	0.127	0.115	0.163
Manganese, dissolved	mg/L	8	8		0.17		0.48	0.247	0.122	0.247	0.122
Manganese, total	mg/L	2	2		0.18		0.183	0.182	0.002	0.182	0.002
Molybdenum, dissolved	mg/L	8	0	<	0.02	<	0.02	0.0100	0.0000	0.0000	0.0000
Molybdenum, total	mg/L	2	0	<	0.02	<	0.02	0.0100	0.0000	0.0000	0.0000
Selenium, dissolved	mg/L	8	0	<	0.005	<	0.005	0.0025	0	0	0
Selenium, total	mg/L	2	0	<	0.005	<	0.005	0.0025	0	0	0
Silver, dissolved	mg/L	8	0	<	0.01	<	0.01	0.0050	0.0000	0.0000	0.0000
Silver, total	mg/L	2	0	<	0.01	<	0.01	0.005	0	0	0
Chromium, dissolved	mg/L	8	0	<	0.005	<	0.005	0.0025	0.0000	0.0000	0.0000
Chromium, total	mg/L	2	0	<	0.005	<	0.005	0.0025	0.0000	0.0000	0.0000
Cobalt, dissolved	mg/L	8	0	<	0.01	<	0.01	0.0050	0.0000	0.0000	0.0000
Cobalt, total	mg/L	2	0	<	0.01	<	0.01	0.0050	0.0000	0.0000	0.0000
Nickel, dissolved	mg/L	8	0	<	0.03	<	0.03	0.0150	0.0000	0.0000	0.0000
Nickel, total	mg/L	2	0	<	0.03	<	0.03	0.0150	0.0000	0.0000	0.0000
Antimony, dissolved	mg/L	8	0	<	0.005	<	0.2	0.038	0.039	0.00000	0.00000
Antimony, total	mg/L	2	0	<	0.05	<	0.2	0.063	0.053	0	0
Magnesium, dissolved	mg/L	8	8		14.2		16	14.950	0.555	14.950	0.555
Magnesium, total	mg/L	2	2		14		15.3	14.650	0.919	14.650	0.919
Aluminum, dissolved	mg/L	8	1	<	0.05		0.258	0.082	0.080	0.032	0.091
Aluminum, total	mg/L	2	1	<	0.2		0.1	0.100	0.000	0.050	0.071
Cadmium, dissolved	mg/L	8	1	<	0.0001		0.0003	0.00036	0.00020	0.00004	0.00011
Cadmium, total	mg/L	2	0	<	0.0001	<	0.001	0.00028	0.00032	0.00000	0.00000
Copper, dissolved	mg/L	8	0	<	0.03	<	0.03	0.0150	0.0000	0.0000	0.0000
Copper, total	mg/L	2	0	<	0.03	<	0.03	0.0150	0.0000	0.0000	0.0000
Lead, dissolved	mg/L	8	1	<	0.001		0.003	0.0011	0.0008	0.0004	0.0011
Lead, total	mg/L	2	1	<	0.002		0.006	0.0035	0.0035	0.0030	0.0042
Mercury, dissolved	mg/L	8	2	<	0.0002		0.0004	0.00018	0.00014	0.00010	0.00019
Mercury, total	mg/L	2	1	<	0.0002		0.0005	0.00030	0.00028	0.00025	0.00035
Zinc, dissolved	mg/L	8	1	<	0.02		0.031	0.013	0.007	0.004	0.011
Zinc, total	mg/L	2	0	<	0.02	<	0.02	0.010	0.000	0.000	0.000

(1) All non-detects replaced with one-half the detection limit.

(2) All non-detects replaced with zero.

NORTHERN LAKE SERVICE, INC.
Analytical Laboratory and Environmental Services
400 North Lake Avenue - Crandon, WI 54520
Tel:(715)478-2777 Fax:(715)478-3060

WIS. LAB CERT. NO. 721026460

ANALYTICAL REPORT

 NLS PROJECT# 39995

NLS CUST# 11932

Client: Foth & Van Dyke Associates
Attn: Russ Janeshek
2737 S. Ridge Road
PO Box 19012
Green Bay, WI 54307

Project Description: Crandon Project/Nicolet Minerals
Project Title: 93C049

Sample ID: CMC-SPW NLS#: 163104
Ref. Line 2 of COC 29733 Description: CMC-SPW
Collected: 03/05/98 Received: 03/19/98 Reported: 04/10/98

Parameter	Result	Units	LOD	LOQ	Method	Analyzed	Lab
Alkalinity, tot. as CaCO3 (unfiltered)	13	mg/L	2.1	7.4	EPA 310.1	03/23/98	721026460
Alkalinity, carbonate as CaCO3	ND	mg/L	2.1	7.4	SM 2320B	03/23/98	721026460
Aluminum, tot. as Al	0.58	mg/L	0.12	0.40	EPA 200.7	03/26/98	721026460
Arsenic, tot. as As by furnace	ND	ug/L	28	96	EPA 206.2	04/06/98	721026460
Cadmium, tot. as Cd	< 0.032 >	mg/L	0.024	0.086	EPA 200.7	04/01/98	721026460
Calcium, tot. as Ca	360	mg/L	3.0	3.0	EPA 200.7	03/31/98	721026460
Cobalt, tot. as Co	< 0.070 >	mg/L	0.033	0.12	EPA 200.7	03/30/98	721026460
Copper, tot. as Cu	0.25	mg/L	0.022	0.079	EPA 200.7	04/01/98	721026460
Iron, tot. as Fe	ND	mg/L	0.11	0.38	EPA 200.7	04/08/98	721026460
Lead, tot. as Pb	< 0.66 >	mg/L	0.40	1.4	EPA 200.7	04/07/98	721026460
Magnesium, tot. as Mg	3.7	mg/L	3.0	3.0	EPA 200.7	03/31/98	721026460
Manganese, tot. as Mn	0.19	mg/L	0.017	0.057	EPA 200.7	04/02/98	721026460
Mercury, tot. as Hg	ND	ug/L	0.050	0.050	EPA 245.7M	03/31/98	721026460
Nickel, tot. as Ni	ND	mg/L	0.11	0.39	EPA 200.7	04/01/98	721026460
pH, lab	6.9	s.u.	1.0		EPA 150.1	03/20/98	721026460
Sulfate, as SO4 (unfiltered)	680	mg/L	500	500	EPA 375.2	03/25/98	721026460
Zinc, tot. as Zn	11	mg/L	0.12	0.12	EPA 200.7	04/01/98	721026460
Metals digestion - total (water) ICP	yes				EPA 200.7	03/25/98	721026460
Metals digestion - total (water) furnace	yes				EPA 200.0	03/25/98	721026460

Values in brackets represent results greater than the LOD but less than the LOQ and are within a region of "Less-Certain Quantitation". Results greater than the LOQ are considered to be in the region of "Certain Quantitation".

LOD = Limit of Detection
DWB = Dry Weight Basis
LOQ = Limit of Quantitation
NA = Not Applicable
ND = Not Detected
%DWB = (mg/kg DWB)/10000

Thomas R Priebe
Reviewed by:

Authorized by:

R. T. Krueger
Laboratory Manager

NORTHERN LAKE SERVICE, INC.
Analytical Laboratory and Environmental Services
400 North Lake Avenue - Crandon, WI 54520
Tel:(715)478-2777 Fax:(715)478-3060

WIS. LAB CERT. NO. 721026460

ANALYTICAL REPORT

 NLS PROJECT# 38615

NLS CUST# 11932

Client: Foth & Van Dyke Associates
Attn: R. Janeshek
2737 S. Ridge Road
PO Box 19012
Green Bay, WI 54307

Project Description: Crandon Mining
Project Title: 93C049

Sample ID: CMC-SAL NLS#: 157296
Ref. Line 3 of COC 28617 Description: CMC-SAL
Collected: 12/12/97 Received: 12/17/97 Reported: 01/16/98

Parameter	Result	Units	LOD	LOQ	Method	Analyzed	Lab
Aluminum, tot. as Al	31	mg/L	0.12	0.40	EPA 200.7	12/31/97	721026460
Arsenic, tot. as As by furnace	600	ug/L	28	96	EPA 206.2	01/07/98	721026460
Cadmium, tot. as Cd	4.3	mg/L	0.024	0.086	EPA 200.7	12/23/97	721026460
Calcium, tot. as Ca	270	mg/L	3.0	3.0	EPA 200.7	12/31/97	721026460
Cobalt, tot. as Co	1.3	mg/L	0.033	0.12	EPA 200.7	01/10/98	721026460
Copper, tot. as Cu	51	mg/L	0.022	0.079	EPA 200.7	12/23/97	721026460
Iron, tot. as Fe	410	mg/L	0.11	0.38	EPA 200.7	12/31/97	721026460
Lead, tot. as Pb	ND	mg/L	0.40	1.4	EPA 200.7	01/06/98	721026460
Magnesium, tot. as Mg	1400	mg/L	3.0	3.0	EPA 200.7	12/31/97	721026460
Manganese, tot. as Mn	180	mg/L	0.017	0.057	EPA 200.7	01/15/98	721026460
Mercury, tot. as Hg	ND	ug/L	0.10	0.10	EPA 245.7M	12/30/97	721026460
Nickel, tot. as Ni	1.5	mg/L	0.11	0.39	EPA 200.7	12/23/97	721026460
pH, lab	2.5	s.u.	1.0		EPA 150.1	12/17/97	721026460
Sulfate, as SO4 (unfiltered)	6900	mg/L	5000	5000	EPA 375.2	12/22/97	721026460
Zinc, tot. as Zn	1800	mg/L	12	12	EPA 200.7	01/13/98	721026460
Metals digestion - total (water) ICP	yes				EPA 200.7	12/22/97	721026460
Metals digestion - total (water) furnace	yes				EPA 200.0	12/18/97	721026460

Values in brackets represent results greater than the LOD but less than the LOQ and are within a region of "Less-Certain Quantitation".
Results greater than the LOQ are considered to be in the region of "Certain Quantitation".

LOD = Limit of Detection
DWB = Dry Weight Basis
LOQ = Limit of Quantitation
NA = Not Applicable
ND = Not Detected
%DWB = (mg/kg DWB)/10000

Thomas R Pirelo
Reviewed by:

Authorized by:
R. T. Krueger
Laboratory Manager

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400 North Lake Avenue - Crandon, WI 54520
Tel:(715)478-2777 Fax:(715)478-3060

WIS. LAB CERT. NO. 721026460

ANALYTICAL REPORT

 NLS PROJECT# 38615

NLS CUST# 11932

Client: Foth & Van Dyke Associates
Attn: R. Janeshek
2737 S. Ridge Road
PO Box 19012
Green Bay, WI 54307

Project Description: Crandon Mining
Project Title: 93C049

Sample ID: CMC-SPW NLS#: 157297
Ref. Line 4 of COC 28617 Description: CMC-SPW
Collected: 12/12/97 Received: 12/17/97 Reported: 01/16/98

Parameter	Result	Units	LOD	LOQ	Method	Analyzed	Lab
Aluminum, tot. as Al	< 0.14 >	mg/L	0.12	0.40	EPA 200.7	12/31/97	721026460
Arsenic, tot. as As by furnace	ND	ug/L	28	96	EPA 206.2	01/07/98	721026460
Cadmium, tot. as Cd	ND	mg/L	0.024	0.086	EPA 200.7	12/23/97	721026460
Calcium, tot. as Ca	570	mg/L	3.0	3.0	EPA 200.7	12/31/97	721026460
Cobalt, tot. as Co	ND	mg/L	0.033	0.12	EPA 200.7	12/19/97	721026460
Copper, tot. as Cu	0.21	mg/L	0.022	0.079	EPA 200.7	12/23/97	721026460
Iron, tot. as Fe	1.7	mg/L	0.11	0.38	EPA 200.7	12/31/97	721026460
Lead, tot. as Pb	ND	mg/L	0.40	1.4	EPA 200.7	01/06/98	721026460
Magnesium, tot. as Mg	12	mg/L	3.0	3.0	EPA 200.7	12/31/97	721026460
Manganese, tot. as Mn	0.69	mg/L	0.017	0.057	EPA 200.7	01/15/98	721026460
Mercury, tot. as Hg	ND	ug/L	0.10	0.10	EPA 245.7M	12/30/97	721026460
Nickel, tot. as Ni	ND	mg/L	0.11	0.39	EPA 200.7	12/23/97	721026460
pH, lab	9.8	s.u.	1.0		EPA 150.1	12/17/97	721026460
Sulfate, as SO4 (unfiltered)	1100	mg/L	100	100	EPA 375.2	12/22/97	721026460
Zinc, tot. as Zn	9.2	mg/L	0.12	0.12	EPA 200.7	12/23/97	721026460
Metals digestion - total (water) ICP	yes				EPA 200.7	12/18/97	721026460
Metals digestion - total (water) furnace	yes				EPA 200.0	12/18/97	721026460

Values in brackets represent results greater than the LOD but less than the LOQ and are within a region of "Less-Certain Quantitation". Results greater than the LOQ are considered to be in the region of "Certain Quantitation".

LOD = Limit of Detection
DWB = Dry Weight Basis
LOQ = Limit of Quantitation
NA = Not Applicable
ND = Not Detected
%DWB = (mg/kg DWB)/10000

Thomas R Pruelo

Reviewed by:

Authorized by:
R. T. Krueger
Laboratory Manager

Appendix C - Plots of Test Results

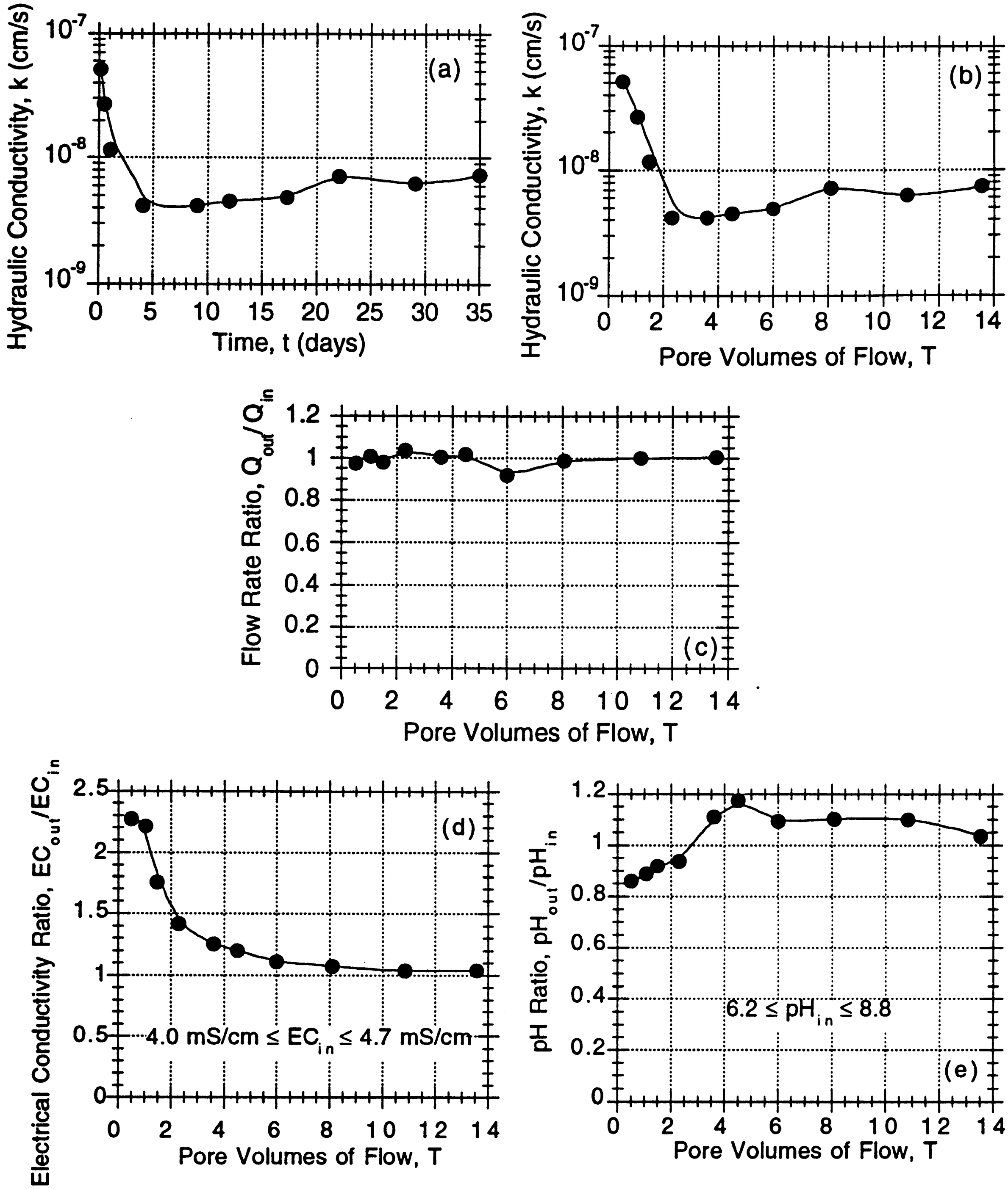

Figure C.1 - Results for Test No. 1: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

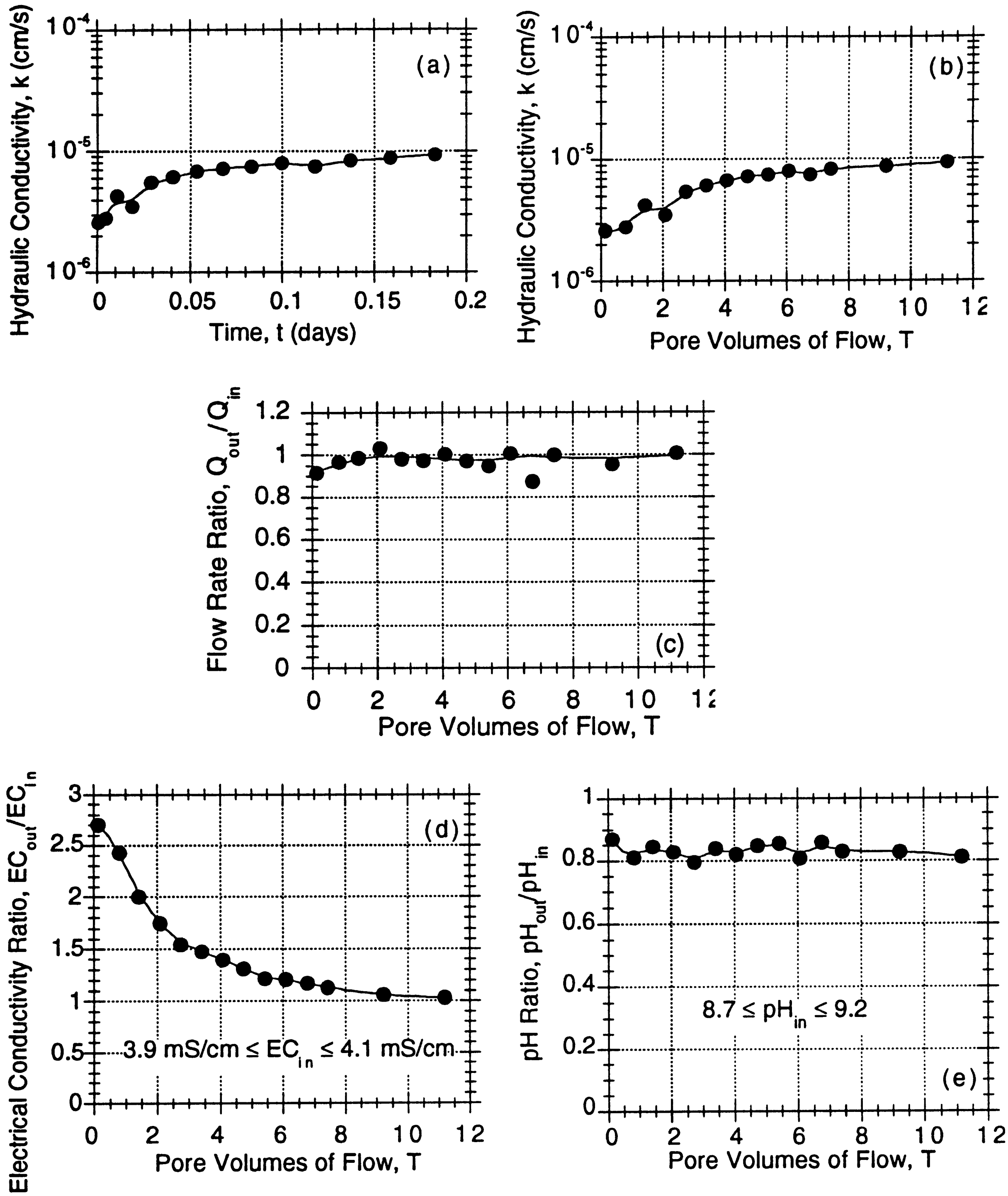

Figure C.2 - Results for Test No. 2: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

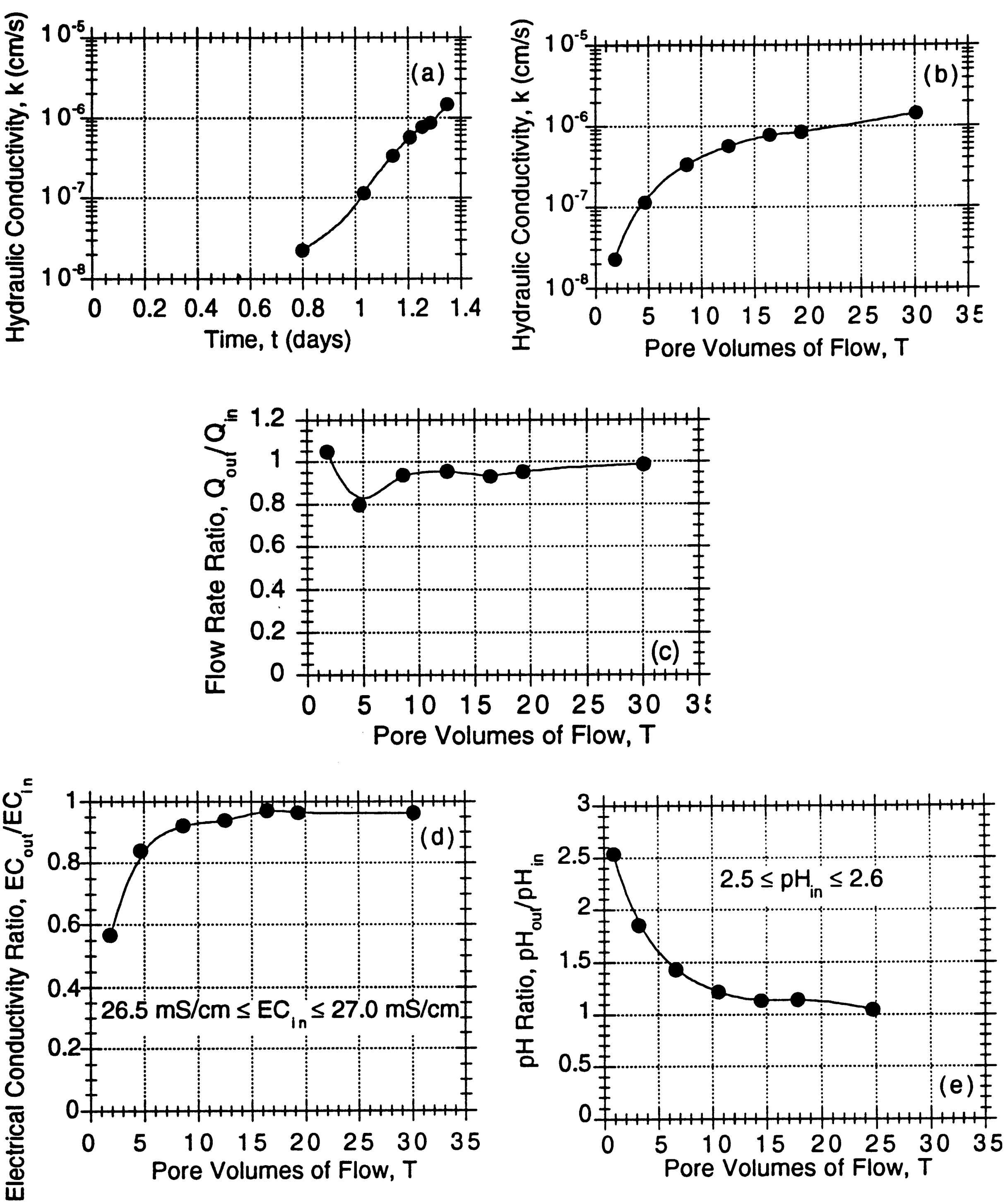

Figure C.3 - Results for Test No. 3: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

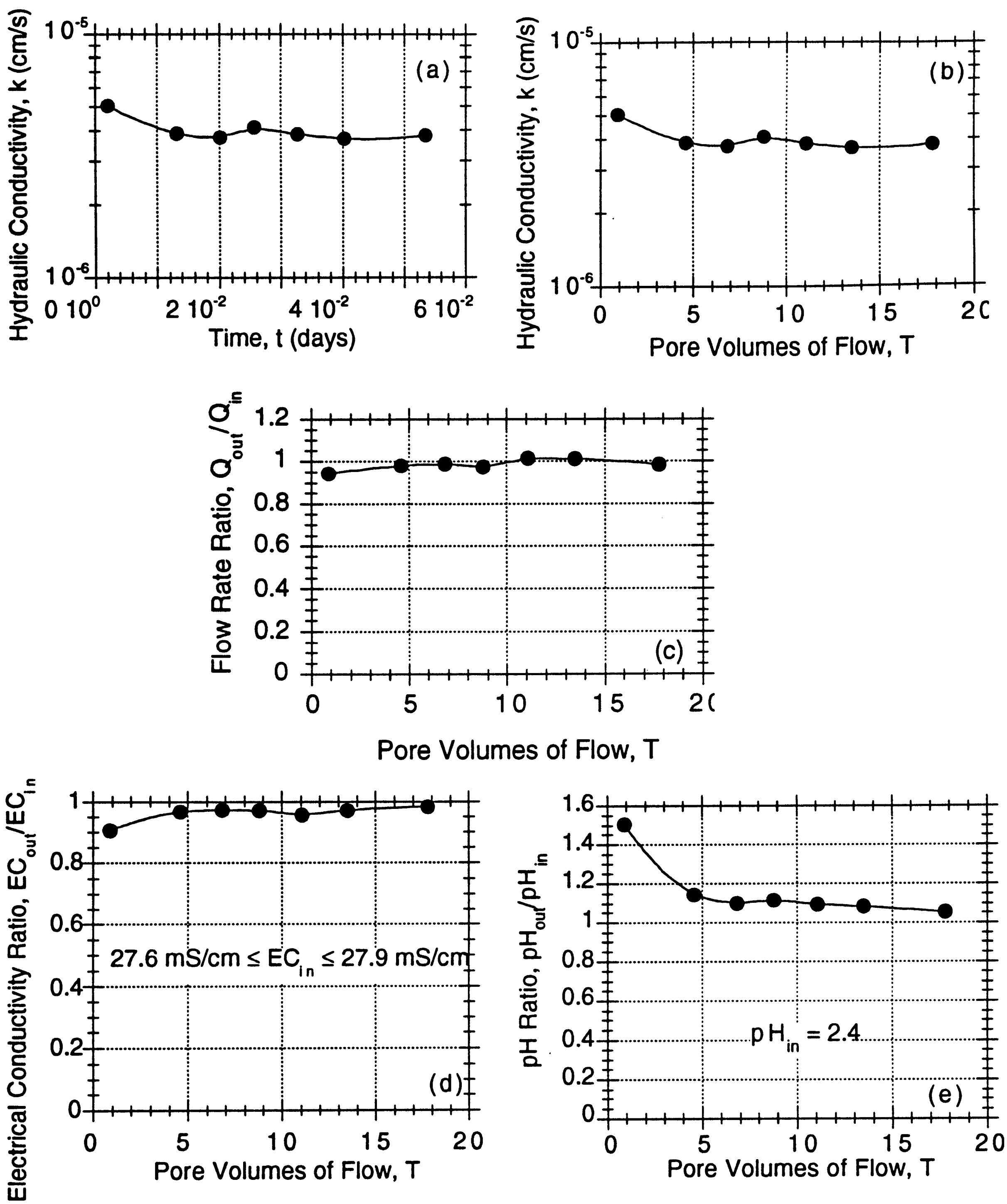

Figure C.4 - Results for Test No. 4: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

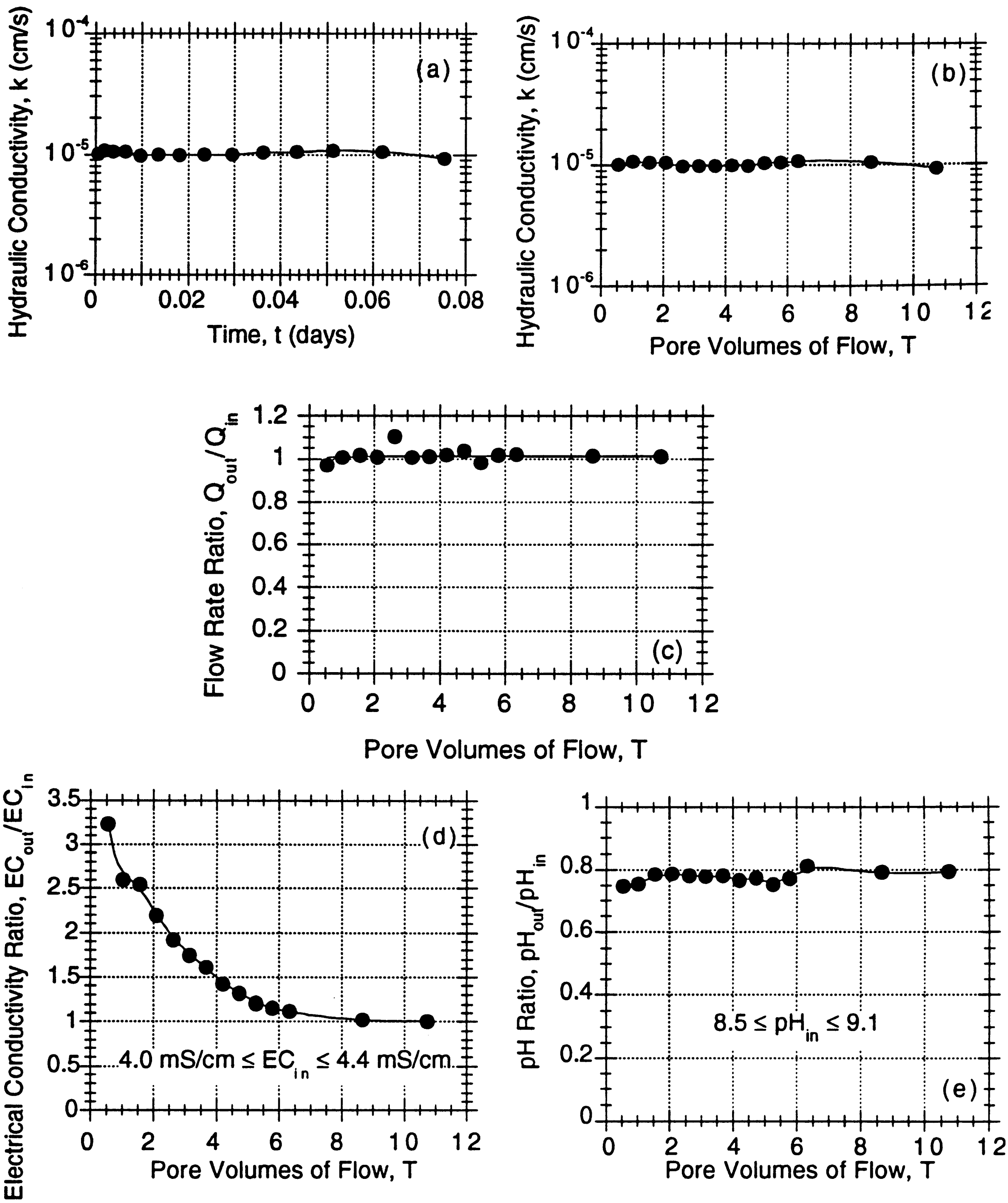

Figure C.5 - Results for Test No. 5: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

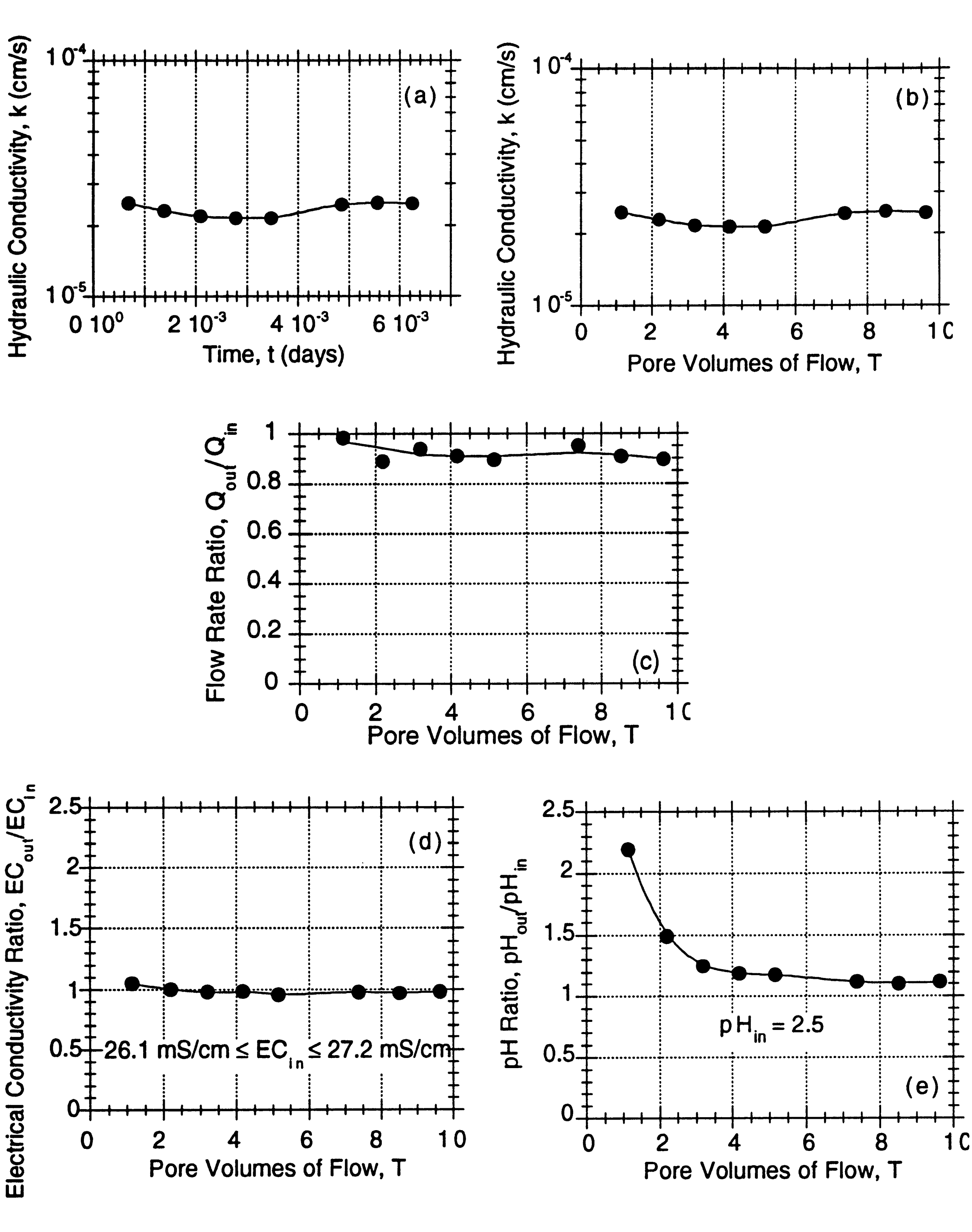

Figure C.6 - Results for Test No. 6: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

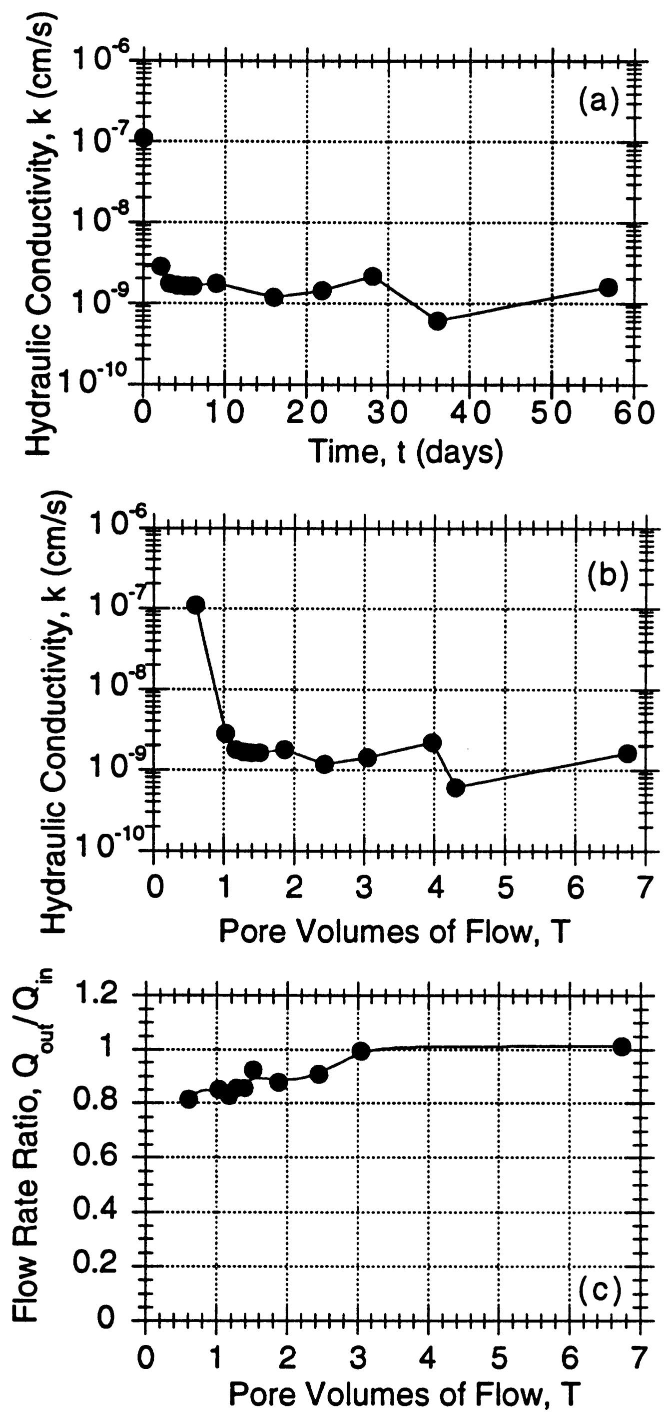

Figure C.7 - Results for Test No. 7: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; and (c) ratio of outflow-to-inflow flow rate versus pore volumes.

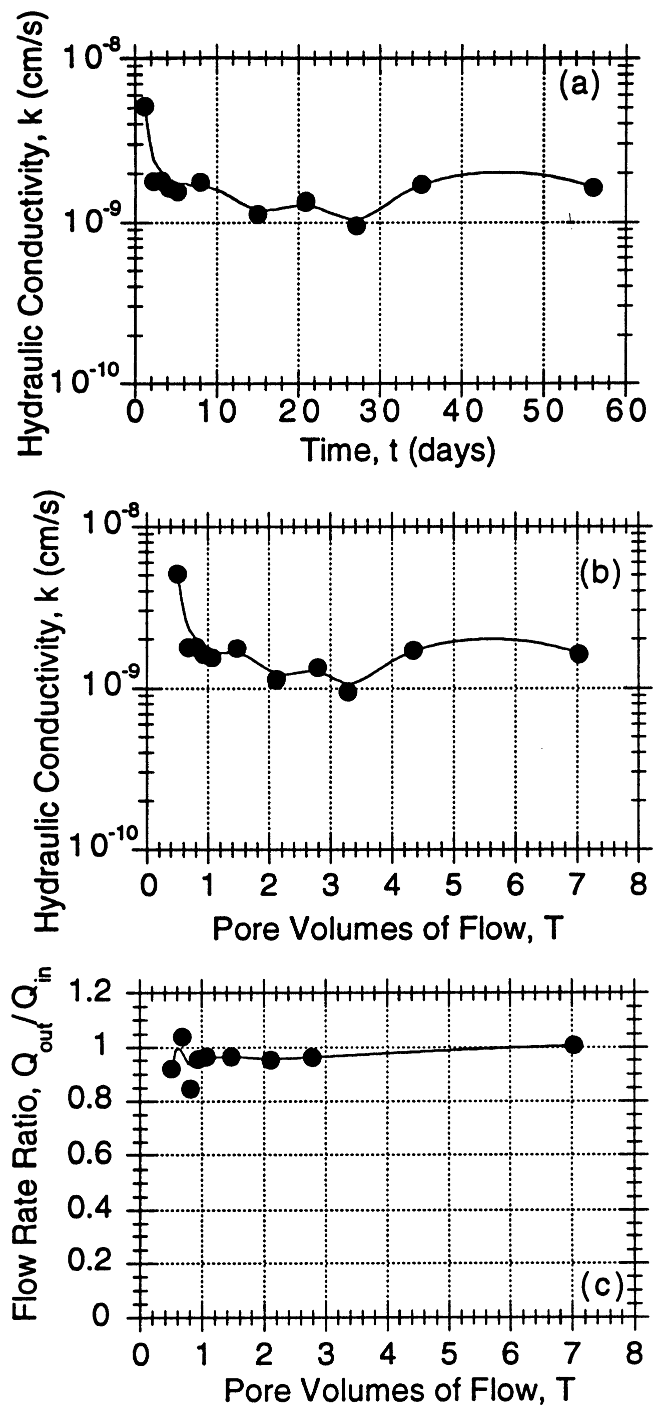

Figure C.8 - Results for Test No. 8: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; and (c) ratio of outflow-to-inflow flow rate versus pore volumes.

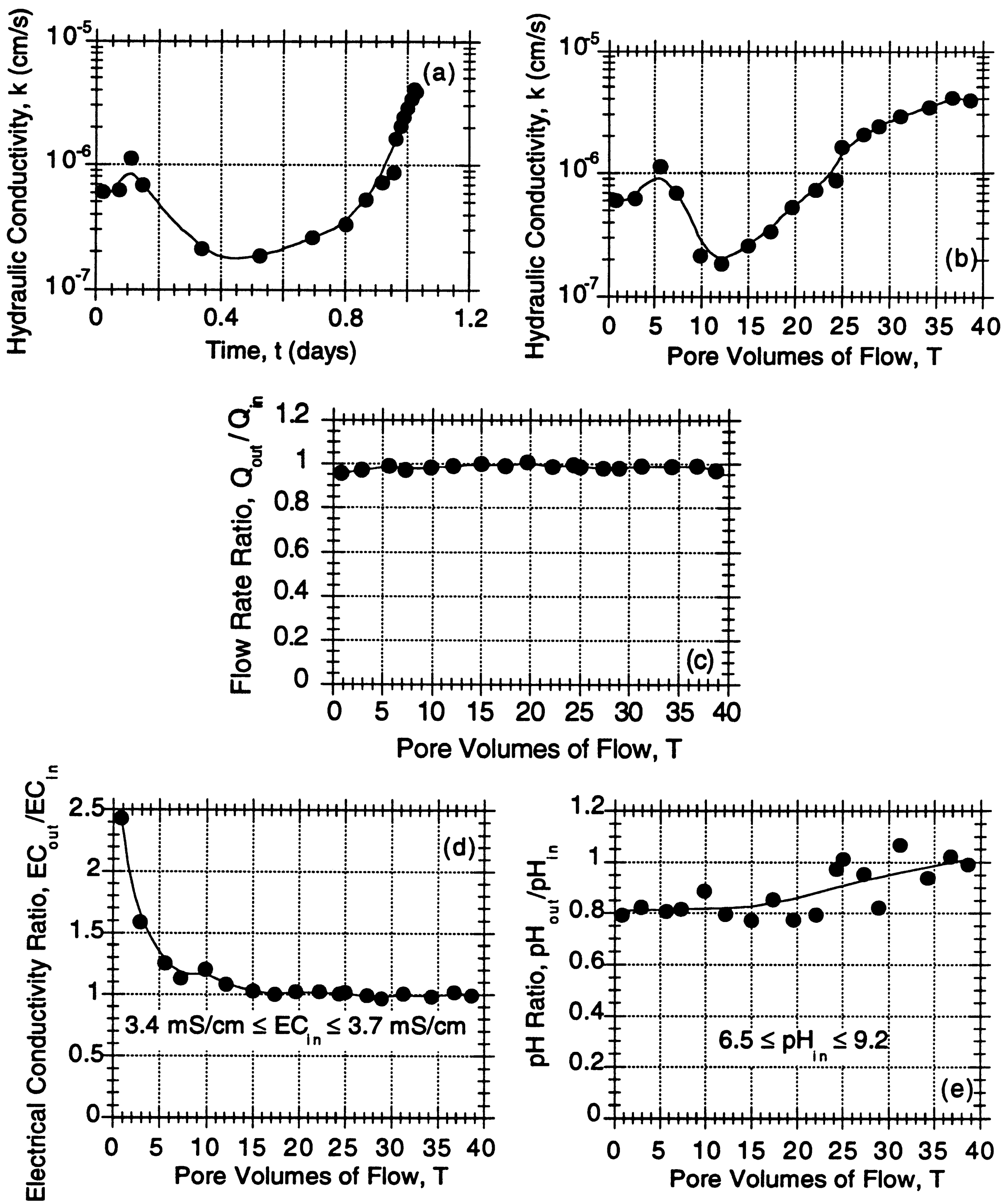

Figure C.9 - Results for Test No. 9: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

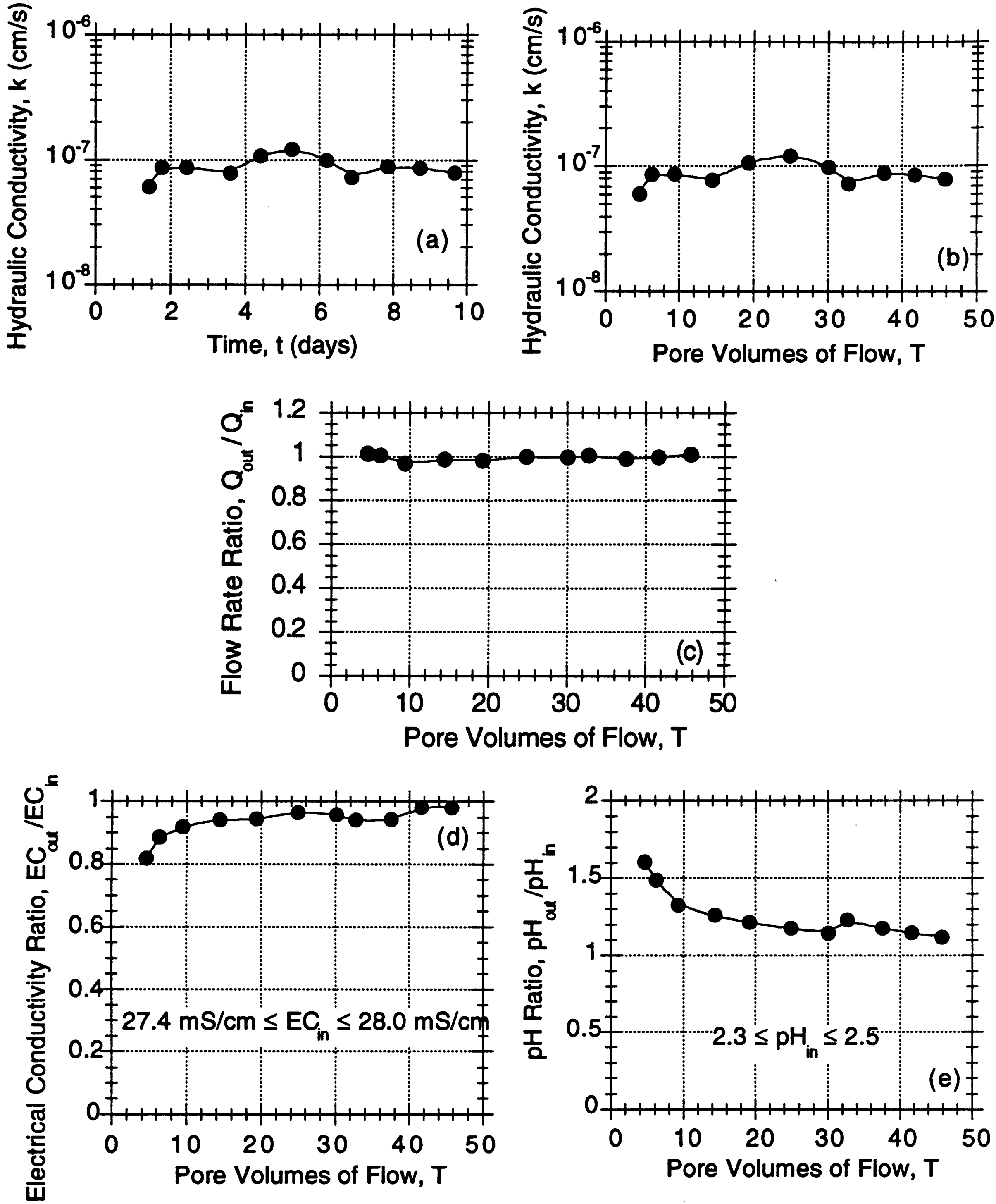

Figure C.10 - Results for Test No. 10: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

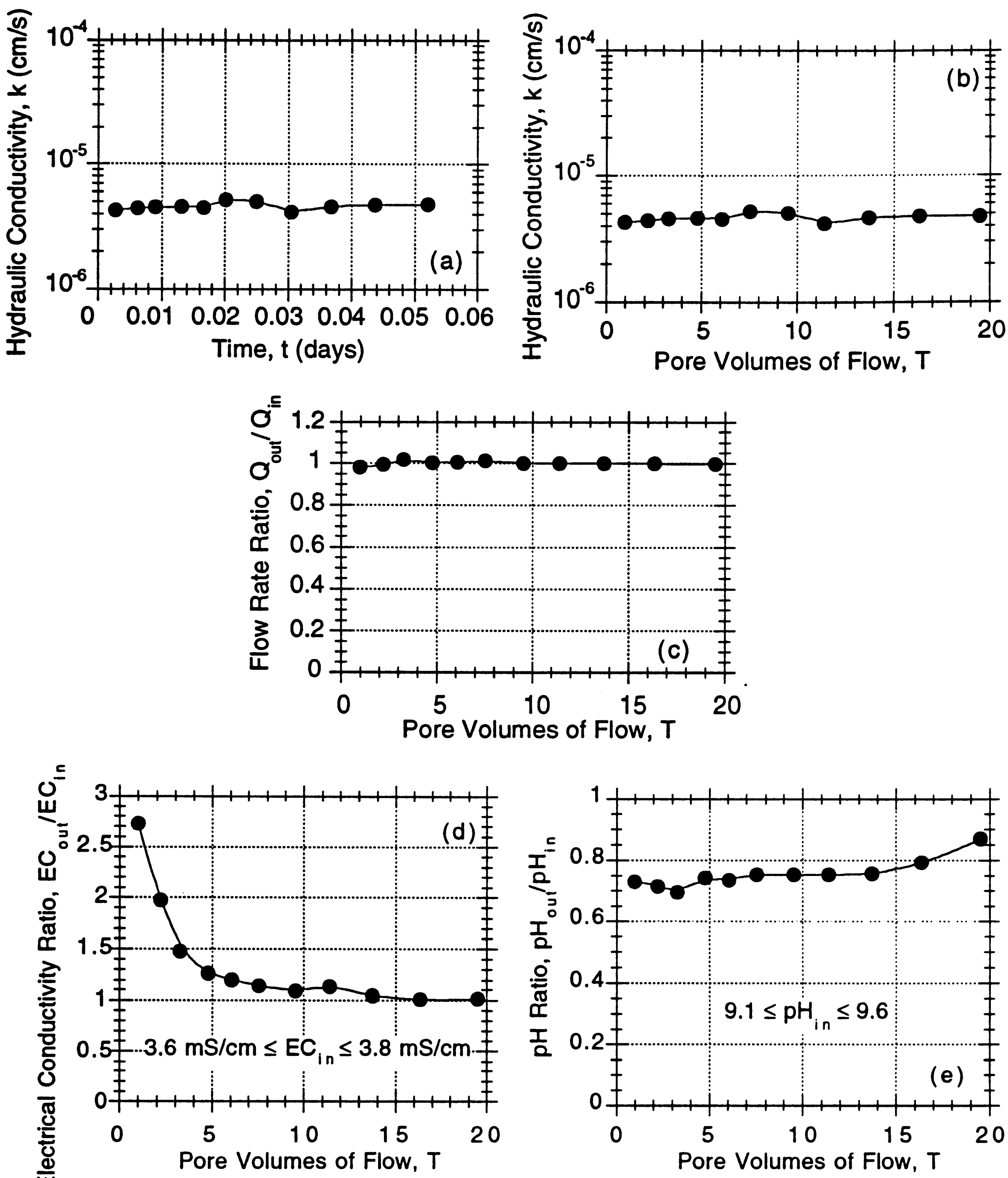

Figure C.11 - Results for Test No. 11: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

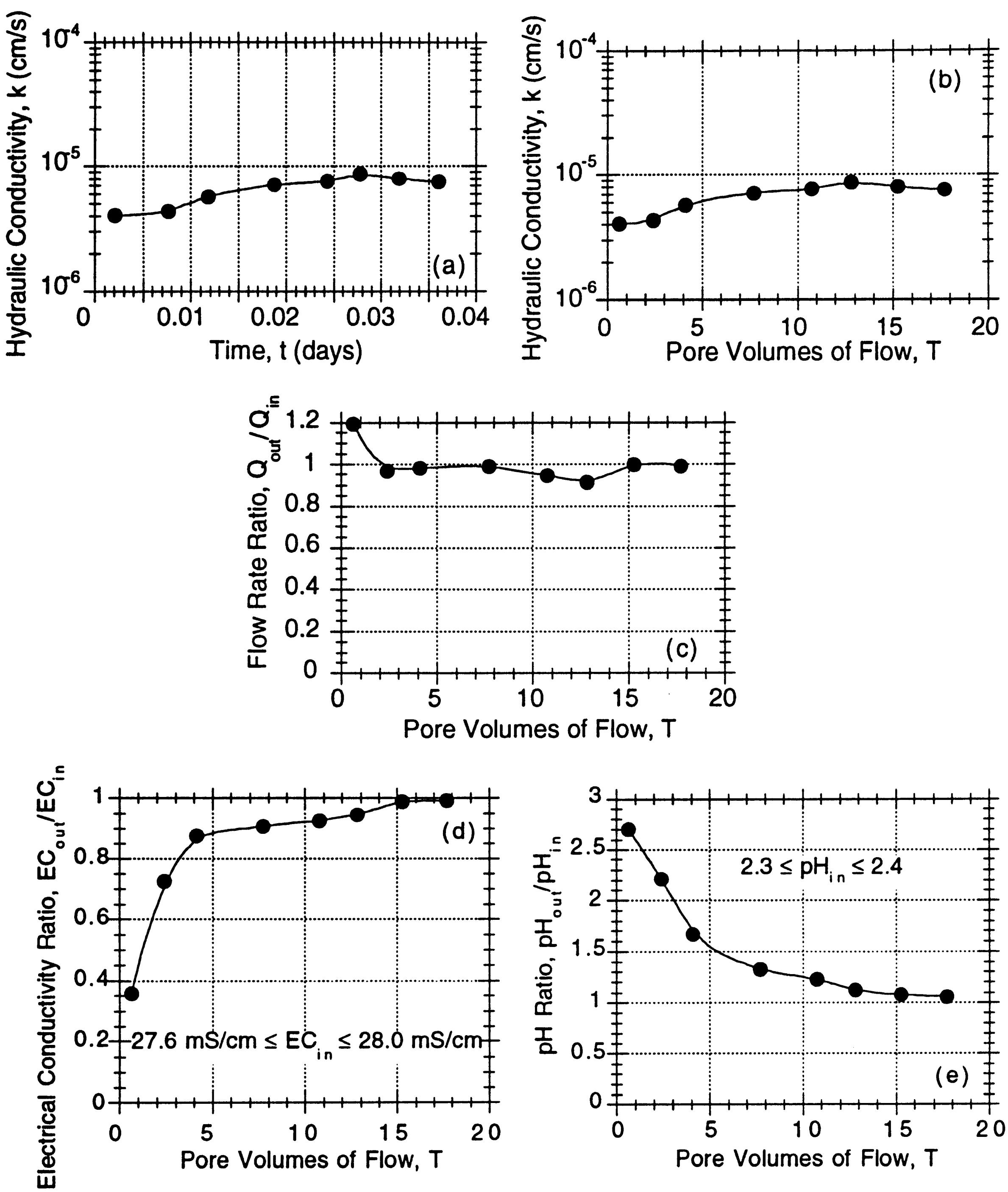

Figure C.12 - Results for Test No. 12: (a) hydraulic conductivity versus time; (b) hydraulic conductivity versus pore volumes; (c) ratio of outflow-to-inflow flow rate versus pore volumes; (d) ratio of outflow-to-inflow electrical conductivity versus pore volumes; and (e) ratio of outflow-to-inflow pH versus pore volumes.

Appendix D - Hydraulic Conductivity Test Data

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	12/17/97
Soil Description	Bentomat
	CRAN #1

	Thickness Measurement for ave thickness (mm)	Diameter Measurement(INI) for average diameter (mm)	Diameter Measurement (FIN) for average diameter (mm)	Initial scoped/piston height (mm)	Sample Weight (grams)	Moisture Content (final)(%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7.24	102.96	105.58	6.14	100.63	111.90	19.79	61.29	41.50
	7.26	103.12	105						
	7.06	103.08	105.84						
	7.26	102.78	104.22						
Averages	7.21	104.07							

*heights from top of table

Height to bottom of sample (mm)	109
Height to top of headwater accumulator (mm	705
Height to top of tailwater accumulator (mm)	703
Height to top of cell water accumulator (mm)	703
Thickness of Specimen (mm)	7.21

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	5.3	5.3
Area of Outflow(cm^2)=	1	5.2
a*(cm^2)=	0.841269841	2.624761905

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Head Difference (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	12/17/97	12:05	7.205	8.05	1	9.35	1	10.75	5	22.21					
											13500	3.85			
Backpressure	12/17/97	15:50	7.565	8	6	9.2	6	10.9	10	21.56					
											17400	3.84			
Backpressure	12/17/97	20:40	7.925	8.4	11	9.6	11	11.6	15	21.92					
											13800	3.83			
Backpressure	12/18/97	0:30	8.105	8.6	16	9.9	16	12.1	20	23.10					
											14400	3.83			
Backpressure	12/18/97	4:30	8.125	8.65	26	9.9	26	12.6	30	22.63					
											13500	3.82			
Backpressure	12/18/97	8:15	8.105	8.9	36	9.9	36	13.6	40	20.10					
											1479600	3.81			
Backpressure	1/5/98	11:15	8.065	9.3	41	10	41	15.8	45	17.06					
											32760	3.77			
Backpressure	1/5/98	20:21	8.165	9.5	46	10.1	46	15.15	50	16.17					
											58500	3.78			
Backpressure	1/6/98	12:36	8.165	9.45	46	10	46	16.5	50	15.67					
								reset cw			171600	3.76			
Permeation	1/8/98	12:16	8.165	3.9	48	24	44	4.9	50	3023.84					
											13800	3.93	5.1127E-08	5.0892E-08	344.73
Permeation	1/8/98	16:06	8.165	8	48	2.8	44	4.95	50	2770.84					
											52740	3.93			344.73
Permeation	1/9/98	6:45	8.165	11.8	48	24.1	44	4.8	50	2945.84					
											28440	3.93	2.687E-08	2.6876E-08	344.73
Permeation	1/9/98	14:39	8.165	16	48	1.7	44	4.7	50	2679.84					
											9960	3.93			344.73
Permeation	1/9/98	17:25	8.165	0.5	48	23.9	44	4.8	50	3056.84					
											52090	3.93	1.1607E-08	1.1583E-08	338.51
Permeation	1/10/98	7:53	8.465	4	48	5.7	44	4.7	50	2840.14					
											188880	3.93			332.51
Permeation	1/12/98	12:21	8.465	0.25	48	25	44	4.6	50	3070.64					
						switch to both					259140	3.93	4.1751E-09	4.2395E-09	338.51
Permeation	1/15/98	12:20	8.165	6.4	48	18.5	44	4.7	50	2943.84					
											360	3.93			344.73
Permeation	1/15/98	12:26	8.165	10.2	48	25	44	4.7	50	2970.84					
											427980	3.93	4.1768E-09	4.1823E-09	348.57
Permeation	1/20/98	11:19	7.985	20.35	48	14.6	44	5.1	50	2765.16					
											240	3.93			352.50
Permeation	1/20/98	11:23	7.985	0.65	48	24	44	5.1	50	3056.16					
											258360	3.93	4.5079E-09	4.5466E-09	350.74
Permeation	1/23/98	11:09	8.065	7.55	48	16.85	44	5.2	50	2915.74					
											180	3.92			349.00
Permeation	1/23/98	11:12	8.065	11	48	24	44	5.2	50	2952.74					
											451980	3.92	4.8722E-09	4.672E-09	342.63
Permeation	1/28/98	16:45	8.365	23.7	48	12.1	44	5.8	50	2707.04					
											660	3.92			336.48
Permeation	1/28/98	16:56	8.365	3.1	48	24	44	5.8	50	3032.04					
											412380	3.92	7.1991E-09	7.1402E-09	340.55
Permeation	2/3/98	11:29	8.165	19.7	48	7.3	44	5.4	50	2698.84					
											660	3.92			344.73
Permeation	2/3/98	11:40	8.165	1	48	24	44	5.4	50	3052.84					
											610140	3.92	6.2883E-09	6.2708E-09	349.00
Permeation	2/10/98	13:09	7.965	22.6	48	2	44	7	50	2616.64					
											420	3.90			353.38
Permeation	2/10/98	13:16	7.965	2.9	48	24	44	7	50	3033.64					
											508500	3.90	7.3467E-09	7.3471E-09	354.49
Permeation	2/16/98	10:31	7.915	24.1	48	2.3	44	8.1	50	2604.59					

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date 12/17/97

Soil Description Bentomat CRAN #2

Thickness Measurement for average thickness (mm)	Diameter Measurement(INI) for average diameter (mm)	Diameter Measurement (FIN) for average diameter (mm)	Initial scoped/piston height (mm)	Sample Weight (grams)	Moisture Content Final (%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
6.24	99.62	102.52	7.14	87.80	118.50	16.74	52.69	35.94
6.96	99.68	102.02						
6.8	100.26	102.4						
6.26	99.6	102.58						
Averages 6.57	101.09							

*heights from top of table

Height to bottom of sample (mm)	110
Height to top of headwater accumulator (mm)	700
Height to top of tailwater accumulator (mm)	705
Height to top of cell water accumulator (mm)	702
Thickness of Specimen (mm)	6.57

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	4.97	4.97
Area of Outflow(cm^2)=	1	4.65
a*(cm^2)=	0.832495812	2.402338877

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Head Difference (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	12/17/97	12:20	6.565	2.6	1	11.5	1	10.1	5	90.57					
											12600	3.86			
Backpressure	12/17/97	15:50	6.825	2.8	6	11	6	11.2	10	83.82					
											18000	3.84			
Backpressure	12/17/97	20:50	7.285	3.8	11	10.6	11	12.5	15	70.28					
											14100	3.82			
Backpressure	12/18/97	0:45	7.385	5	16	9.6	16	14.2	20	48.39					
											14100	3.80			
Backpressure	12/18/97	4:40	7.545	5.8	26	9	26	15.2	30	34.54					
											13800	3.78			
Backpressure	12/18/97	8:30	7.465	6.5	36	8.5	36	17	40	22.47					
											1478880	3.76			
Backpressure	1/5/98	11:18	7.375	7.4	41	7.9	41	22	45	7.38					
								reset to 10			-10440	3.69			
Backpressure	1/5/98	8:24	7.325	7.4	46	7.8	46	10.6	50	6.32					
											101640	3.85			
Backpressure	1/6/98	12:38	7.425	7.4	46	7.8	46	11.6	50	6.43					
						reset tw					171540	3.83			
Permeation	1/8/98	12:17	7.425	3.5	48	24	44	10.9	50	3020.10					
											60	3.84	2.606E-06	2.562E-06	380.98
Permeation	1/8/98	12:18	7.325	4.6	48	19	44	10.8	50	2959.00					
								reset to 11.6			4920	3.85			383.50
Permeation	1/8/98	13:40	7.325	7.6	48	24	44	11.6	50	2979.00					
											285	3.83	2.799E-06	2.781E-06	382.22
Permeation	1/8/98	13:45	7.375	12.7	48	-0.5	44	11.5	50	2683.05					
											15000	3.84			380.52
Permeation	1/8/98	17:55	7.375	15.5	48	21.55	44	11.5	50	2875.55					
											170	3.84	4.256E-06	4.243E-06	380.78
Permeation	1/8/98	17:58	7.375	19.9	48	0	44	11.5	50	2616.05					
											2820	3.84			380.43
Permeation	1/8/98	18:45	7.375	0.4	48	23.8	44	11.6	50	3049.05					
											213	3.83	3.518E-06	3.532E-06	381.02
Permeation	1/8/98	18:48	7.375	5.05	48	0	44	11.55	50	2764.55					
											8220	3.84			380.63
Permeation	1/8/98	21:05	7.375	8.5	48	23.9	44	11.5	50	2969.05					
											142	3.84	5.497E-06	5.475E-06	380.91
Permeation	1/8/98	21:07	7.375	13.4	48	0	44	11.5	50	2681.05					
											3180	3.84			380.52
Permeation	1/8/98	22:00	7.375	16.65	48	23.95	44	11.5	50	2888.05					
											132	3.84	6.13E-06	6.098E-06	379.51
Permeation	1/8/98	22:02	7.425	21.6	48	0	44	11.5	50	2599.10					
											6180	3.84			377.85
Permeation	1/8/98	23:45	7.425	0.6	48	23.9	44	11.5	50	3048.10					
											113	3.84	6.74E-06	6.737E-06	378.45
Permeation	1/8/98	23:47	7.425	5.4	48	0	44	11.4	50	2761.10					
											63480	3.84			378.07
Permeation	1/9/98	17:25	7.425	8.5	48	24.1	44	11.4	50	2971.10					
											110	3.84	7.218E-06	7.174E-06	378.35
Permeation	1/9/98	17:27	7.425	13.5	48	0	44	11.4	50	2680.10					
											4560	3.84			377.96
Permeation	1/9/98	18:43	7.425	16.4	48	24	44	11.4	50	2891.10					
											110	3.84	7.452E-06	7.377E-06	376.97
Permeation	1/9/98	18:45	7.475	21.5	48	0	44	11.45	50	2600.15					
											77280	3.84			375.32
Permeation	1/10/98	16:13	7.475	6.4	48	24	44	11.5	50	2991.15					
											98	3.84	8.01E-06	8.012E-06	375.84
Permeation	1/10/98	16:14	7.475	11.2	48	0	44	11.4	50	2703.15					
											91860	3.84			374.21
Permeation	1/11/98	17:45	7.525	14.3	48	23.7	44	11.6	50	2909.20					
											115	3.83	7.468E-06	8.35E-06	374.48
Permeation	1/11/98	17:47	7.475	20	48	-1	44	11.65	50	2605.15					
				use for calc							60300	3.83			375.33
Permeation	1/12/98	10:32	7.475	0.7	48	23.8	44	11.8	50	3046.15					
											92	3.83	8.31E-06	8.3E-06	375.92
Permeation	1/12/98	10:33	7.475	5.5	48	0	44	11.8	50	2760.15					
											6480	3.83			375.54
Permeation	1/12/98	12:21	7.475	0.25	48	24.8	44	11.8	50	3060.65					
						switch from pipet to both					240	3.83	8.727E-06	8.517E-06	375.94
Permeation	1/12/98	12:25	7.475	13.8	48	11	44	11.8	50	2787.15					
											9360	3.83			375.57
Permeation	1/12/98	15:01	7.475	0.6	48	25	44	11.1	50	3059.15					
											240	3.84	9.37E-06	9.386E-06	375.94
Permeation	1/12/98	15:05	7.475	14.7	48	9.85	44	11.15	50	2766.65					

Flexible Wall Hydraulic Conductivity

Foth and Van Dyke: Crandon Mine

Start Date 12/12/97

Soil Description Bentomat CRAN #3

Panel Position #3

	Thickness Measurement for average thickness (mm)	Diameter Measurement (Ini for average diameter (mm)	Diameter Meas. Final for average diameter (mm)	Distance from top of sample to ref point (mm)	Fin. Moist. Content of Specimen (%)	Sample Weight (grams)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	6.38	98.84	104.28	6.62	92.87	81.39	17.58	53.00	35.42
	6.58	101.02	104.32						
	6.32	101.78	103.54						
	6.58	99.32	104.27						
Averages	6.47	102.17							

Diameter of Accumulators		
Headwater (cm)	Tailwater (cm)	Cellwater (cm)
3.79	3.8	1

Height to bottom of sample (mm)	106.9
Height to bottom of headwater marriote (mm)	289
Height to top of tailwater marriote (mm)	508
Height to top of cell water pipet (mm)	701

Area of Inflow(cm^2)= 11.28153776
Area of Outflow(cm^2)= 11.34114948
a*(cm^2)= 5.65563254

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (mm)	Headwater Pressure (psi)	Tailwater Reading (mm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity (cm/s)	End of Incr.TW Pore Vol. of Flow (PVF)	End of Incr.HW Pore Vol. of Flow (PVF)	Hydraulic Gradient
Backpressure	12/17/97	12:05	6.465	9.6	1	10.5	1	11	5						
Backpressure	12/17/97	15:50		9.6	6	10.8	6	11.8	10						
Backpressure	12/17/97	20:40	5.285	10.25	11	11	11	13.4	15						
Backpressure	12/18/97	0:30	5.405	10.8	16	11.4	16	13.5	20						
Backpressure	12/18/97	4:25	5.385	11.1	26	11.65	26	14.2	30						
Backpressure	12/18/97	8:15	5.405	11.7	36	12	36	14.6	40						
Backpressure	1/5/98	11:15	5.545	12.6	41	12.6	41	17.7	45						
Backpressure	1/5/98	20:15	5.645	12.6	46	12.7	46	18.25	50						
Backpressure	1/7/98	12:37	5.645	12.6	46	12.7	46	18.9	50						
Permeation	1/13/98	16:35	5.795	283	48	0	44	16.6	50						
										69000	4.43	2.177E-08			463.16
Permeation	1/14/98	11:45	5.405	230	48	50.3	44	17.3	50				1.610	1.688	
										2100	4.43	0.000E+00			479.87
Permeation	1/14/98	12:20	5.405	212	48	0	44	17.3	50				1.610		
										20280	4.43	1.103E-07			485.25
Permeation	1/14/98	17:58	5.285	149	48	78.5	44	18.2	50				4.124	3.695	
										2760	4.43	0.000E+00			490.76
Permeation	1/14/98	18:44	5.285	119.9	48	0	44	18.2	50				4.124		
										9420	4.43	3.219E-07			494.03
Permeation	1/14/98	21:21	5.215	17.9	48	108.3	44	18.85	50				7.591	6.943	
										51840	4.43	0.000E+00			497.35
Permeation	1/15/98	11:45	5.215	297	48	0	44	18.85	50				7.591		
										5580	4.43	5.439E-07			495.92
Permeation	1/15/98	13:18	5.245	192.5	48	108.8	44	19.3	50				11.075	10.271	
										1200	4.43	0.000E+00			494.51
Permeation	1/15/98	13:38	5.245	174.5	48	0	44	19.3	50				11.075		
										4020	4.43	7.389E-07			498.31
Permeation	1/15/98	14:45	5.165	74.4	48	107	44	19.5	50				14.501	13.459	
										4920	4.43	0.000E+00			502.16
Permeation	1/15/98	16:07	5.165	216	48	0	44	19.5	50				14.501		
										2700	4.43	8.141E-07			506.08
Permeation	1/15/98	16:52	5.085	139	48	80.42	44	20	50				17.076	15.912	
										1320	4.43	0.000E+00			510.06
Permeation	1/15/98	17:14	5.085	294	48	0	44	20	50				17.076		
										5580	4.43	1.401E-06			525.57
Permeation	1/15/98	18:47	4.785	0	48	297	44	22.3	50				26.585	25.275	
										#REF!	4.43	#REF!			

Flexible Wall Hydraulic Conductivity

Foth and Van Dyke: Crandon Mine

Start Date 1/19/98

Soil Description Bentomat CRAN #4

Panel Position #4

	Thickness Measurement for average thickness (mm)	Diameter Measurement (Ini) for average diameter (mm)	Diameter Meas. Final for average diameter (mm)	Distance from top of sample to ref point (mm)	Fin. Moist Content of Specimen (%)	Sample Weight (grams)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	6.54	97.4	95.44	32.50	86.20	71.06	15.90	48.69	32.79
	6.56	96.74	95.36						
	6.62	99.72	96.1						
	6.74	97.12	96.58						
Averages	6.62	96.81							

Diameter of Accumulators		
Headwater (cm)	Tailwater (cm)	Cellwater (cm)
3.7	3.81	1

Height to bottom of sample (mm)	105
Height to bottom of headwater marriote (mm)	346
Height to top of tailwater marriote (mm)	479
Height to top of cell water pipet (mm)	702

Area of Inflow(cm^2)= 10.75210086
Area of Outflow(cm^2)= 11.40091828
a*(cm^2)= 5.533504144

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (mm)	Headwater Pressure (psi)	Tailwater Reading (mm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity (cm/s)	End of Incr. TW Pore Vol. of Flow (PVF)	End of Incr. HW Pore Vol. of Flow (PVF)	Hydraulic Gradient
Backpressure	1/19/98	20:40	6.615	238	1	238	1	13.6	5						
										45840	4.41				
Backpressure	1/20/98	9:24	6.615	236	6	236	6	18.8	10						
										17160	4.41				
Backpressure	1/20/98	14:10	6.515	236	11	236	11	21.5	15						
								move to 10		10800	4.41				
Backpressure	1/20/98	17:10	6.315	230	16	230	16	11.2	20						
										53400	4.41				
Backpressure	1/21/98	8:00	6.015	226	21	226	21	12.2	25						
										11280	4.41				
Backpressure	1/21/98	11:08	6.415	224	26	224	26	13	30						
										19080	4.41				
Backpressure	1/21/98	16:26	6.315	222	31	222	31	13.8	35						
										59220	4.41				
Backpressure	1/22/98	8:53	6.415	220	36	220	36	14.6	40						
										16380	4.41				
Backpressure	1/22/98	13:26	6.415	219	41	219	41	15.5	45						
										9540	4.41				
Backpressure	1/22/98	16:05	6.415	219	46	219	46	16.3	50						
								move to 10		1483800	4.41				
Backpressure	2/9/98	20:15	6.415	181	46	181	46	14.1	50						
										3960	4.41	0.000E+00			
Permeation	2/9/98	21:21	6.415	269	48	0	44	14.2	50				0.000	0.000	
										180	4.41	5.150E-06			417.72
Permeation	2/9/98	21:24	6.415	244	48	25	44	14	50				0.869	0.820	
										1860	4.41	0.000E+00			417.72
Permeation	2/9/98	21:55	6.415	225	48	0	44	14	50				0.869		
										960	4.41	3.963E-06			417.72
Permeation	2/9/98	22:11	6.415	118.5	48	102.6	44	13.8	50				4.437	4.312	
										1560	4.41	0.000E+00			417.72
Permeation	2/9/98	22:37	6.415	286	48	0	44	13.8	50				4.437		
										600	4.41	3.838E-06			417.72
Permeation	2/9/98	22:47	6.415	221	48	62.1	44	13.9	50				6.596	6.444	
										3960	4.41	0.000E+00			417.72
Permeation	2/9/98	23:53	6.415	198	48	0	44	13.9	50				6.596		
										480	4.41	4.195E-06			417.72
Permeation	2/10/98	0:01	6.415	142	48	54.3	44	14.15	50				8.484	8.280	
										2460	4.41	0.000E+00			417.72
Permeation	2/10/98	0:42	6.415	117	48	0	44	14.15	50				8.484		
										600	4.41	3.937E-06			417.72
Permeation	2/10/98	0:52	6.415	48.6	48	63.7	44	14.1	50				10.699	10.523	
										2460	4.41	0.000E+00			417.72
Permeation	2/10/98	1:33	6.415	295	48	0	44	14.1	50				10.699		
										660	4.41	3.775E-06			417.72
Permeation	2/10/98	1:44	6.415	223	48	67.2	44	14.1	50				13.036	12.884	
										1740	4.41	0.000E+00			417.72
Permeation	2/10/98	2:13	6.415	188	48	0	44	14.1	50				13.036		
										1140	4.41	3.871E-06			417.72
Permeation	2/10/98	2:32	6.415	64	48	119	44	14.2	50				17.173	16.950	

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date 12/17/97

Soil Description Bentomat CRC
CRAN #5

	Thickness Measurement for average thickness (mm)	Diameter Measurement(INI) for average diameter (mm)	Diameter Measurement (FIN) for average diameter (mm)	Initial scoped/piston height (mm)	Sample Weight (grams)	Moisture Content Final (%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7.32	109.28	108.54	7.34	102.29	122.10	19.19	64.50	45.31
	6.54	106.68	108.2						
	7.1	109.42	109.06						
	6.8	110.26	108.84						
Averages	6.94	108.79							

*heights from top of table

Height to bottom of sample (mm)	108.2
Height to top of headwater accumulator (mm	701
Height to top of tailwater accumulator (mm)	700
Height to top of cell water accumulator (mm)	700
Thickness of Specimen (mm)	6.94

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	4.95	4.95
Area of Outflow(cm^2)=	1	5.18
a*(cm^2)=	0.831932773	2.531194472

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Head Difference (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	12/17/97	12:20	6.940	3.3	1	7.7	1	8.8	5	51.94					
											30000	3.87			
Backpressure	12/17/97	20:40	6.820	3.15	6	7.4	6	10.5	10	50.32					
											14400	3.85			
Backpressure	12/18/97	0:40	6.700	3.5	11	7.4	11	11.7	15	46.70					
											14100	3.83			
Backpressure	12/18/97	4:35	6.700	3.9	16	7.4	16	12.6	20	42.70					
											13800	3.82			
Backpressure	12/18/97	8:25	6.660	4.5	26	7	26	13.4	30	32.66					
											1479120	3.81			
Backpressure	1/5/98	11:17	6.350	6.2	36	5.3	36	18	40	-1.65					
											32820	3.74			
Backpressure	1/5/98	20:24	6.200	6.1	46	5.3	46	19.4	50	-0.80					
											58380	3.72			
Backpressure	1/6/98	12:37	6.450	6.1	46	5.3	46	21.1	50	-0.55					
											171600	3.70			
Permeation	1/8/98	12:17	6.450	3.8	48	24	44	21.4	50	3022.13					
						reset tw					60	3.69	1.009E-05	1.003E-05	438.24
Permeation	1/8/98	12:18	6.400	9	48	-1	44	21.3	50	2720.08					
											4920	3.70			439.48
Permeation	1/8/98	13:40	6.400	11.8	48	22.05	44	21.3	50	2922.58					
											50	3.70	1.071E-05	1.072E-05	438.09
Permeation	1/8/98	13:41	6.450	16.15	48	0.4	44	21.2	50	2662.63					
											15240	3.70			435.99
Permeation	1/8/98	17:55	6.450	18.7	48	24.1	44	21.25	50	2874.13					
											58	3.70	1.055E-05	1.056E-05	436.31
Permeation	1/8/98	17:56	6.450	23.5	48	0	44	21.1	50	2585.13					
											2940	3.70			435.87
Permeation	1/8/98	18:45	6.450	0.3	48	23.95	44	21.3	50	3056.63					
											54	3.70	1.056E-05	1.057E-05	436.60
Permeation	1/8/98	18:46	6.450	5.1	48	0	44	21.1	50	2769.13					
											8340	3.70			436.15
Permeation	1/8/98	21:05	6.450	8.1	48	24	44	21.1	50	2979.13					
											59	3.70	9.803E-06	9.95E-06	436.48
Permeation	1/8/98	21:06	6.450	12.5	48	0	44	21.05	50	2695.13					
											3240	3.70			436.04
Permeation	1/8/98	22:00	6.450	16.1	48	24	44	21.1	50	2899.13					
											60	3.70	9.993E-06	9.993E-06	438.05
Permeation	1/8/98	22:01	6.400	20.9	48	0.1	44	21	50	2612.08					
											6240	3.70			439.31
Permeation	1/8/98	23:45	6.400	0.5	48	24	44	20.95	50	3055.08					
											57	3.70	9.951E-06	9.959E-06	440.00
Permeation	1/8/98	23:46	6.400	5.3	48	0	44	20.8	50	2767.08					
											63540	3.70			439.55
Permeation	1/9/98	17:25	6.400	8.5	48	23.9	44	20.9	50	2974.08					
											58	3.70	1E-05	1.002E-05	439.88
Permeation	1/9/98	17:26	6.400	13.25	48	0	44	20.8	50	2687.58					
											4620	3.70			439.43
Permeation	1/9/98	18:43	6.400	15.9	48	24.1	44	20.8	50	2902.08					
											60	3.70	9.979E-06	1.003E-05	439.77
Permeation	1/9/98	18:44	6.400	20.6	48	0	44	20.8	50	2614.08					
											77160	3.70			439.32
Permeation	1/10/98	16:10	6.400	0.7	48	23.8	44	20.8	50	3051.08					
											54	3.70	1.048E-05	1.044E-05	440.00
Permeation	1/10/98	16:11	6.400	5.6	48	0	44	20.75	50	2764.08					
											92040	3.70			439.55
Permeation	1/11/98	17:45	6.400	8.5	48	23.85	44	20.8	50	2973.58					
											55	3.70	1.055E-05	1.057E-05	439.02
Permeation	1/11/98	17:46	6.425	13.25	48	0	44	20.85	50	2687.61					
											60360	3.70			440.29
Permeation	1/12/98	10:32	6.350	16.1	48	24	44	21	50	2899.03					
											57	3.70	1.082E-05	1.085E-05	439.76
Permeation	1/12/98	10:33	6.450	21	48	-0.7	44	21.1	50	2603.13					
											6480	3.70			435.89
Permeation	1/12/98	12:21	6.450	0.9	48	24.8	44	21.1	50	3059.13					
						switch from pipet to both					240	3.70	1.059E-05	1.063E-05	440.01
Permeation	1/12/98	12:25	6.350	22	48	4.4	44	21.2	50	2644.03					
											9360	3.70			442.82
Permeation	1/12/98	15:01	6.350	0.9	48	25	44	20.8	50	3061.03					
											240	3.70	9.304E-06	9.341E-06	441.74
Permeation	1/12/98	15:05	6.400	19.7	48	6.85	44	20.9	50	2691.58					

Flexible Wall Hydraulic Conductivity

Foth and Van Dyke: Crandon Mine

Start Date	12/17/97
Soil Description	Bentomat CRC
	CRAN #6
Panel Position	# 3

	Thickness Measurement for average thickness (mm)	Diameter Measurement (Ini for average diameter (mm)	Diameter Meas. Final for average diameter (mm)	Distance from top of sample to ref point (mm)	Fin. Moist. Content of Specimen (%)	Sample Weight (grams)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7.56	101.34	99.86	31.60	95.60	86.86	18.50	58.45	39.95
	7.22	100.74	97.84						
	7.72	96.96	100.2						
	7.42	99.76	101.28						
Averages	7.48	99.75							

Diameter of Accumulators		
Headwater (cm)	Tailwater (cm)	Cellwater (cm)
3.79	3.8	1

Area of Inflow(cm^2)= 11.28153776
Area of Outflow(cm^2)= 11.34114948
a*(cm^2)= 5.65563254

Height to bottom of sample (mm)	102.6
Height to bottom of headwater marriote (mm)	281.5
Height to top of tailwater marriote (mm)	505
Height to top of cell water pipet (mm)	701

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (mm)	Headwater Pressure (psi)	Tailwater Reading (mm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity (cm/s)	End of Incr. TW Pore Vol. of Flow (PVF)	End of Incr. HW Pore Vol. of Flow (PVF)	Hydraulic Gradient
Backpressure	12/17/97	0:20	7.680	150.5	1	150.5	1	10.25	5						
										49740	4.44				
Backpressure	12/17/97	14:09	8.380	150.5	6	150.5	6	15.4	10						
										14880	4.44				
Backpressure	12/17/97	18:17	8.380	167	11	167	11	18.5	15						
										15060	4.44				
Backpressure	12/17/97	22:28	6.880	163	16	163	16	19.7	20						
								move to 10.0		9480	4.43				
Backpressure	12/18/97	1:06	7.080	161.3	26	161.3	26	10.9	30						
										57360	4.44				
Backpressure	12/18/97	17:02	7.080	159.1	36	159.1	36	12.8	40						
								move to 10.0		1445100	4.44				
Backpressure	1/5/98	10:27	6.880	155.5	41	155.5	41	14.2	45						
										34500	4.44				
Backpressure	1/5/98	20:02	6.880	155.5	46	155.5	46	14.85	50						
										61140	4.44				
Backpressure	1/6/98	13:01	6.680	156	46	156	46	15.7	50						
										5760	4.44	0.000E+00			
Permeation	1/6/98	14:37	6.680	263	48	0	44	15.6	50				0.000	0.000	
										60	4.44	2.490E-05			393.49
Permeation	1/6/98	14:38	6.480	223	48	40.5	44	15.7	50				1.150	1.130	
										142	4.44	0.000E+00			393.49
Permeation	1/6/98	15:05	6.680	195	48	0	44	15.7	50				1.150		
										60	4.44	2.309E-05			387.60
Permeation	1/6/98	15:06	6.680	162	48	37	44	15.7	50				2.200	2.062	
										900	4.44	0.000E+00			387.60
Permeation	1/6/98	15:21	6.680	149	48	0	44	15.7	50				2.200		
										60	4.44	2.184E-05			387.60
Permeation	1/6/98	15:22	6.680	116	48	35	44	15.6	50				3.194	2.993	
										1020	4.44	0.000E+00			387.60
Permeation	1/6/98	15:39	6.680	100	48	0	44	15.6	50				3.194		
										60	4.44	2.153E-05			387.60
Permeation	1/6/98	15:40	6.680	68.5	48	34.5	44	15.7	50				4.173	3.883	
										210	4.44	0.000E+00			387.60
Permeation	1/6/98	15:58	6.680	56	48	0	44	15.7	50				4.173		
										60	4.44	2.153E-05			387.60
Permeation	1/6/98	15:59	6.680	25	48	34.5	44	15.7	50				5.153	4.758	
										270	4.44	0.000E+00			387.60
Permeation	1/6/98	16:24	6.680	196	48	0	44	15.7	50				5.153		
										120	4.44	2.449E-05			387.60
Permeation	1/6/98	16:26	6.680	121	48	78.5	44	15.5	50				7.381	6.876	
										1140	4.44	0.000E+00			387.60
Permeation	1/6/98	16:45	6.680	104	48	0	44	15.5	50				7.381		
										60	4.44	2.496E-05			387.60
Permeation	1/6/98	16:46	6.680	67.5	48	40	44	15.6	50				8.517	7.907	
										1200	4.44	0.000E+00			387.60
Permeation	1/6/98	17:06	6.680	57	48	0	44	15.6	50				8.517		
										60	4.44	2.465E-05			387.60
Permeation	1/6/98	17:07	6.680	21.5	48	39.5	44	15.6	50				9.638	8.910	

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date 1/20/98

Soil Description Bentomat
CRAN #7

	Thickness Measurement for average thickness (mm)	Diameter Measurement(INI) for average diameter (mm)	Diameter Measurement (FIN) for average diameter (mm)
	6.44	103.22	105.52
	7.06	105.06	108.72
	7.4	105	107.52
	6.38	103.28	106.04
Averages	6.82	105.55	

Sample Weight (grams)	Moisture Content (%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
108.04	130.00	19.57	59.67	40.10

*heights from top of table

Height to bottom of sample (mm)	108
Height to top of headwater accumulator (mm)	701
Height to top of tailwater accumulator (mm)	700
Height to top of cell water accumulator (mm)	700
Thickness of Specimen (mm)	6.82

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	5.25	5.25
Area of Outflow(cm^2)=	1	5.06
a*(cm^2)=	0.84	2.576624636

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	h1 (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	1/20/98	17:57	6.820	1.4	1	2.1	1	14.2	5	14.82					
											49680	3.80			
Backpressure	1/21/98	7:45	6.740	2.1	6	1.05	6	15.2	10	-2.76					
											11220	3.78			
Backpressure	1/21/98	10:52	6.540	3.5	11	2.8	11	15.65	15	0.54					
											19080	3.78			
Backpressure	1/21/98	16:10	6.200	3.7	16	3.6	16	15.7	20	6.20					
											61020	3.78			
Backpressure	1/22/98	9:07	6.460	4.2	21	4.3	21	14.7	25	8.46					
											19680	3.79			
Backpressure	1/22/98	14:35	6.520	4.5	26	4.6	26	15.7	30	8.52					
											73500	3.78			
Backpressure	1/23/98	11:00	6.620	5	31	5.5	31	14.9	35	12.62					
											19560	3.79			
Backpressure	1/23/98	16:26	6.680	5.3	41	4.75	41	15.7	45	2.18					
											26940	3.78			
Backpressure	1/23/98	23:55	6.680	5.4	46	6	46	17	50	13.68					
											41400	3.76			
Backpressure	1/24/98	11:25	6.690	5.6	46	6	46	14.4	50	11.69					
											1440	3.79			
Permeation	1/24/98	11:49	6.690	1.3	48	24.2	44	17.4	50	3049.37					
						pipet					6120	3.75	1.089E-07	1.05E-07	417.46
Permeation	1/24/98	13:31	6.790	6.95	48	0	44	16	50	2750.97					
											1380	3.77			414.39
Permeation	1/24/98	13:54	6.790	6.95	48	24.15	44	16	50	2992.47					
						turn to both					180360	3.77	2.792E-09	2.587E-09	401.09
Permeation	1/26/98	16:00	7.240	10.8	48	20.75	44	12.6	50	2920.42					
						turn to pipet					94320	3.82	1.77E-09	1.712E-09	389.98
Permeation	1/27/98	18:12	7.190	12.1	48	15.1	44	12.2	50	2850.87					
											80880	3.83	1.667E-09	1.625E-09	389.98
Permeation	1/28/98	16:40	7.240	13.1	48	10.6	44	11.9	50	2795.92					
											77580	3.83	1.635E-09	1.6E-09	387.96
Permeation	1/29/98	14:13	7.265	14	48	6.45	44	11.8	50	2745.44					
											92100	3.83	1.629E-09	1.607E-09	387.96
Permeation	1/30/98	15:48	7.240	15	48	1.6	44	11.5	50	2686.92					
											0	3.84			388.63
Permeation	1/30/98	15:48	7.240	15	48	24	44	11.5	50	2910.92					
											243360	3.84	1.772E-09	1.734E-09	385.96
Permeation	2/3/98	11:24	7.340	18.1	48	9.7	44	10.65	50	2737.02					
											0	3.85			383.34
Permeation	2/3/98	11:24	7.340	18.1	48	24	44	10.65	50	2880.02					
											611700	3.85	1.187E-09	1.169E-09	375.66
Permeation	2/10/98	13:19	7.640	22.9	48	1.1	44	9.2	50	2603.32					
											0	3.87			368.28
Permeation	2/10/98	13:19	7.640	1	48	24	44	9.2	50	3051.32					
											509700	3.87	1.425E-09	1.423E-09	365.89
Permeation	2/16/98	10:54	7.740	5.6	48	0	44	9.8	50	2765.42					
											0	3.86			363.52
Permeation	2/16/98	10:54	7.740	5.6	48	24	44	9.8	50	3005.42					
											537780	3.86		2.183E-09	358.32
Permeation	2/22/98	16:17	7.965	12.7	48	0	44	10.5	50	2694.64					
											166380	3.85			353.14
Permeation	2/24/98	14:30	7.970	16.9	48	24.3	44	10.9	50	2895.65					
											686040	3.84		6.086E-10	366.13
Permeation	3/2/98	13:04	7.400	19.4	48	0	44	24.3	50	2627.08					
								move to 10			20760	3.65			380.23
Permeation	3/2/98	18:50	7.400	1	48	24	44	10	50	3051.08					
											1802220	3.86	1.599E-09	1.605E-09	379.20
Permeation	3/23/98	15:27	7.440	19.4	48	4.7	44	12	50	2674.12					

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date 1/20/98

Soil Description Bentomat - CR
CRAN #8

	Thickness Measurement for average thickness (mm)	Diameter Measurement(INI for average diameter (mm)	Diameter Measurement (FIN for average diameter (mm)	Sample Weight (grams)	Moisture Content (%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7	105.4	102.46	95.49	124.40	17.73	56.12	38.39
	6.64	106	105.28					
	6.16	102.8	107.12					
	6.16	104.62	105.72					
Averages	6.49	104.93						

*heights from top of table

Height to bottom of sample (mm)	108
Height to top of headwater accumulator (mm	700
Height to top of tailwater accumulator (mm)	701
Height to top of cell water accumulator (mm)	703
Thickness of Specimen (mm)	6.49

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	4.81	4.81
Area of Outflow(cm^2)=	1	4.89
a*(cm^2)=	0.82788296	2.424835052

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	h1 (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	1/20/98	17:56	6.490	3.4	1	3	1	9.5	5	1.49					
											49800	3.87			
Backpressure	1/21/98	7:46	6.490	3.4	6	2.3	6	16	10	-5.51					
											11040	3.78			
Backpressure	1/21/98	10:50	6.030	5.7	11	4	11	0	15	-11.97					
								move to 10			19500	4.00			
Backpressure	1/21/98	16:15	5.710	6.6	16	5.1	16	5.1	20	-10.29					
											60900	3.93			
Backpressure	1/22/98	9:10	6.150	7.2	21	6.1	21	1.6	25	-5.85					
								move to 10			19200	3.98			
Backpressure	1/22/98	14:30	6.210	7.3	26	6.5	26	9.8	30	-2.79					
											73500	3.86			
Backpressure	1/23/98	10:55	6.250	7.7	31	7.7	31	9.5	35	5.25					
											19500	3.87			
Backpressure	1/23/98	16:20	6.250	7.8	41	7.9	41	9.7	45	6.25					
											27300	3.87			
Backpressure	1/23/98	23:55	6.250	7.9	46	8.1	46	10.6	50	7.25					
											41520	3.85			
Backpressure	1/24/98	11:27	6.430	7.8	46	8.2	46	11.3	50	9.43					
											87360	3.84			
Permeation	1/25/98	11:43	6.630	1.6	48	24	44	11.3	50	3042.31					
						pipet					101700	3.84	5.1069E-09	5.0301E-09	424.08
Permeation	1/26/98	15:58	6.630	6	48	4.5	44	10.4	50	2803.31					
											0	3.86			424.08
Permeation	1/26/98	15:58	6.630	6	48	24	44	10.4	50	2998.31					
											94260	3.86	1.7752E-09	1.7867E-09	424.08
Permeation	1/27/98	18:09	6.630	7.3	48	17.5	44	10.1	50	2920.31					
											81060	3.86	1.7902E-09	1.7364E-09	424.08
Permeation	1/28/98	16:40	6.630	8.6	48	12.2	44	9.9	50	2854.31					
											77520	3.86	1.6179E-09	1.6038E-09	425.69
Permeation	1/29/98	14:12	6.580	9.6	48	7.6	44	9.9	50	2798.26					
											92100	3.86	1.5418E-09	1.5343E-09	424.08
Permeation	1/30/98	15:47	6.680	10.7	48	2.5	44	9.7	50	2736.36					
											0	3.87			420.91
Permeation	1/30/98	15:47	6.680	10.7	48	24	44	9.7	50	2951.36					
											243420	3.87	1.7613E-09	1.7496E-09	422.49
Permeation	2/3/98	11:24	6.630	14.1	48	8.2	44	9.2	50	2759.31					
											0	3.87			424.08
Permeation	2/3/98	11:24	6.630	14.1	48	24	44	9.2	50	2917.31					
											611700	3.87	1.1262E-09	1.1165E-09	417.78
Permeation	2/10/98	13:19	6.830	19.4	48	-0.3	44	9.9	50	2621.51					
											0	3.86			411.67
Permeation	2/10/98	13:19	6.830	1	48	24	44	9.9	50	3048.51					
											509640	3.86	1.3386E-09	1.328E-09	414.70
Permeation	2/16/98	10:53	6.730	6.4	48	-1	44	10.4	50	2744.41					
											0	3.86			417.78
Permeation	2/16/98	10:53	6.730	6.4	48	24	44	10.4	50	2994.41					
											537840	3.86		9.5089E-10	417.78
Permeation	2/22/98	16:17	6.730	10.3	48	0	44	9.4	50	2715.41					
											166380	3.87			417.78
Permeation	2/24/98	14:30	6.730	14.2	48	24.2	44	9.7	50	2918.41					
											685980	3.87		1.7014E-09	413.48
Permeation	3/2/98	13:03	6.870	22.7	48	0	44	10.8	50	2591.55					
											20880	3.85			409.27
Permeation	3/2/98	18:51	6.870	1	48	24	44	10.8	50	3048.55					
											1809360	3.85	1.6125E-09	1.6158E-09	404.56
Permeation	3/23/98	17:27	7.030	22.3	48	2.9	44	12.1	50	2624.71					

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date 3/26/98

Soil Description Bentomat CR
CRAN #9

	Thickness Measurement for average thickness (mm)	Diameter Measurement(INI) for average diameter (mm)	Diameter Measurement (FIN) for average diameter (mm)	Sample Weight (grams)	Moisture Content (%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7.46	97.06	97.96	82.94	116.00	16.00	55.99	39.99
	7.22	99.06	99.9					
	7.34	99.22	97.96					
	7.42	98.14	98.02					
Averages	7.36	98.42						

*heights from top of table

Height to bottom of sample (mm)	109.5
Height to top of headwater accumulator (mm)	700
Height to top of tailwater accumulator (mm)	700
Height to top of cell water accumulator (mm)	700
Thickness of Specimen (mm)	7.36

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	5	5
Area of Outflow(cm^2)=	1	5
a*(cm^2)=	0.833333333	2.5

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	h1 (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	3/26/98	11:35	7.360	4.8	1	2.9	1	0.1	5	-11.64					
				flush lines							16140	4.00			
Backpressure	3/26/98	16:04	7.300	11.4	6	8.5	6	7.1	10	-21.70					
											13860	3.90			
Backpressure	3/26/98	19:55	6.960	11.9	11	9.1	11	24.2	15	-21.04					
								move to 10			40800	3.88			
Backpressure	3/27/98	7:15	7.180	12.3	16	9.5	16	9.9	20	-20.82					
											11880	3.86			
Backpressure	3/27/98	10:33	7.280	12.2	26	9.9	26	10.4	30	-15.72					
											10440	3.85			
Backpressure	3/27/98	13:27	7.280	12.4	36	10.4	36	11.2	40	-12.72					
											64680	3.84			
Backpressure	3/28/98	7:25	7.280	12.2	46	11	46	12.4	50	-4.72					
											9660	3.82			
Backpressure	3/28/98	10:06	7.280	12.1	46	11.1	46	13.5	50	-2.72					
											12420	3.81			
Permeation	3/28/98	13:33	7.260	3.3	48	24.5	44	13.5	50	3031.94					
											1800	3.81	6.03751E-07	5.902E-07	
Permeation	3/28/98	14:03	7.260	10.2	48	17.9	44	13.2	50	2896.94					
											1320	3.81			387.53
Permeation	3/28/98	14:25	7.260	1	48	24.5	44	13.2	50	3054.94					
											4500	3.81	6.1989E-07	6.101E-07	385.09
Permeation	3/28/98	15:40	7.360	18	48	8	44	12.4	50	2720.04					
											235	3.82			382.02
Permeation	3/28/98	15:50	7.360	0.1	48	24.6	44	12.5	50	3065.04					
											3300	3.82	1.12139E-06	1.114E-06	385.63
Permeation	3/28/98	16:45	7.240	22.1	48	2.8	44	13.7	50	2626.92					
											360	3.81			388.23
Permeation	3/28/98	16:51	7.240	0.1	48	24.4	44	13.7	50	3062.92					
											3240	3.81	6.87321E-07	6.767E-07	389.37
Permeation	3/28/98	17:45	7.220	14	48	10.9	44	13.2	50	2788.90					
											240	3.81			389.52
Permeation	3/28/98	17:49	7.220	0	48	24.4	44	13.2	50	3063.90					
											420	3.81			748.70
Permeation	3/28/98	17:56	0.300	off	48		44		50	#VALUE!					
											139140				
Permeation	3/30/98	8:35	0.300	on	48		44		50	#VALUE!					
											16380	3.81	2.12478E-07	2.101E-07	389.91
Permeation	3/30/98	13:01	7.220	21.1	48	3.7	44	13.3	50	2645.90					
											360	3.81			389.33
Permeation	3/30/98	13:07	7.220	0.1	48	24.6	44	13.3	50	3064.90					
											16140	3.81	1.85762E-07	1.845E-07	387.76
Permeation	3/30/98	17:36	7.300	18.3	48	6.8	44	13.3	50	2702.98					
											-28680	3.81			385.14
Permeation	3/31/98	9:38	7.300	0.3	48	24.9	44	13.5	50	3065.98					
											14580	3.81	2.60587E-07	2.598E-07	394.28
Permeation	3/31/98	13:41	6.980	23.2	48	2	44	13.8	50	2607.66					
											420	3.80			402.66
Permeation	3/31/98	13:48	6.980	0.1	48	24.7	44	13.8	50	3065.66					
											9360	3.80	3.35201E-07	3.332E-07	394.28
Permeation	3/31/98	16:24	7.300	19.4	48	5.6	44	14.1	50	2681.98					
											71700	3.80			385.11
Permeation	4/1/98	12:19	7.300	0.3	48	24.6	44	14.1	50	3062.98					
											5580	3.80	5.29663E-07	5.302E-07	390.45
Permeation	4/1/98	13:52	7.120	18.2	48	6.6	44	14.7	50	2703.80					
											76080	3.79			394.88
Permeation	4/2/98	11:00	7.120	0	48	24.6	44	14.7	50	3065.80					
											4560	3.79	7.24966E-07	7.182E-07	398.75
Permeation	4/2/98	12:16	7.000	20.5	48	4.4	44	15.5	50	2658.68					
											7320	3.78			401.58
Permeation	4/2/98	14:18	7.000	0	48	24.8	44	15.5	50	3067.68					
											3180	3.78	8.65451E-07	8.62E-07	401.02
Permeation	4/2/98	15:11	7.040	17.3	48	7.6	44	15.7	50	2722.72					
											436200	3.78			399.39
Permeation	4/7/98	16:21	7.040	0.1	48	24.7	44	16	50	3065.72					
											540	3.77	1.6091E-06	1.595E-06	399.88

Permeation	4/7/98	16:30	7.040	5.8	48	19.1	44	16.7	50	2952.72				
											157620	3.76			399.72
Permeation	4/9/98	12:17	7.040	0.2	48	24.8	44	16.8	50	3065.72				
											1470	3.76	2.04536E-06	2.02E-06	402.74
Permeation	4/9/98	12:41	6.940	19.2	48	6.2	44	17.3	50	2689.62				
											6000	3.75			405.10
Permeation	4/9/98	14:21	6.940	0	48	24.8	44	17.3	50	3067.62				
											840	3.75	2.39182E-06	2.362E-06	406.23
Permeation	4/9/98	14:35	6.920	13.1	48	12	44	17.3	50	2808.60				
											348240	3.75			408.80
Permeation	4/13/98	15:19	6.840	0	48	24.8	44	17.6	50	3067.52				
											1020	3.75	2.85311E-06	2.834E-06	410.97
Permeation	4/13/98	15:36	6.860	18.7	48	6.3	44	18.3	50	2695.54				
											54240	3.74			409.83
Permeation	4/14/98	6:40	6.860	0	48	25	44	18.2	50	3069.54				
											1154	3.74	3.4101E-06	3.381E-06	409.78
Permeation	4/14/98	6:59	6.880	24.7	48	0.6	44	18.5	50	2578.56				
											1140	3.74			408.47
Permeation	4/14/98	7:18	6.880	0	48	24.9	44	18.5	50	3068.56				
											780	3.74	4.0591E-06	4.032E-06	410.37
Permeation	4/14/98	7:31	6.840	20.2	48	4.9	44	18.7	50	2666.52				
											600	3.73			410.99
Permeation	4/14/98	7:41	6.840	0	48	24.9	44	18.7	50	3068.52				
											600	3.73	3.88432E-06	3.816E-06	412.78
Permeation	4/14/98	7:51	6.800	15.4	48	10	44	18.7	50	2765.48				

Flexible Wall Hydraulic Conductivity

Foth and Van Dyke: Crandon Mine

Start Date 3/26/98

Soil Description Bentomat CR CRAN #10

Panel Position #1

	Thickness Measurement for average thickness (mm)	Diameter Measurement (init) for average diameter (mm)	Diameter Meas. Final for average diameter (mm)	Moisture Content of Specimen (%)	Sample Weight (grams)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7.26	102	101.24	112.70	84.56	16.56	59.01	42.45
	7.1	100.32	100.7					
	7.14	100.16	100.12					
	7.96	102.64	100.86					
Averages	7.37	101.01						

Diameter of Accumulators		
Headwater (cm)	Tailwater (cm)	Cellwater (cm)
3.67	3.79	1

Height to bottom of sample (mm)	108.7
Height to bottom of headwater marriote (mm)	342
Height to top of tailwater marriote (mm)	510
Height to top of cell water pipet (mm)	702

Area of Inflow(cm^2)= 10.57844932
Area of Outflow(cm^2)= 11.28153776
a*(cm^2)= 5.458343367

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (mm)	Headwater Pressure (psi)	Tailwater Reading (mm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity (cm/s)	End of Incr.TW Pore Vol. of Flow (PVF)	End of Incr. HW Pore Vol. of Flow (PVF)	Hydraulic Gradient
Backpressure	3/26/98	12:50	7.365	3.1	1	3.6	1	2.7	5						
				flush line						14400	4.39				
Backpressure	3/26/98	16:50	7.365	13.2	6	19.6	6	8.1	10						
										60010	4.39				
Backpressure	3/26/98	20:20	7.705	13.2	11	19.3	11	11.8	15						
										12900	4.39				
Backpressure	3/26/98	23:55	7.885	13.4	16	19.4	16	12.5	20						
										27720	4.39				
Backpressure	3/27/98	7:37	7.985	13.7	21	19.6	21	12.8	25						
										11580	4.39				
Backpressure	3/27/98	10:50	8.225	13.8	26	19.6	26	13.5	30						
										10500	4.39				
Backpressure	3/27/98	13:45	8.205	14	36	19.4	36	14.1	40						
										62100	4.39				
Backpressure	3/28/98	7:00	8.205	14.4	46	19.1	46	15.7	50						
										12240	4.39				
Backpressure	3/28/98	10:24	8.205	14.6	46	19.1	46	17.2	50						
										7320	4.39				
Permeation	3/28/98	12:26	8.225	277	48	0	44	17.2	50						
										123360	4.39	6.046E-08			330.38
Permeation	3/29/98	22:42	7.785	88	48	175	44	20.3	50				4.651	4.710	
										37380	4.39	0.000E+00			339.71
Permeation	3/30/98	9:05	7.785	286	48	0	44	20.3	50				4.651		
										30420	4.39	8.548E-08			338.41
Permeation	3/30/98	17:32	7.845	219	48	62.5	44	21	50				6.312	6.380	
										1860	4.39	0.000E+00			337.12
	3/30/98	18:03	7.845	200	48	0	44	21	50				6.312		
										55860	4.39	8.618E-08			339.28
	3/31/98	9:34	7.745	80	48	116	44	21.6	50				9.395	9.370	
										45900	4.39	0.000E+00			341.47
	3/31/98	22:19	7.745	295	48	0	44	21.6	50				9.395		
										101160	4.39	7.783E-08			340.15
	4/1/98	10:54	7.805	94	48	189	44	21.9	50				14.418	14.379	
										4440	4.39	0.000E+00			338.84
	4/1/98	12:08	7.805	275	48	0	44	21.9	50				14.418		
										71100	4.39	1.068E-07			339.28
	4/2/98	7:53	7.785	83	48	183	44	22.7	50				19.282	19.164	
										26220	4.39	0.000E+00			339.71
	4/2/98	15:10	7.785	298	48	0	44	22.7	50				19.282		
										72960	4.39	1.208E-07			340.15
	4/3/98	11:28	7.765	71	48	213	44	24.1	50				24.943	24.821	
										281460	4.39	0.000E+00			340.59
	4/6/98	17:37	7.765	280	48	0	44	24.1	50				24.943		
										81600	4.39	9.815E-08			339.28
	4/7/98	16:17	7.825	75	48	193	44	24.2	50				30.072	29.930	
										516900	4.39	0.000E+00			337.98
	4/13/98	15:52	7.825	287	48	0	44	24.2	50				30.072		
										57780	4.39	7.201E-08			338.41
	4/14/98	7:55	7.805	180	48	100	44	25	50				32.730	32.596	
								move to 10.0		86340	4.39	0.000E+00			338.84
	4/15/98	7:54	7.805	287	48	0	44	10	50				32.730		
										84780	4.39	8.811E-08			339.28
	4/16/98	7:27	7.785	97	48	180	44	10.5	50				37.514	37.331	
										107100	4.39	0.000E+00			339.71
	4/17/98	13:12	7.785	273	48	0	44	10.5	50				37.514		
										76020	4.39	8.461E-08			339.28
	4/18/98	10:19	7.805	108	48	155	44	10.5	50				41.633	41.443	
										108720	4.39	0.000E+00			338.84
	4/19/98	16:31	7.805	284	48	0	44	10.5	50				41.633		
										81840	4.39	7.860E-08			341.47
	4/20/98	15:15	7.685	116	48	156	44	10.7	50				45.779	45.630	

Flexible Wall Hydraulic Conductivity

Foth and Van Dyke: Crandon Mine

Start Date 2/18/98

Soil Description CR Bentomat
CRAN #11

Panel Position # 1

	Thickness Measurement for average thickness (mm)	Diameter Measurement (Ini) for average diameter (mm)	Diameter Meas. Final for average diameter (mm)	Moisture Content of Specimen (%)	Sample Weight (grams)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	6.89	98.34	98.9	111.39	84.83	16.72	57.53	40.81
	7.34	102.14	100.12					
	7.66	99.9	102.04					
	7.12	101.48	101.10					
Averages	7.25	100.50						

Diameter of Accumulators		
Headwater (cm)	Tailwater (cm)	Cellwater (cm)
3.67	3.79	1

Height to bottom of sample (mm)	109
Height to bottom of headwater marriote (mm)	342
Height to top of tailwater marriote (mm)	510
Height to top of cell water pipet (mm)	702

Area of Inflow(cm^2)= 10.57844932
Area of Outflow(cm^2)= 11.28153776
a*(cm^2)= 5.459343367

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (mm)	Headwater Pressure (psi)	Tailwater Reading (mm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity (cm/s)	End of Incr.TW Pore Vol. of Flow (PVF)	End of Incr.HW Pore Vol. of Flow (PVF)	Hydraulic Gradient
Backpressure	2/18/98	23:20	7.253	4.7	1	5.1	1	14.6	5						
										43500	4.39				
Backpressure	2/19/98	11:25	7.253	10.7	6	7.6	6	15	10						
										78420	4.39				
Backpressure	2/20/98	9:12	7.053	11.5	11	8.1	11	15.8	15						
										269640	4.39				
Backpressure	2/23/98	12:06	6.353	11.5	16	8.9	16	16.5	20						
										84240	4.39				
Backpressure	2/24/98	11:30	6.153	11.4	21	9.3	21	17.3	25						
										11100	4.39				
Backpressure	2/24/98	14:35	6.153	11.4	26	9.6	26	17.9	30						
										169800	4.39				
Backpressure	2/26/98	13:45	5.853	11.3	31	10	31	18.9	35						
										435000	4.39				
Backpressure	3/1/98	14:35	5.753	10.8	36	10.8	36	19.6	40						
										81720	4.39				
Backpressure	3/2/98	13:17	5.753	10.8	46	10.8	46	20.3	50						
								move to 10		1282680	4.39				
Backpressure	3/17/98	9:35	5.253	10.9	46	10.9	46	12.9	50						
										172800	4.39				
Backpressure	3/19/98	9:35	5.953	10.8	46	11	46	13.3	50						
										15720	4.39				
Permeation	3/19/98	13:57	5.953	285	48	0	44	9	50						
										180	4.39	4.054E-06			444.30
Permeation	3/19/98	14:00	5.953	256	48	22.8	44	9	50				0.630	0.752	
										4980	4.39	0.000E+00			444.30
Permeation	3/19/98	15:23	5.953	231	48	0	44	9	50						
										480	4.39	4.339E-06			436.96
Permeation	3/19/98	15:31	6.153	165	48	64	44	9.2	50				2.399	2.462	
										2280	4.39	0.000E+00			429.85
Permeation	3/19/98	16:09	6.153	145	48	0	44	9.2	50						
										360	4.39	5.698E-06			429.85
Permeation	3/19/98	16:15	6.153	80.1	48	62	44	9.4	50				4.113	4.144	
										85680	4.39	0.000E+00			429.85
Permeation	3/20/98	16:03	6.153	276	48	0	44	9.5	50						
										600	4.39	7.132E-06			433.38
Permeation	3/20/98	16:13	6.053	138.3	48	130.4	44	10.3	50				7.717	7.713	
										237360	4.39	0.000E+00			440.60
Permeation	3/23/98	10:09	5.953	281	48	0	44	10.6	50						
										480	4.39	7.643E-06			426.39
Permeation	3/23/98	10:17	6.453	170	48	110	44	11.2	50				10.758	10.590	
										2340	4.39	0.000E+00			409.87
Permeation	3/23/98	10:56	6.453	137	48	0	44	11.2	50						
										300	4.39	8.674E-06			409.87
Permeation	3/23/98	11:01	6.453	64	48	75	44	11.4	50				12.831	12.482	
										1980	4.39	0.000E+00			409.87
Permeation	3/23/98	11:34	6.453	277	48	0	44	11.4	50						
										360	4.39	7.955E-06			436.96
Permeation	3/23/98	11:40	5.653	183.5	48	88	44	11.4	50				15.263	14.906	
										1620	4.39	0.000E+00			467.88
Permeation	3/23/98	12:07	5.653	164	48	0	44	11.4	50						
										360	4.39	7.514E-06			467.88
Permeation	3/23/98	12:13	5.653	70	48	89	44	11.4	50				17.724	17.342	
										-2930904780	4.39	0.000E+00			935.76

Flexible Wall Hydraulic Conductivity

Crandon Mine GCL Testing: Foth and Van Dyke

Start Date 2/18/98

Soil Description CR Bentomat
CRAN #12

	Thickness Measurement for average thickness (mm)	Diameter Measurement(INI) for average diameter (mm)	Diameter Measurement (FIN) for average diameter (mm)	Sample Weight (grams)	Moisture Content (%)	Volume of Solids (cm^3)	Total Volume (cm^3)	Pore Volume (cm^3)
	7.2	101.04	101.48	89.07	125.49	16.46	55.10	38.64
	7.52	97.74	95.66					
	7.6	98.88	102.4					
	5.9	100.38	100.16					
Averages	7.06	99.72						

*heights from top of table

Height to bottom of sample (mm)	113
Height to top of headwater accumulator (mm)	703
Height to top of tailwater accumulator (mm)	700
Height to top of cell water accumulator (mm)	703
Thickness of Specimen (mm)	7.06

	Tailwater set to pipet	Tailwater set to both
Area of Inflow(cm^2)=	4.96	4.96
Area of Outflow(cm^2)=	1	4.93
a*(cm^2)=	0.832214765	2.47247725

Stage	Date	Time	GCL Thickness (mm)	Headwater Reading (cm)	Headwater Pressure (psi)	Tailwater Reading (cm)	Tailwater Pressure (psi)	Cell Reading (cm)	Cell Pressure (psi)	h1 (mm)	Change in Time (sec)	Average Effective Stress (psi)	Hydraulic Conductivity FHRT(cm/s)	Hydraulic Conductivity CH (cm/s)	Hydraulic Gradient
Backpressure	2/18/98	23:17	7.055	3.7	1	4.3	1	9.7	5	16.06					
											43680	3.86			
Backpressure	2/19/98	11:25	7.055	12.7	6	12	6	12.3	10	3.06					
											78300	3.83			
Backpressure	2/20/98	9:10	7.055	13	11	12.7	11	12.8	15	7.05					
											269700	3.82			
Backpressure	2/23/98	12:05	6.855	12.7	16	13.1	16	14.4	20	13.85					
											84000	3.80			
Backpressure	2/24/98	11:25	6.655	12.6	21	13.2	21	15.5	25	15.66					
											11400	3.78			
Backpressure	2/24/98	14:35	6.655	12.7	26	13.3	26	16	30	15.65					
											169800	3.77			
Backpressure	2/26/98	13:45	6.455	12.9	31	13.3	31	16.7	35	13.46					
											435000	3.76			
Backpressure	3/1/98	14:35	6.455	13.1	36	13.3	36	17.4	40	11.46					
											81660	3.75			
Backpressure	3/2/98	13:16	6.455	13.1	46	13.3	46	18.1	50	11.46					
											1282440	3.74			
Backpressure	3/17/98	9:30	6.255	13.2	46	13.4	46	20.3	50	11.25					
											2040	3.71			
Permeation	3/17/98	10:04	6.255	0.1	48	24.1	44	9.9	50	3061.93					
											240	3.86	4.2863E-06	4.2448E-06	450.53
Permeation	3/17/98	10:08	6.255	7.9	48	16.4	44	10	50	2906.93					
											3840	3.86			450.28
Permeation	3/17/98	11:12	6.255	11.8	48	24.6	44	10	50	2949.93					
											300	3.86	4.4425E-06	4.4274E-06	450.35
Permeation	3/17/98	11:17	6.255	21.4	48	15	44	10.1	50	2757.93					
											540	3.86			450.05
Permeation	3/17/98	11:26	6.255	0.6	48	24.6	44	10.1	50	3061.93					
											240	3.86	4.5422E-06	4.5825E-06	450.53
Permeation	3/17/98	11:30	6.255	8.7	48	16.3	44	10	50	2897.93					
											2220	3.86			450.27
Permeation	3/17/98	12:07	6.255	12.6	48	24.8	44	10	50	2943.93					
											360	3.86	4.5762E-06	4.5791E-06	450.34
Permeation	3/17/98	12:13	6.255	24.3	48	13	44	10	50	2708.93					
											7080	3.86			449.97
Permeation	3/17/98	14:11	6.255	0.6	48	24.3	44	10	50	3058.93					
											300	3.86	4.52E-06	4.5293E-06	446.95
Permeation	3/17/98	14:16	6.355	10.6	48	14.2	44	9.8	50	2858.03					
											2640	3.86			443.12
Permeation	3/17/98	15:00	6.355	0.6	48	24.7	44	9.8	50	3063.03					
											300	3.86	5.1961E-06	5.2205E-06	446.96
Permeation	3/17/98	15:05	6.255	12	48	13.1	44	9.85	50	2832.93					
											57	3.86			450.17
Permeation	3/17/98	16:01	6.255	1	48	24.3	44	9.85	50	3054.93					
											420	3.86	5.0622E-06	5.0583E-06	450.52
Permeation	3/17/98	16:08	6.255	16.5	48	8.7	44	9.6	50	2743.93					
											60420	3.87			450.02
Permeation	3/18/98	8:55	6.255	0.9	48	24.7	44	9.7	50	3059.93					
											480	3.86	4.1824E-06	4.1803E-06	450.53
Permeation	3/18/98	9:03	6.255	15.6	48	9.9	44	9.6	50	2764.93					
											1680	3.87			450.06
Permeation	3/18/98	9:31	6.255	0.6	48	24.8	44	9.6	50	3063.93					
											540	3.87	4.5973E-06	4.59E-06	450.54
Permeation	3/18/98	9:40	6.255	18.6	48	6.7	44	9.55	50	2702.93					
											1560	3.87			449.96
Permeation	3/18/98	10:06	6.255	0.6	48	24.7	44	9.55	50	3062.93					
											600	3.87	4.7554E-06	4.7444E-06	450.53
Permeation	3/18/98	10:16	6.255	21.1	48	4.1	44	9.6	50	2651.93					
											4440	3.87			449.88
Permeation	3/18/98	11:30	6.255	0.1	48	24.9	44	9.6	50	3069.93					
											720	3.87	4.7934E-06	4.7765E-06	450.55
Permeation	3/18/98	11:42	6.255	24.6	48	0.3	44	9.6	50	2578.93					

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

		Pore Volume (cm^3)
Start Date	12/17/97	41.50
Specimen Description	Bentomat Cran#1	

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	40.8	92.1	1	100.93	1	100.02	4008.02	9102.92	2.27	8.8	7.56	0.86	0.51	0.51	21.20
1.1	40.7	87.1	1	100.53	1	102.41	3982.09	8808.36	2.21	8.63	7.65	0.89	1.05	0.54	22.40
1.1	39.7	70.8	1	102.95	1	100.05	3974.97	6974.59	1.75	8.47	7.77	0.92	1.49	0.44	18.20
1.1	41.4	58.4	1	100.97	1	100.85	4070.19	5779.81	1.42	8.11	7.6	0.94	2.30	0.81	33.80
1.1	40.8	52	1	103.22	1	100.71	4098.93	5127.24	1.25	6.65	7.39	1.11	3.61	1.30	54.08
1.1	44.2	52.3	1	100.64	1	101.43	4338.68	5194.32	1.20	6.24	7.34	1.18	4.50	0.90	37.18
1.1	44.9	53	0.98	104.14	1	99.62	4655.52	5171.38	1.11	6.65	7.26	1.09	5.99	1.49	61.88
1.1	44.5	47.2	1.01	99.44	1.01	100.34	4274.07	4580.98	1.07	6.33	6.98	1.10	8.09	2.09	86.84
1.1	44.2	43.7	1.02	101.87	1	104.5	4305.61	4452.80	1.03	6.38	7.02	1.10	10.84	2.76	114.40
1.1	42.4	43.6	1	102.83	1	103.65	4247.98	4406.23	1.04	6.77	7	1.03	13.56	2.72	112.84

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	12/17/97
Specimen Description	Bentomat Cran#2

Pore Volume
(cm^3)
35.94

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	40.6	108.9	1.01	102.61	1	100.63	4014.07	10849.01	2.70	8.97	7.8	0.87	0.14	0.14	5.00
1.1	41	97.9	1.01	101.25	1	100.42	4000.98	9721.76	2.43	8.73	7.09	0.81	0.82	0.68	24.50
1.1	40.8	80.1	1	99.75	1	100.45	3961.18	7936.65	2.00	8.72	7.37	0.85	1.42	0.60	21.55
1.1	40.9	70	1	100.08	1	100.99	3984.28	6959.31	1.75	8.86	7.33	0.83	2.08	0.66	23.80
1.1	39.7	62.3	1	102.92	1	100.37	3973.81	6143.74	1.55	9	7.16	0.80	2.75	0.66	23.90
1.1	40.5	59.1	1	100.05	1	100.52	3943.07	5831.26	1.48	8.73	7.33	0.84	3.41	0.67	23.95
1.1	40.8	56.5	1	100.11	1	100.33	3975.47	5559.38	1.40	9.1	7.46	0.82	4.08	0.66	23.90
1.1	41.3	53.7	1	99.46	1	99.58	3999.39	5239.01	1.31	8.92	7.56	0.85	4.75	0.67	24.10
1.1	41.4	51	1	100	1.02	100.05	4031.10	4895.70	1.21	8.99	7.69	0.86	5.42	0.67	24.00
1.1	41.6	50	1	100.34	1	100.25	4064.87	4903.33	1.21	9.07	7.32	0.81	6.08	0.67	24.00
1.1	40.9	47.7	1	100.83	1	100.53	4014.13	4685.80	1.17	8.54	7.33	0.86	6.77	0.69	24.70
1.1	41	47	1.01	101.99	1.01	100.01	4030.21	4546.11	1.13	8.93	7.4	0.83	7.43	0.66	23.80
1.1	41.2	43.7	1	100.57	1	100.34	4033.96	4275.58	1.06	9.12	7.54	0.83	9.22	1.79	64.17
1.1	41.2	42	1	100.05	1	100.88	4013.11	4127.09	1.03	9.2	7.47	0.81	11.18	1.96	70.45

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	12/17/97
Specimen Description	Bentomat Cran#3

Pore Volume (cm^3): 35.42

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	268	152	1	100.44	1	100.93	26808.54	15231.44	0.57	2.55	6.46	2.53	1.83	1.83	64.65
1.1	267	228	1	99.59	1.02	99.97	26482.08	22239.52	0.84	2.63	4.88	1.86	4.67	2.85	100.89
1.1	269	244	1.01	100.19	1	100.98	26576.25	24529.14	0.92	2.52	3.61	1.43	8.60	3.93	139.19
1.1	268	250	1.01	100.91	1	100.6	26667.32	25040.44	0.94	2.52	3.07	1.22	12.55	3.95	139.84
1.1	267	258	1	100.23	1.01	101.71	26652.26	25871.69	0.97	2.56	2.91	1.14	16.43	3.88	137.52
1.1	268	255	1	100.1	1	101.39	26717.79	25744.02	0.96	2.58	2.95	1.14	19.35	2.92	103.36
1.1	268	261	1	101.23	1.02	102.11	27019.39	26019.13	0.96	2.61	2.73	1.05	30.13	10.78	381.72

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Pore Volume (cm^3)
32.79

Start Date	1/19/98
Specimen Description	Bentomat Cran#4

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	269	259	0.99	103.11	1.01	99.02	27903.29	25285.51	0.91	2.43	3.66	1.51	0.87	0.87	28.50
1.1	280	260	1.01	100.16	1	103.38	27659.14	26766.18	0.97	2.43	2.78	1.14	4.44	3.57	116.97
1.1	269	278	1.03	106.98	1.02	99.64	27826.29	27050.43	0.97	2.41	2.65	1.10	6.60	2.16	70.80
1.1	277	267	1	100.35	1.02	103.06	27687.67	26867.43	0.97	2.41	2.69	1.12	8.48	1.89	61.91
1.1	264	269	1	106.39	1	99.9	27971.03	26764.31	0.96	2.42	2.65	1.10	10.70	2.21	72.62
1.1	272	271	1.03	105.5	1.02	101.8	27748.62	26938.18	0.97	2.42	2.62	1.08	13.04	2.34	76.61
1.1	266	273	1.01	105.76	1	100.31	27739.54	27275.39	0.98	2.41	2.54	1.05	17.17	4.14	135.67

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	12/17/97
Specimen Description	Bentomat CRC Cran#5

Pore Volume (cm^3): 45.31

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	41.2	131.1	1	100.27	1	100.1	4021.93	13014.10	3.24	8.85	6.61	0.75	0.55	0.55	25.00
1.1	45.3	114.5	1	100.25	1	101.6	4432.15	11522.54	2.60	8.99	6.78	0.75	1.03	1.03	46.65
1.1	41.2	105.4	1.01	100.44	1.02	99.19	3988.87	10143.76	2.54	8.61	6.76	0.79	1.56	1.56	70.75
1.1	39.5	87.8	1.01	104.31	1	100.52	3966.95	8716.18	2.20	8.67	6.82	0.79	2.09	2.09	94.70
1.1	40.8	77.4	1	100.89	1	100.88	4006.43	7698.24	1.92	8.86	6.92	0.78	2.62	2.62	118.70
1.1	40.9	70.4	1	100.07	1	100.34	3983.89	6954.66	1.75	8.92	6.94	0.78	3.15	3.15	142.60
1.1	41.1	65.1	1	100.26	1	100.72	4011.50	6447.18	1.61	8.96	6.99	0.78	3.68	3.68	166.60
1.1	38.9	57.6	0.96	102.5	1	101.42	4037.04	5731.33	1.42	9.04	6.92	0.77	4.20	4.20	190.50
1.1	41.4	55.2	1.02	101.71	1.03	100.94	4019.64	5302.90	1.32	9.02	6.97	0.77	4.74	0.53	24.10
1.1	41.3	49.5	1	100.99	1	101.1	4060.90	4894.34	1.21	9.09	6.84	0.75	5.26	0.53	23.80
1.1	41	47.9	1.01	101.6	1.01	100.3	4014.80	4648.66	1.16	8.83	6.81	0.77	5.79	0.53	23.85
1.1	41.3	45.9	1	100.72	1	100.91	4050.04	4521.87	1.12	8.5	6.89	0.81	6.33	0.55	24.70
1.1	41.1	42	1	100.28	1	100.17	4012.30	4098.05	1.02	9.06	7.16	0.79	8.66	2.33	105.67
1.1	37.9	42.5	1	109.55	1.02	100.24	4032.54	4069.66	1.01	9.14	7.24	0.79	10.74	2.07	94.02

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	12/17/97
Specimen Description	Bentomat CRC Cran#6

Pore Volume (cm^3): 39.95

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	268	278	1	99.97	1.02	103.13	26683.09	27997.86	1.05	2.54	5.57	2.19	1.15	1.15	45.93
1.1	267	264	1	100.48	1.01	102.74	26718.73	26744.02	1.00	2.5	3.73	1.49	2.20	1.05	41.96
1.1	267	256	1	100.95	1	102.96	26843.71	26245.60	0.98	2.51	3.14	1.25	3.19	0.99	39.69
1.1	270	265	1.01	99.97	1.01	100.04	26616.88	26140.26	0.98	2.53	3.01	1.19	4.17	0.98	39.13
1.1	271	260	1	100.61	1	100.55	27155.74	26033.50	0.96	2.5	2.94	1.18	5.15	0.98	39.13
1.1	268	265	1	101.11	1.01	100.73	26987.36	26320.55	0.98	2.49	2.78	1.12	7.38	2.23	89.03
1.1	263	261	1.01	103.87	1	100.53	26935.31	26128.85	0.97	2.48	2.74	1.10	8.52	1.14	45.36
1.1	267	257	1	100.27	1	102.19	26662.89	26151.52	0.98	2.48	2.77	1.12	9.64	1.12	44.80

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	3/26/98
Specimen Description	Bentomat CR Cran#9

Pore Volume (cm^3)
39.99

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	36.3	88.9	1.01	102.41	1.01	99.96	3570.24	8690.69	2.43	8.99	7.11	0.7909	0.80	0.80	32.11
1.1	34.5	51.2	1	101.27	1	106.83	3383.52	5353.28	1.58	8.8	7.25	0.8239	2.81	2.01	80.27
1.1	31.6	44	1.01	112.05	1.01	99.93	3384.79	4245.65	1.25	8.98	7.24	0.8062	5.46	2.65	106.05
1.1	35.4	40.2	1	102.38	1	101.57	3512.73	3972.49	1.13	9.2	7.5	0.8152	7.10	1.64	65.67
1.1	37.3	43	1	100.26	1	104.23	3630.51	4368.34	1.20	8.11	7.2	0.8878	9.62	2.52	100.70
1.1	36.9	39.9	1	100.4	1	100.23	3595.42	3890.02	1.08	8.88	7.08	0.7973	11.81	2.19	87.56
1.1	35.3	37.8	1	104.9	1	100.39	3588.68	3685.41	1.03	8.64	6.68	0.7731	14.60	2.79	111.40
1.1	36.1	36.4	1	102.58	1.01	103.05	3591.40	3602.75	1.00	7.96	6.79	0.853	16.92	2.32	92.91
1.1	38.2	37.6	1.02	99.32	1	101.14	3613.62	3692.71	1.02	8.56	6.64	0.7757	19.11	2.19	87.56
1.1	37.5	38.1	1.01	100.09	1	99.53	3608.30	3683.71	1.02	8.07	6.4	0.7931	21.57	2.46	98.26
1.1	36.9	37.5	1.01	101.31	1	99.26	3592.09	3614.16	1.01	6.46	6.29	0.9737	23.66	2.09	83.67
1.1	37	38.4	0.5	50.44	0.5	49.52	3622.69	3695.29	1.02	6.57	6.65	1.0122	24.34	0.68	27.24
1.1	34.9	36.5	0.5	53.8	0.5	50.74	3637.98	3593.49	0.99	6.85	6.53	0.9533	26.60	2.26	90.48
1.1	38.8	36.6	0.5	49.27	0.5	50.73	3716.06	3602.93	0.97	8.08	6.63	0.8205	28.16	1.56	62.27
1.1	37	36.9	0.5	49.89	0.5	50.27	3583.20	3600.43	1.00	6.54	6.98	1.0673	30.41	2.25	89.99
1.1	37.3	37.2	0.51	51.84	0.5	49.91	3680.72	3604.60	0.98	6.65	6.25	0.9398	33.38	2.97	118.70
1.1	36.9	37.7	0.51	50.98	0.5	49.82	3579.70	3647.92	1.02	6.98	7.14	1.0229	35.81	2.43	97.29
1.1	37	36.6	0.5	50.66	0.51	51.71	3638.49	3600.52	0.99	6.46	6.39	0.9892	37.62	1.81	72.48

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	3/26/98
Specimen Description	Bentomat CR Cran #10

Pore Volume (cm^3): 42.45

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	275	225	1	99.97	1.01	101.09	27382.883	22411.1	0.82	2.35	3.77	1.60	4.65	4.65	197.43
1.1	277	235	1.01	101.45	1	104.98	27714.0257	24555.9	0.89	2.31	3.44	1.49	6.31	1.66	70.51
1.1	273	253	1	100.87	1	99.9	27427.65	25165.91	0.92	2.36	3.13	1.33	9.40	3.08	130.87
1.1	277	254	1	99.98	1	102.51	27585.58	25925.88	0.94	2.32	2.92	1.26	14.42	5.02	213.22
1.1	281	267	1.01	100.95	1	99.35	27977.24	26418.26	0.94	2.35	2.85	1.21	19.28	4.86	206.45
1.1	278	265	1	99.93	1	101.07	27671.72	26673.47	0.96	2.35	2.76	1.17	24.94	5.66	240.30
1.1	272	243	0.5	51.34	0.5	54.94	27817.11	26581.07	0.96	2.48	2.84	1.15	30.07	5.13	217.73
1.1	273	266	0.5	50.39	0.51	49.58	27403.18	25753.54	0.94	2.34	2.88	1.23	32.73	2.66	112.82
1.1	285	261	0.5	49.08	0.5	50.6	27868.72	26302.98	0.94	2.32	2.72	1.17	37.51	4.78	203.07
1.1	275	265	0.5	50.19	0.5	51.06	27495.18	26950.57	0.98	2.32	2.66	1.15	41.63	4.12	174.86
1.1	267	260	0.5	52.04	0.49	51.25	27675.97	27079.93	0.98	2.52	2.82	1.12	45.78	4.15	175.99

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	2/18/98
Specimen Description	Bentomat CR Cran#11

Pore Volume (cm^3)
40.81

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	279	100	1	99.26	1	99.86	27585.45	9877.25	0.36	2.5	6.75	2.70	0.63	0.63	25.72
1.1	272	198	1.01	103.04	1	101.77	27638.26	20039.61	0.73	2.44	5.4	2.21	2.40	1.77	72.20
1.1	281	243	1	99.29	1	100.62	27792.37	24341.08	0.88	2.34	3.91	1.67	4.11	1.71	69.95
1.1	279	248	1	99.17	1	101.32	27560.44	25017.01	0.91	2.32	3.08	1.33	7.72	3.60	147.11
1.1	278	260	1	100.66	1	99.73	27873.85	25821.20	0.93	2.33	2.86	1.23	10.76	3.04	124.10
1.1	281	270	1.01	101.13	1.01	99.49	28027.13	26489.08	0.95	2.31	2.6	1.13	12.83	2.07	84.61
1.1	278	262	1	99.67	0.99	103.65	27599.72	27316.54	0.99	2.32	2.5	1.08	15.26	2.43	99.28
1.1	274	277	1	101.91	1	100.06	27812.34	27607.65	0.99	2.32	2.46	1.06	17.72	2.46	100.41

Chemical Analysis of Influent and Effluent
Crandon Mine GCL Testing: Foth and Van Dyke

Start Date	2/18/98
Specimen Description	Bentomat CR Cran#12

Pore Volume (cm^3): 38.64

All values in micromhos/cm

EC DDW	ECo-measured	EC measured	grams (ECo) permeant	grams(ECo) dilution	grams permeant	grams dilution	ECo-actual	EC actual	EC/ECo	pH in	pH eff	Ratio of pHeff to pHin	Cummulative PVF (tail)at Reading	Effluent Samp. Vol. (pore vol's)	Effluent Samp. Vol. (mL)
1.1	38.3	92.9	1	100.75	1.01	112.45	3749.00	10221.80	2.73	9.13	6.66	0.73	0.98	0.98	37.96
1.1	37.5	66.8	1.01	100.8	1	109.39	3633.89	7188.02	1.98	9.37	6.69	0.71	2.21	1.22	47.33
1.1	37.7	54.5	1.01	100.1	1.01	101.22	3628.49	5352.73	1.48	9.58	6.64	0.69	3.27	1.06	40.92
1.1	37.3	46	1.01	101.24	1	102.25	3629.70	4592.13	1.27	9.08	6.73	0.74	4.77	1.51	58.17
1.1	37.5	44.5	1	101.36	1	101.77	3690.60	4417.92	1.20	9.36	6.88	0.74	6.06	1.29	49.79
1.1	37.1	41.2	1	100.42	1	102.84	3616.22	4124.98	1.14	9.33	7.03	0.75	7.54	1.48	57.19
1.1	37	40.4	1	100.4	1	100.26	3605.46	3941.32	1.09	9.56	7.2	0.75	9.53	1.99	76.91
1.1	34.7	41.2	1	105.49	1.02	102.57	3545.56	4033.51	1.14	9.16	6.9	0.75	11.42	1.89	72.96
1.1	35.9	38	1	102.83	1	101.6	3579.58	3750.14	1.05	9.3	7.03	0.76	13.73	2.31	89.23
1.1	36.4	37	1	100.71	1.01	100.97	3556.16	3590.03	1.01	9.33	7.39	0.79	16.36	2.63	101.56
1.1	37.1	37.4	1	99.6	1.01	101.5	3586.70	3649.07	1.02	9.12	7.93	0.87	19.50	3.14	121.28

Appendix E - Literature Review

LITERATURE REVIEW ON GCL COMPATIBILITY TESTING

by

Charles D. Shackelford

(04/02/98)

INTRODUCTION

The objective of this review is to evaluate the state-of-the-art of GCL compatibility testing with respect to the GCL testing protocol for the base liner at the tailings management area for the proposed Nicolet Mineral Company's zinc/copper mine near Crandon, Wisconsin. In particular, the following four specific aspects of compatibility testing are addressed in this review:

- the effect of prehydration on the measurement of the hydraulic conductivity of GCLs permeated with chemicals or chemical solutions;
- the effect of hydraulic gradient on the measurement of the hydraulic conductivity of GCLs permeated with chemicals or chemical solutions;
- the appropriateness of use of pH and electrical conductivity (EC) as parameters to evaluate chemical equilibrium; and
- the interpretation of the some hydraulic conductivity test results involving permeation of GCLs with different permeant liquids.

In addition, the applicability of existing standards on hydraulic conductivity testing, viz., ASTM D 5084 (*Standard Test Method for the Measurement of the Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*) and GRI-GCL2 (*Standard Test Method for Permeability of Geosynthetic Clay Liners (GCLs)*) in terms of GCL compatibility testing is evaluated.

PREHYDRATION EFFECT

Several studies have reported that the order in which permeant liquids are introduced to porous materials containing high swelling bentonite, such as GCLs and sand-bentonite mixtures, can have a significant effect on the final hydraulic conductivity of the materials (e.g., Daniel et al. 1993, Shackelford 1994, Didier and Comeaga 1997, Gleason et al. 1997, Quaranta et al. 1997, Ruhl and Daniel 1997, and Stern and Shackelford 1998). In particular, the effect of hydrating the bentonite portion of GCLs and sand-bentonite mixtures prior to permeation with chemical solutions is well documented. In general, the hydraulic conductivity of GCLs and sand-bentonite mixtures that are permeated directly with chemical solutions typically is significantly higher (≥ 1.5 orders of magnitude) than the hydraulic conductivity of the same materials that are permeated with the same chemical solutions after prehydration.

For example, Daniel et al. (1993) performed tests in which specimens consisting of the bentonite portion of Gundseal® GCLs were prehydrated to initial gravimetric water contents (w) of 50 %, 100 %, and 125 % before being permeated in flexible-wall permeameters. After prehydration, the specimens were permeated with benzene, gasoline, methanol, tertbutylethylether (MTBE), or trichloroethylene (TCE) for approximately 2 months using applied hydraulic gradients ranging from 80 to 120. Air-dried (w = 17%) and saturated (w = 145 %) Gundseal® bentonite specimens also were tested under the same conditions. The resulting hydraulic conductivity values for specimens at initial water contents of 17 %, 50 %, and 125 % are shown in Fig. 1. The hydraulic conductivity results for specimens prehydrated to initial water contents of 125 % and 145 % are not shown in Fig. 1 because no flow was observed for these specimens.

The results in Fig. 1 indicate that the hydraulic conductivity values for the non-prehydrated (i.e., air-dried) specimens are from 3.8 (benzene) to 5.1 (TCE) orders-of-magnitude higher than the hydraulic conductivity values of the specimens prehydrated to an initial water content of 100 %. In addition, the hydraulic conductivity values for the specimens prehydrated to an initial water content of 50 % still are from 3.1 (TCE) to 4.5 (MTBE) orders-of-magnitude higher than the hydraulic conductivity values of the specimens prehydrated to an initial water content of 100 %.

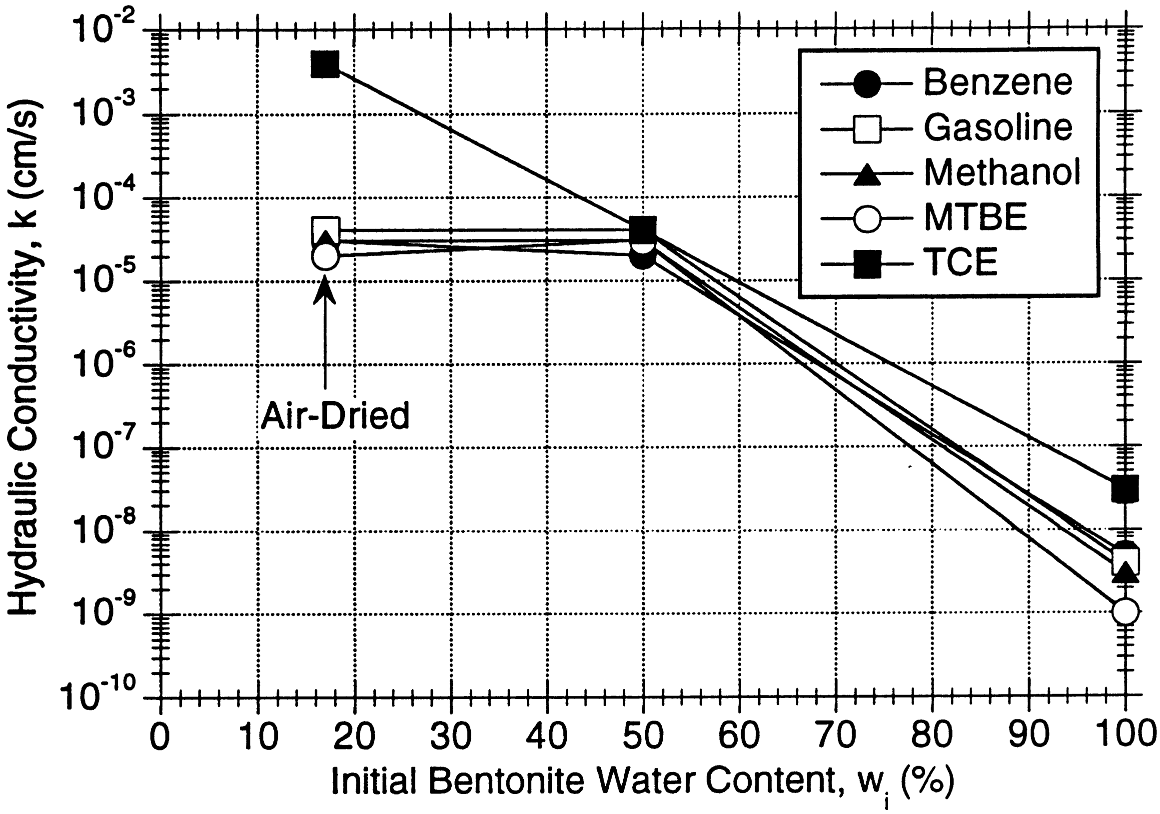

Figure 1 - Effect of initial bentonite water content on hydraulic conductivity of Gundseal® permeated with different liquids (data from Daniel et al. 1993).

Finally, the hydraulic conductivity values for specimens that either were not prehydrated or were prehydrated insufficiently are all greater than 10^{-5} cm/s. Thus, the results of Daniel et al. (1993) also illustrate that the hydraulic conductivity of a GCL is a function not only of whether or not the GCL has been hydrated prior to permeation with a chemical solution, but also of the extent of prehydration.

The extent of prehydration, as measured by water content or degree of saturation, is expected to be a function, in part, of the stress condition on the specimen during prehydration and the amount of water available for prehydration. For example, the greatest extent of prehydration typically is expected for the free-swell case where the specimen has access to an abundant source of water and is unconstrained against swelling. Lower extents of prehydration are expected when the specimen is confined against swelling and/or the amount of water available to the specimen is restricted.

For example, consider the data shown in Fig. 2. In this case, the degree of hydration of Gundseal® GCL specimens buried in sand is shown to be a function of the water content of the sand, with greater degrees of hydration associated with the higher sand water contents. In addition, the time required for equilibration between the GCL and the sand varies between about 2 and 6 weeks, with the equilibration time decreasing with increasing water content of the sand.

Methods of Prehydration

In general, three methods can be used to induce prehydration of GCLs: (1) back-pressure saturation as recommended by ASTM D 5084 and GRI GCL-2, (2) permeation with water prior to permeation with chemicals (e.g., Shan and Daniel 1991, Ruhl and Daniel 1997, Petrov et al. 1997a,b), or (3) imbibition of water either before or after assembling the GCL in the permeameter (e.g., Didier and Comeaga 1997). Important factors that probably contribute to differences in prehydration resulting from the use of different methods include the stress condition on the specimen during prehydration, particularly with respect to the back-pressure saturation and

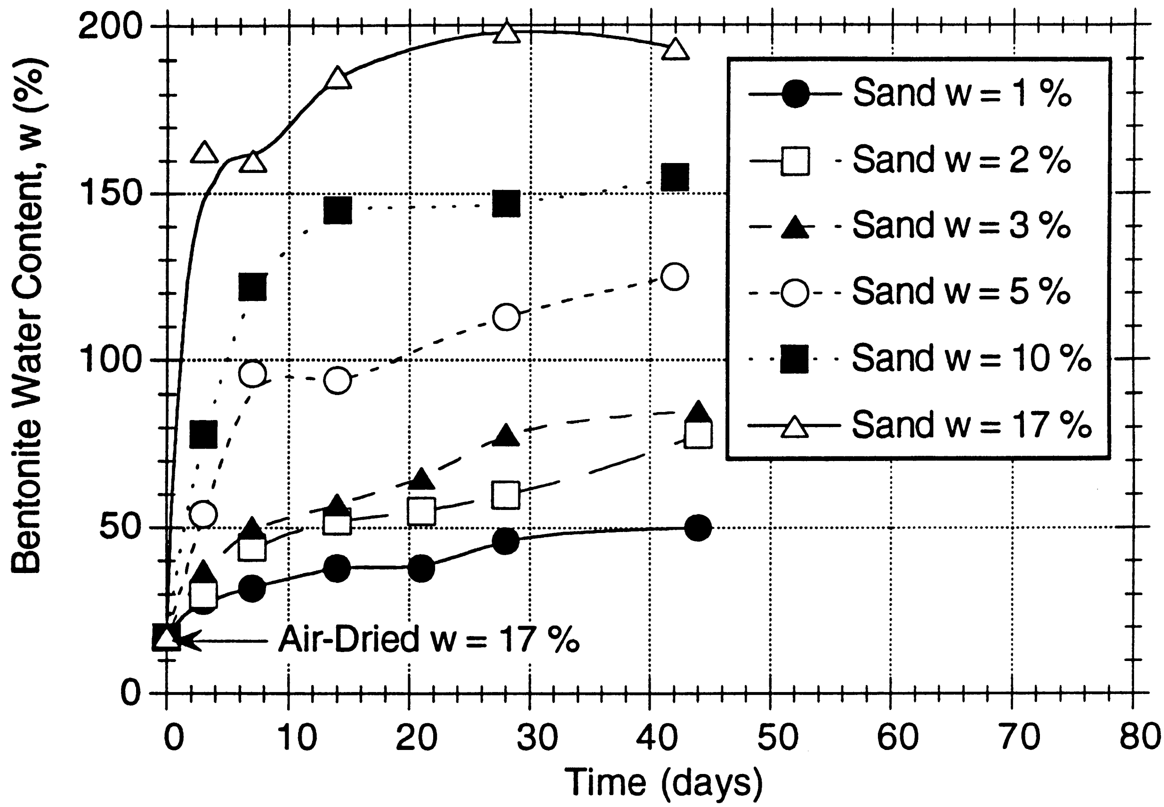

Figure 2- Effect of initial sand gravimetric water content (w) on rate and extent of hydration of the bentonite portion of Gundseal® in contact with the sand (data from Daniel et al. 1993).

permeation methods, and whether the GCL is hydrated by exposure to only one or both sides of the GCL.

PERMEATION

EFFECT OF PERMEAMETER TYPE

Petrov et al. (1997a) evaluated the use of fixed-ring, double-ring, and flexible-wall permeameters on the measurement of the hydraulic conductivity of a needle-punched GCL permeated with distilled water (DW) or a tap water (TW) and/or either 0.6 N NaCl or 2.0 N NaCl solutions. Their results indicate that reasonable reproducibility of hydraulic conductivity values can be obtained for a given permeant liquid and stress condition regardless of the type of permeameter used in the test provided consistent specimen preparation and installation procedures are used.

HYDRAULIC GRADIENT AND EFFECTIVE STRESS

In practice, relatively high hydraulic gradients often are preferred when testing low-permeability soils to reduce the test duration. However, the use of hydraulic gradients in the laboratory that are high relative to the field application may result in the measurement of a relatively low hydraulic conductivity due to consolidation of the specimen resulting from the generation of unrealistically high seepage forces. As a result, some consideration must be given to the magnitude of the hydraulic gradient used in hydraulic conductivity testing. For example, the maximum hydraulic gradient recommended by ASTM D 5084 for testing soils with hydraulic conductivity values, k, $\leq 10^{-7}$ cm/s is 30. However, hydraulic gradients ranging from ~ 50 to 550 typically are used for measuring the hydraulic conductivity of GCLs (e.g., Shan and Daniel 1991, Daniel et al. 1993, Didier and Comeaga 1997, Petrov et al. 1997a,b, Quaranta et al. 1997, and Ruhl and Daniel 1997). Thus, some discussion of the potential effect of the use relatively high hydraulic gradients in GCL compatibility testing is warranted.

The effect of hydraulic gradient on the hydraulic conductivity of a needle-punched GCL tested by Petrov et al. (1997a) is shown in Fig. 3. The data in Fig. 3 cover a wide range of

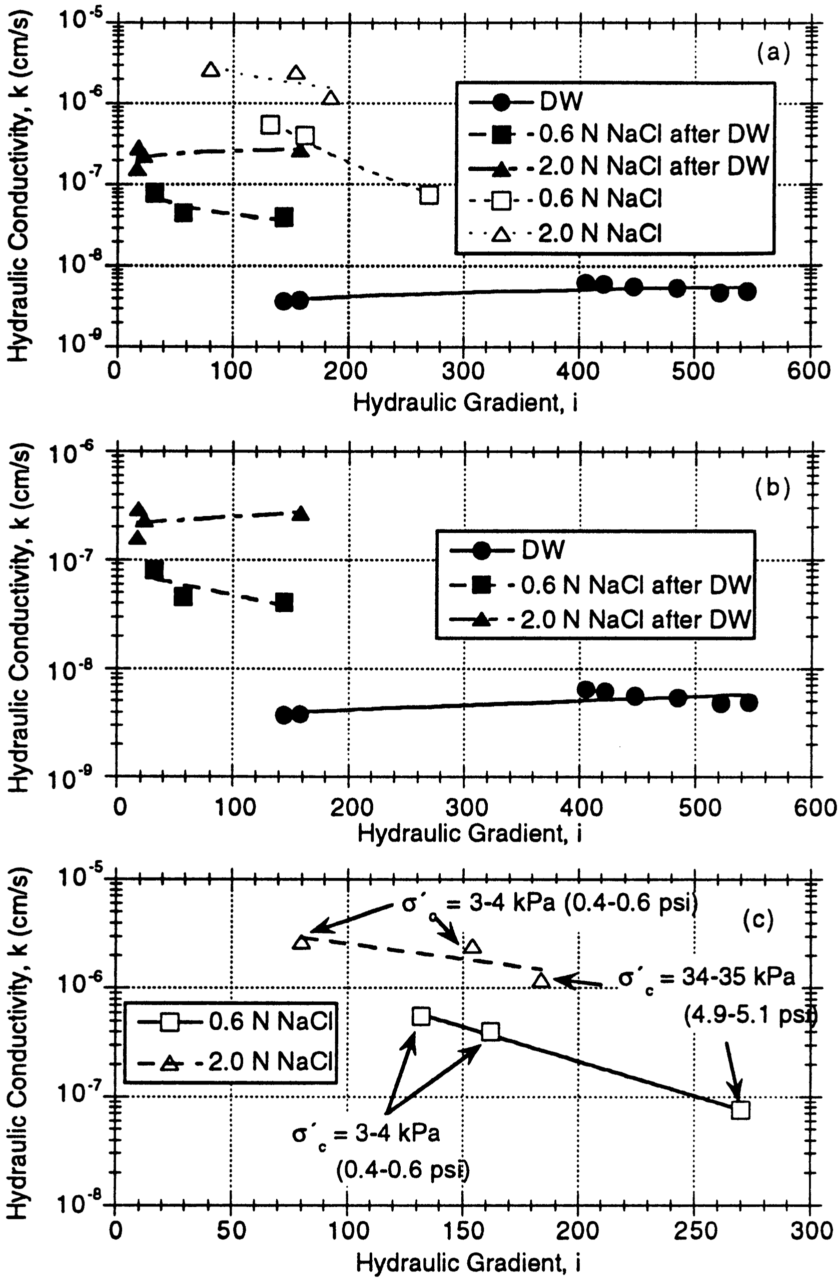

Figure 3 - Effect of hydraulic gradient on hydraulic conductivity of a needle-punched GCL based on data from Petrov et al. (1997a): (a) all test results; (b) test results based on common static confining stress, σ'_c, of 3-4 kPa (0.4-0.6 psi); (c) test results based on two different static confining stresses (DW = distilled water).

hydraulic gradients ($17 \leq i \leq 546$) for permeation with distilled water (DW) as well as permeation with 0.6 N NaCl or 2.0 N NaCl solutions both with and without prior permeation with DW.

As indicated in Fig. 3a, the overall effect of hydraulic gradient is relatively minor in all cases, with essentially no effect for permeation with either DW or 2.0 N NaCl after permeation with DW, a slight decrease in k (~ 2X) for permeation with either 2.0 N NaCl or 0.6 N NaCl after permeation with DW, and a somewhat greater effect (~7X) for permeation with 0.6 N NaCl. However, all of the tests involving permeation with DW were performed at a constant static confining stress (Fig. 3b), whereas the tests involving permeation solely with 0.6 N NaCl and 2.0 N NaCl solutions were performed at two different static confining stresses (Fig. 3c). Thus, part of the decrease in k for the tests involving permeation solely with 0.6 N NaCl and 2.0 N NaCl solutions can be attributed to an increase in static confining stress at the highest hydraulic gradient.

The effects of hydraulic gradient and stress on the hydraulic conductivity of a needle-punched GCL are compared in Fig. 4. As indicated in Fig. 4a, the hydraulic conductivity of a needle-punched GCL permeated with DW decreases by about one order of magnitude as the static confining stress increases from ~ 3 kPa (~0.4 psi) to ~ 117 kPa (~17 psi). This effect of increasing stress on hydraulic conductivity also is observed in Fig. 5 where the hydraulic conductivity of Claymax® GCL permeated with DW decreases by ~ 7X as the effective confining stress increases from 13.8 kPa (2 psi) to 138 kPa (20 psi). As indicated in Fig. 4b, the hydraulic conductivity of the needle-punched GCL permeated with DW also decreases by ~ an order of magnitude when considering the full range of hydraulic gradients, i, or $144 \leq i \leq 893$. However, the decrease is significantly less for $406 \leq i \leq \sim 590$, and actually increases for i in the range $\sim 590 \leq i \leq 893$. Thus, the hydraulic conductivity results for permeation of the needle-punched GCL with DW shown in Fig. 4 are significantly affected for $i < \sim 590$.

Relationship Between Hydraulic Gradient and Effective Stress

As indicated by the data in Figs. 3, 4, and 5, the hydraulic conductivity of GCLs tends to be more sensitive to effective or static confining stress than to the hydraulic gradient in the test, and

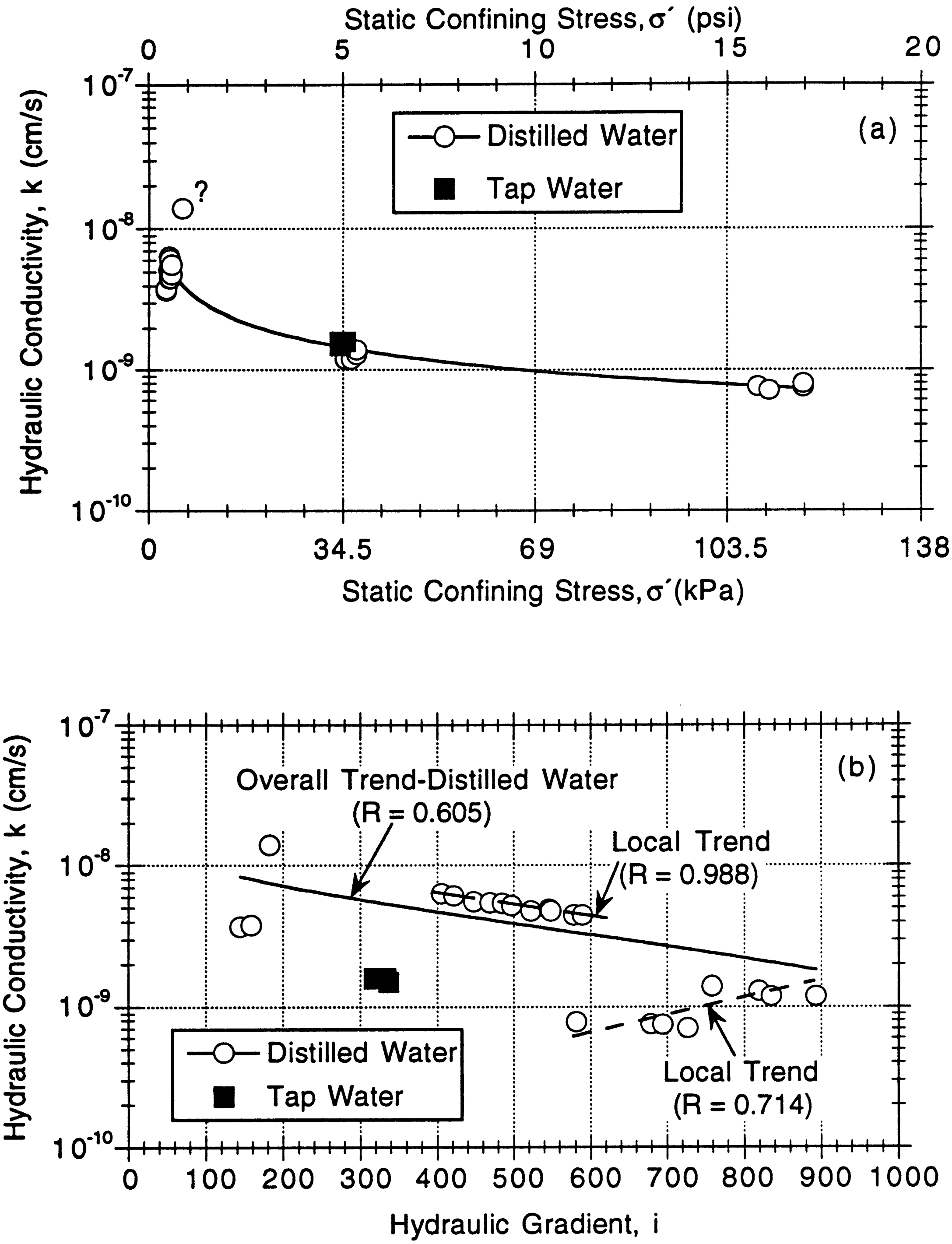

Figure 4 - Effect of (a) static confining stress and (b) hydraulic gradient for a needle-punched GCL permeated with water (data from Petrov et al. 1997b).

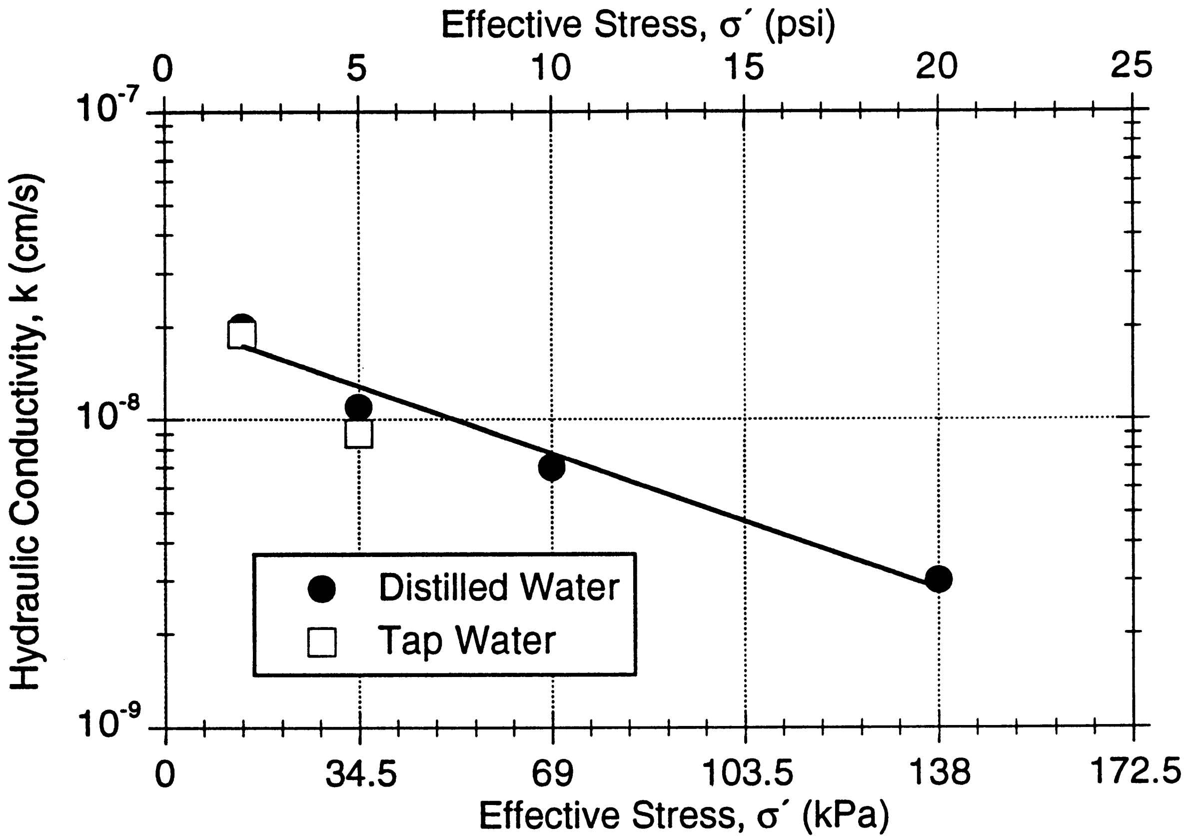

Figure 5- Effective of effective confining stress on hydraulic conductivity of Claymax® permeated with water (data from Shan and Daniel 1993).

relatively high hydraulic gradients (i.e., $50 \leq i \leq 590$) have very little effect on the hydraulic conductivity of the GCL. These observed trends can be explained, in part, by considering the relationship between hydraulic gradient and effective stress in the specimen.

For example, consider the relationship between the effective stress and hydraulic gradient resulting from permeating specimens under constant-head conditions using flexible-wall permeameters after back-pressure saturation and water as the permeant liquid. In addition, assume that the desire is to maintain an average effective stress in the specimen during permeation that is the same as the effective stress at the end of back-pressure saturation. As illustrated in Fig. 6, this condition can be achieved by simultaneously increasing the headwater pressure and decreasing the tailwater pressure by an equal amount to induce flow. In this case, the maximum and minimum effective stresses ($\sigma'_{max,min}$) in the specimen during permeation are given as follows:

$$\sigma'_{max,min} = \left(\sigma_{cell} - u_{bp}\right) \pm \Delta\sigma' = \sigma'_{bp} \pm \Delta\sigma' \quad (1)$$

where σ_{cell}, u_{bp}, and σ'_{bp} are the cell pressure, back pressure, and effective stress, respectively, existing at the end of the back-pressure saturation stage of the test, and $\Delta\sigma'$ is the maximum change in effective stress that, as indicated in Fig. 6, can be given by the following relationship:

$$\Delta\sigma' = \frac{\Delta u}{2} = \frac{i\gamma_{water}L}{2} = \frac{jL}{2} \quad (2)$$

where Δu is the change in pore water pressure across the specimen, i is the applied hydraulic gradient, γ_{water} is the unit weight of water, L is the length or thickness of the specimen, and j is the seepage force per unit volume of the specimen. Thus, in this case, the change in effective stress is directly proportional to the applied hydraulic gradient or seepage force.

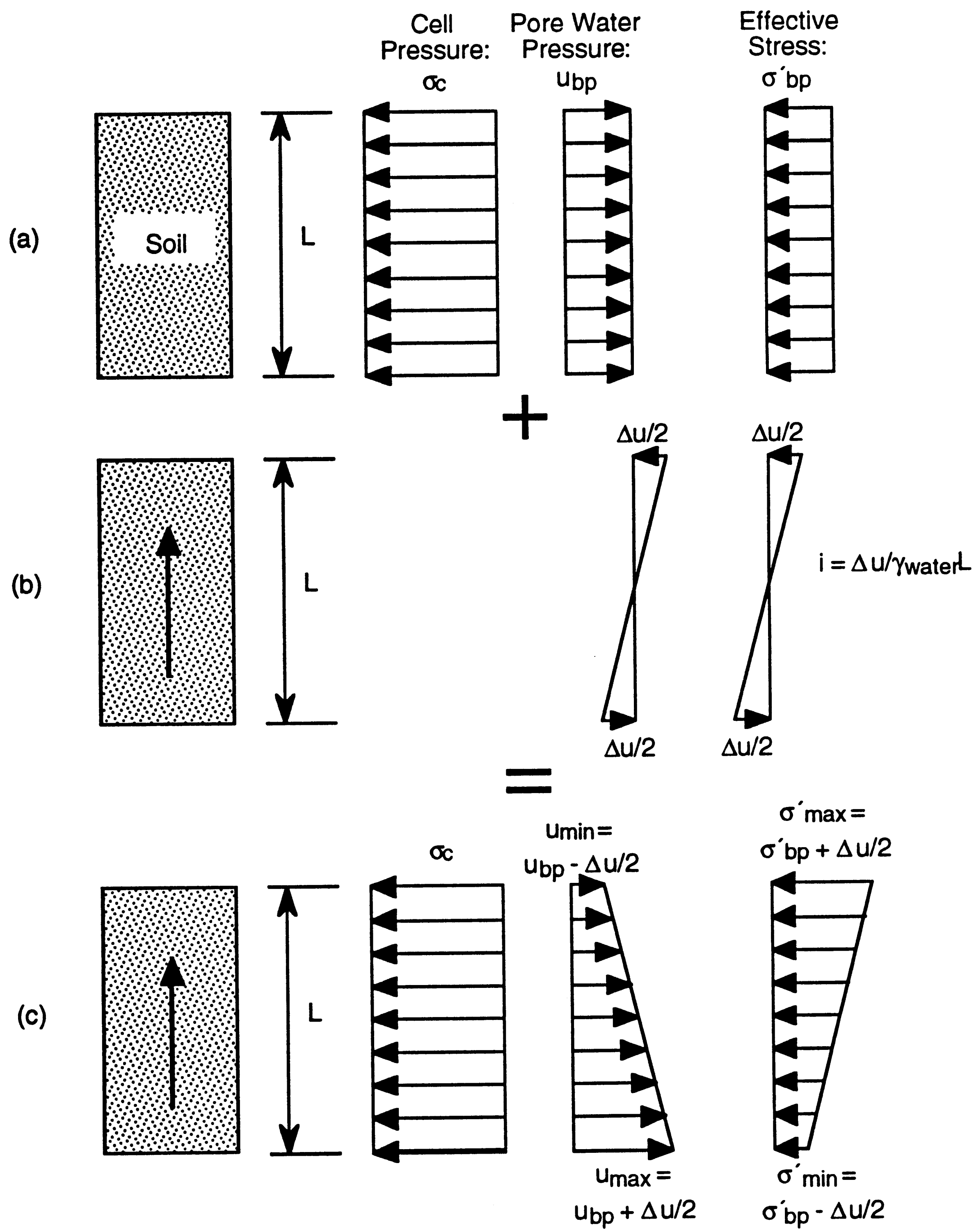

Figure 6 - Stress conditions for a constant-head hydraulic conductivity test: (a) back-pressure stage; (b) permeation stage; (c) stresses at steady-state flow.

Now consider two hydraulic conductivity tests performed in accordance with the procedure just described and illustrated in Fig. 6. One test is performed on a GCL specimen and the other test is performed on a specimen of the same bentonite that has been compacted in a Proctor mold (e.g., ASTM D 698). In order to minimize the potential effect of a change in effective stress resulting from the applied hydraulic gradient, the tests are to be performed such that the maximum change in effective stress in each specimen is the same. Thus, from Eq. 2,

$$\Delta\sigma' = \left(\frac{i\gamma_{water}L}{2}\right)_{PM} = \left(\frac{i\gamma_{water}L}{2}\right)_{GCL} \tag{3}$$

where the subscript PM stands for "Proctor mold". Equation 3 can be rearranged and solved for the equivalent hydraulic gradient for the GCL, i_{GCL}, as a function of the hydraulic gradient used for the compacted specimen, i_{PM}, the thickness of the compacted specimen, L_{PM}, and the thickness of the GCL, L_{GCL}, or

$$i_{GCL} = i_{PM}\left(\frac{L_{PM}}{L_{GCL}}\right) = i_{PM}\left(\frac{116.4\text{mm}}{L_{GCL}}\right) \tag{4}$$

Given that the maximum recommended hydraulic gradient for the compacted bentonite specimen (i.e., according to ASTM D 5084) is 30 based on the assumption that the hydraulic conductivity of the compacted bentonite will be $\leq 10^{-7}$ cm/s, Eq. 4 may be reduced further as follows:

$$i_{GCL} = \frac{(30)(116.4)}{L_{GCL}(\text{mm})} = \frac{3492}{L_{GCL}(\text{mm})} \tag{5}$$

Thus, the hydraulic gradient for the GCL required to provide the same maximum and minimum effective stresses as occur with the compacted (Proctor mold) bentonite specimen is inversely proportional to the thickness of the GCL.

The relationship given by Eq. 5 is plotted in Fig. 7 for typical GCL thicknesses ranging from 5 mm to 15 mm. As indicated in Fig. 7, GCL hydraulic gradients ranging from a low of ~230

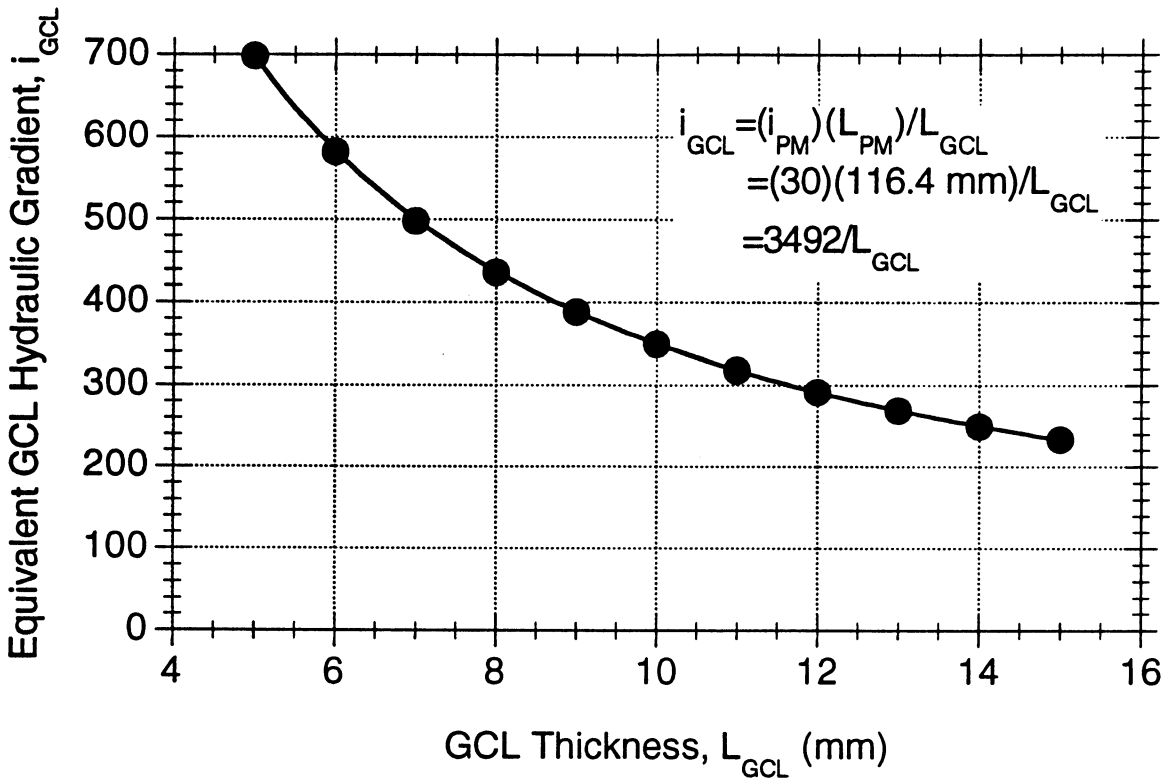

Figure 7 - Equivalent GCL hydraulic gradient as a function of GCL thickness required to maintain the same effective stress conditions as those imposed on a low-permeability ($k \leq 10^{-7}$ cm/s) soil specimens compacted in a Proctor mold (ASTM D 698) and permeated in accordance with ASTM D 5084 under constant-head conditions.

for a 15-mm-thick GCL to as high as ~ 700 for a 5-mm-thick specimen result in the same effective stress distribution as a Proctor mold specimen subjected to a much lower hydraulic gradient of 30. Alternatively, the application of the same hydraulic gradient for both the GCL and the Proctor mold specimen would result in significantly greater change in effective stresses in the Proctor mold specimen relative to the GCL due to the significantly greater thickness of the Proctor mold specimen relative to the GCL. Thus, while somewhat limited, the results of this analysis support the previously noted trends observed in the data presented in Figs. 3, 4, and 5, viz., the hydraulic conductivity of GCLs seems to be relatively insensitive to the use of relatively high hydraulic gradients, and the effective stress conditions imposed on the GCL during permeation tend to have a greater effect on the hydraulic conductivity of the specimen than does the hydraulic gradient.

Relationship between Laboratory and Field Hydraulic Gradients

While the effect of hydraulic gradient and associated stress conditions on the measurement of hydraulic conductivity is an important consideration in laboratory hydraulic conductivity testing, the use of laboratory hydraulic gradients that are representative of the field application also is important. In the context of the use of GCLs for hydraulic containment applications, the hydraulic gradient, i, is a function of the height of ponded liquid, h_p, thickness of the GCL, L, and the pressure head at the interface between the GCL and the foundation soil, h_w (< 0), as follows:

$$i = \frac{h_p + L - h_w}{L} = \frac{h_p}{L} + 1 - \frac{h_w}{L} \qquad (6)$$

where all the parameters are defined schematically in Fig. 8. As indicated by Eq. 6 in Fig. 8a, for a given h_w and L, the field hydraulic gradient increases linearly with an increase in h_p. In addition, the hydraulic gradient increases linearly with an decrease in h_w for a given L and h_p.

As a result of the thinness of GCLs, field hydraulic gradients for GCLs may be significantly higher than normally expected in the case of thicker compacted clay liners (CCLs)

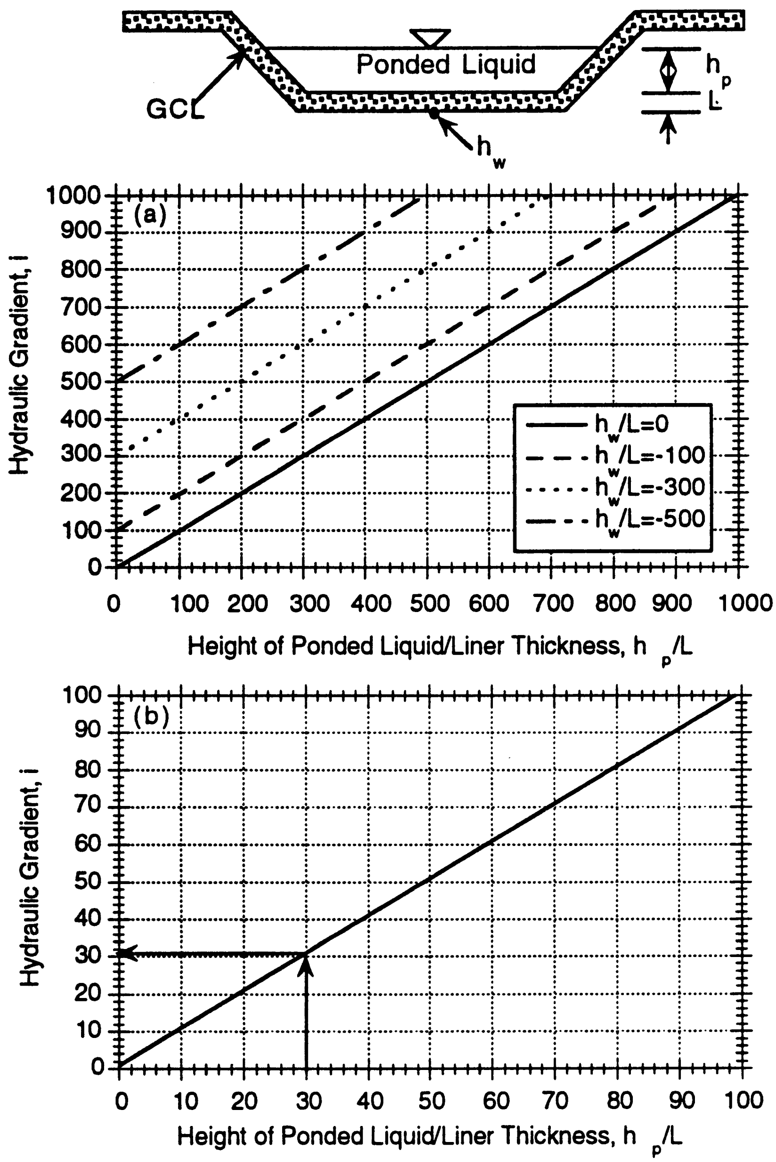

Figure 8 - Hydraulic gradient for steady-state flow through GCL as a function of the height of ponded liquid (h_p), thickness of GCL (L), and suction head at the bottom of the GCL (h_w): (a) relationship for several values of h_w; (b) limiting h_p/L for i = 30 and $h_w/L = 0$.

used for the same applications. For example, the maximum leachate head for CCLs used in municipal and hazardous facilities currently is restricted to ≤ 30 cm (≤ 12 in) by federal regulations. In the case of a 60-cm (2-ft)-thick CCL, this maximum leachate head corresponds to a minimum hydraulic gradient in the case of $h_w/L = 0$ of 1.5 in accordance with Eq. 6. However, in the case of a 10-mm-thick GCL, this same maximum leachate head results in a hydraulic gradient of 31 under the same conditions (Fig. 8b). Thus, the field hydraulic gradient for the GCL is ~ 15 times greater than that for the CCL under the same boundary conditions simply due to the thinness of the GCL. Thus, greater heights of ponded liquid in other hydraulic containment applications and/or negative pressure heads at the interface between the GCL and the foundation soil may result in field hydraulic gradients that are commensurate with the relatively high hydraulic gradients that commonly are used in laboratory hydraulic conductivity testing of GCLs.

TERMINATION CRITERIA

The typical criteria used to determine when a hydraulic conductivity test in which water is the permeant liquid can be terminated are as follows (Daniel 1994):

(1) rates of inflow and outflow for the test are reasonably equal;

(2) the measured hydraulic conductivity is steady; and

(3) sufficient measurements to ensure representative test results.

With respect to criterion (1), Daniel (1994) recommends that the outflow-to-inflow ratio (Q_{out}/Q_{in}) should be 1.0±0.1. However, for specimens with very low hydraulic conductivity values (i.e., $k < 10^{-8}$ cm/s), Q_{out}/Q_{in} values of 1.0±0.1 may be difficult to achieve for testing times less than several weeks. In such cases, Daniel (1994) recommends that Q_{out}/Q_{in} values of 1.0±0.25 be considered acceptable.

Criteria (2) and (3) usually are evaluated qualitatively from plots of hydraulic conductivity versus either time or pore volumes of flow. However, ASTM D 5084 requires a quantitative evaluation of steady k by requiring that four or more consecutive hydraulic conductivity values fall within ±25 % of the mean value for $k \geq 1 \times 10^{-8}$ cm/s or ±50 % for $k < 1 \times 10^{-8}$ cm/s.

In addition to the three termination criteria recommended by Daniel (1994) for permeating specimens with water, Daniel (1994) also recommends two additional termination criteria when permeating specimens with chemical solutions or waste liquids:

(4) a minimum of two pore volumes of flow should be permeated through the specimen to ensure that the remnant water in the specimen has been displaced by the permeant liquid, and

(5) permeation should not terminate until the chemical composition of the outflow is similar to that of the inflow.

In addition to these two criteria, Petrov et al. (1997a) also required that the height of the GCL be constant before terminating their tests performed on a needle-punched GCL.

Shackelford(1994) notes that in some cases, two pore volumes of flow may not be sufficient to establish chemical equilibrium between the outflow and the inflow, and cites data from a study by Bowders (1988) that indicated a sudden and significant increase (17X) in the hydraulic conductivity of a compacted specimen of kaolin permeated with acetic acid after more than six pore volumes of flow had occurred even though the hydraulic conductivity initially had stabilized at six pore volumes of flow. As a result, Shackelford (1994) recommends that the primary criterion for termination of tests involving permeation with chemicals or chemical solutions is establishment of chemical equilibrium between the outflow and the inflow regardless of the number of pore volumes of flow and the time required to establish hydraulic conductivity equilibrium.

One aspect associated with ensuring that chemical equilibrium between the outflow and inflow has been achieved is the relative difficulty, expense, and time associated with measuring the concentrations of all key chemical constituents inherent in the permeant liquid (e.g., Bowders 1988). However, in the case of inorganic chemical solutions, several investigators have used the electrical conductivity (EC) of both the outflow and the inflow as an indicator of chemical equilibrium presumably because the measurement of EC using an electrode and conductivity meter is relatively simple and inexpensive.

For example, Shackelford and Redmond (1995) plotted the relative electrical conductivity values representing the outflow electrical conductivity [EC(L,t)] divided by the inflow electrical conductivity (EC_0), or EC(L,t)/ECo, versus pore volumes of flow for permeation of a kaolin specimen with NaCl solutions. Shackelford and Redmond (1995) concluded that the trends in relative EC values were indicative more or less of the expected behavior of solute breakthrough curves, although no distinction between the contributions of nonreactive and reactive solutes (ions) to the overall EC of the outflow can be ascertained due to the requirement for electrical neutrality in solution. Petrov et al. (1997a) assessed the extent of chemical equilibrium in their hydraulic conductivity tests involving permeation of a needle-punched GCL with NaCl solutions by comparing outflow and inflow salinities that were determined indirectly via calibration of NaCl concentrations with EC measurements. Stern and Shackelford (1998) used relative electrical conductivity as a parameter for determining chemical equilibrium in their tests performed to evaluate the effect of calcium chloride ($CaCl_2$) solutions on the hydraulic conductivity of sand-clay mixtures, including sand-bentonite mixtures.

In addition to the EC, Shackelford (1994) recommends the measurement of pH of the outflow and inflow when performing compatibility tests involving soils. The measurement of pH is essential because (a) pH is a fundamental parameter that controls the equilibrium chemistry of inorganic solutions and, therefore, has a direct influence on the composition of the permeant liquid that ultimately influences changes in hydraulic conductivity of the soil, and (2) extremes in permeant liquid pH (e.g., pH $\leq$ 2), such as in the case of permeation with acidic solutions, can have a direct influence on the hydraulic conductivity of the soil through flocculation of the clay particles, dissolution of clay minerals (aluminosilicates), and/or dissolution of other minerals (e.g., $CaCO_3$) in the clay soil (Shackelford 1994).

Given the apparent importance of establishing chemical equilibrium before terminating a hydraulic conductivity test involving permeation with chemicals or waste liquids, the following questions arise with respect to compatibility testing of GCLs:

(1) "What is the correlation between pore volumes of flow and hydraulic conductivity of GCLs permeated with chemicals or chemical solutions?";

(2) "What is the correlation between pH and hydraulic conductivity with respect to permeation of GCLs with chemicals or chemical solutions?";

(3) "What is the relative importance of pH and pore volumes of flow in establishing chemical equilibrium with respect to permeation of GCLs with chemicals or chemical solutions?"; and

(4) "What is the basis for the use of electrical conductivity as a parameter for establishing chemical equilibrium with respect to permeation of GCLs with chemicals or chemical solutions?"

The remainder of this section of the review addresses these questions.

Correlation between Hydraulic Conductivity and Pore Volumes of Flow

Values for the ratio of the hydraulic conductivity based on permeation with a chemical solution ($k_{chemical}$) to the hydraulic conductivity based on permeation with water (k_{water}), or $k_{chemical}/k_{water}$, are plotted in Fig. 9 as a function of pore volumes of flow (PVF) for two different GCLs that were prehydrated by permeation with water before being permeated with several different permeant liquids. Although the effects of the different permeant liquids on the hydraulic conductivity of the GCLs have not been separated from the effect of PVF, there is a trend of increasing $k_{chemical}/k_{water}$ with increasing PVF, with $k_{chemical}/k_{water}$ typically ≤ 2 when PVF ≤ 6. Shan and Daniel (1991) and Ruhl and Daniel (1997) noted that chemical equilibrium upon permeation with the chemical solution in these tests generally was not achieved because exceptionally long test durations (months to years) would have been required due to the initially low k_{water} values. As a result, Shan and Daniel (1991) and Ruhl and Daniel (1997) indicated that, in many cases, the higher $k_{chemical}$ values could be expected upon establishment of chemical

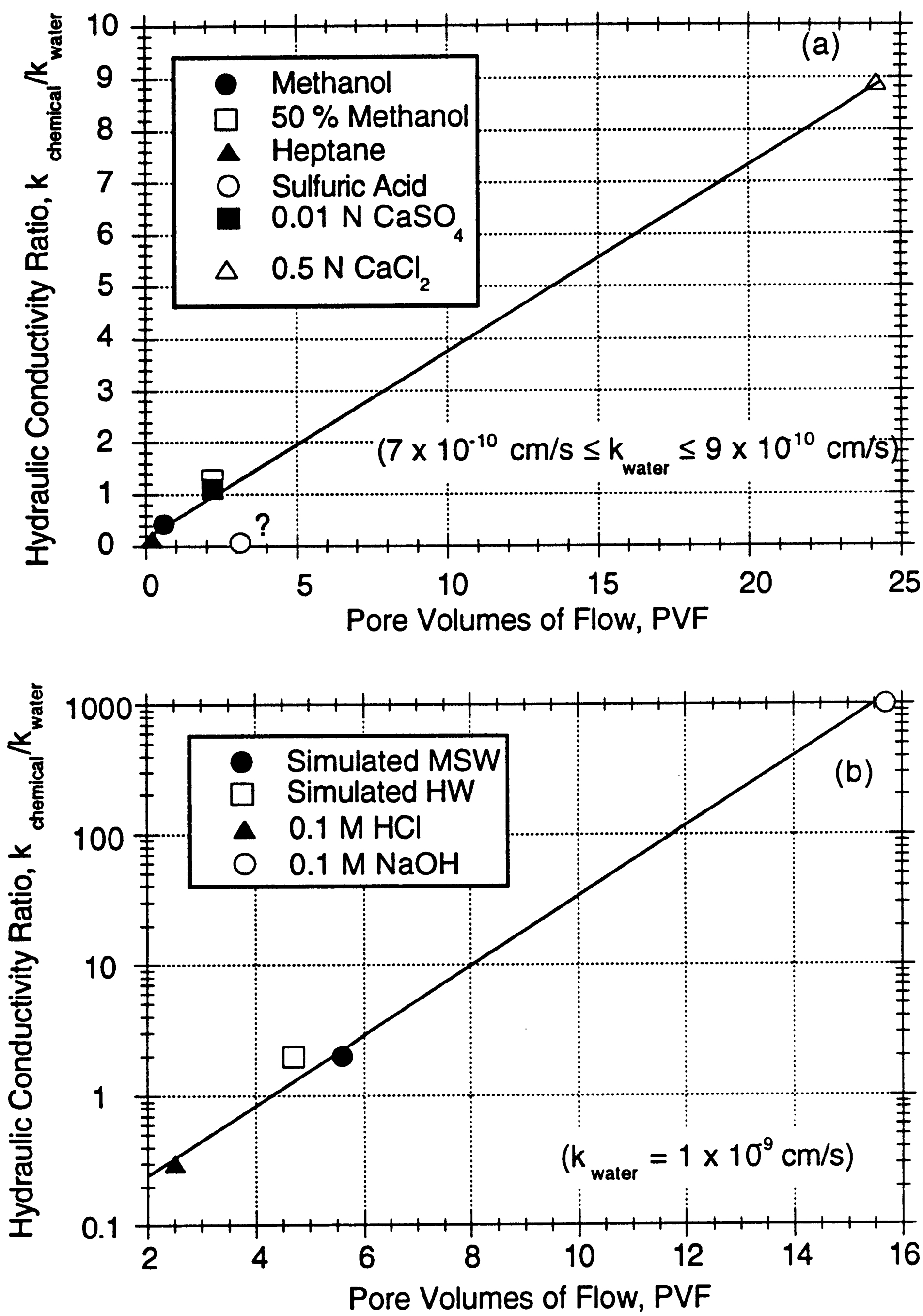

Figure 9 - Hydraulic conductivity ratio as a function of pore volumes of flow for GCLs prehydrated by permeation with water: (a) data from Shan and Daniel (1991) for Claymax®; (b) data from Ruhl and Daniel (1997) for regular Gundseal® (MSW = Municipal Solid Waste; HW = Hazardous Waste).

equilibrium. Nonetheless, the data in Fig. 9 suggest that exceptionally long test durations corresponding to PVF well in excess of those typically assumed to apply may be required before the full effects of the permeant liquid on the hydraulic conductivity of the GCL are observed. This statement is consistent with similar observations made by Petrov et al. (1997a).

The potential effect of prehydration on the number of PVF required to observe the full effect of the permeant liquid for the data reported by Ruhl and Daniel (1997) for regular and contaminant resistant (CR-) Gundseal® is illustrated in Fig. 10. For the non-prehydrated specimens, $k_{chemical}/k_{water} > 100$ in 6 out of the 8 tests, whereas in 7 out of 8 tests involving prehydrated specimens, $k_{chemical}/k_{water} < 2$. Thus, prehydration apparently has a significant effect on the final hydraulic conductivity of the GCL based on permeation with the chemical solution. In addition, more than 7 pore volumes of flow were reported for 7 of the 8 tests involving permeation of non-prehydrated specimens, whereas less than 7 pore volumes of flow were reported for 6 of the 8 tests involving permeation of prehydrated specimens. This difference in pore volumes of flow between non-prehydrated and prehydrated specimens again can be attributed, in part, to the establishment of relatively low k_{water} values in the prehydrated specimens resulting in failure to achieve chemical equilibrium upon subsequent permeation with the chemical solutions due to the requirement for exceptionally long test durations. Thus, the data in Figs. 9 and 10 tend to support the contention of Bowders (1988) and Shackelford (1994) that establishment of chemical equilibrium is more critical in terms of observing the full effect of the permeant liquid on the hydraulic conductivity of GCLs than is adherence to an arbitrarily established minimum number of pore volumes of flow.

Correlation between Hydraulic Conductivity and pH Equilibrium

Plots of inflow pH (pH_{in}) versus outflow pH (pH_{out}) for several different GCLs and test conditions are shown in Figs. 11-16. The data in Figs. 11-16 represent results obtained using 5 different permeant liquids (Ruhl 1994, Ruhl and Daniel 1997): (1) 0.1 M HCl ($pH_{in} = 1$), (2) a simulated hazardous waste ($pH_{in} = 3$), (3) a simulated municipal hazardous waste ($pH_{in} = 4.4$),

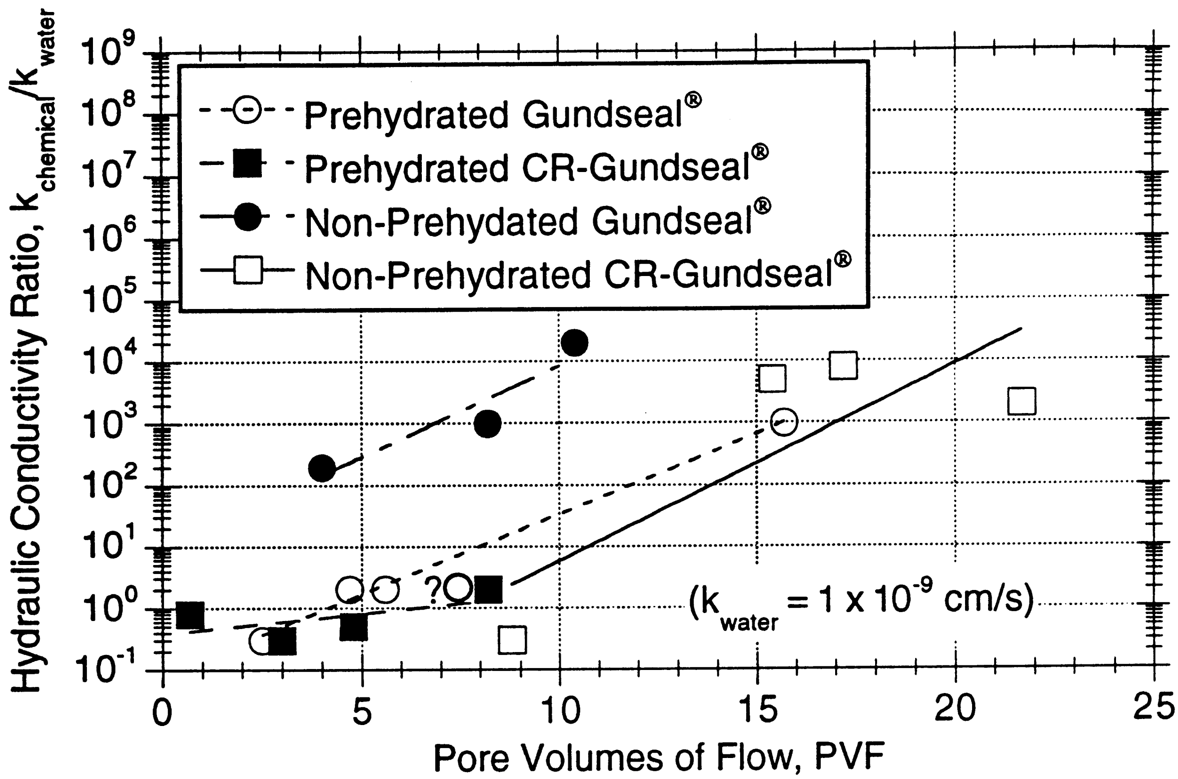

Figure 10 - Effect of prehydration on hydraulic conductivity ratio versus pore volumes for Gundseal® and contaminant resistant Gundseal® (data from Ruhl and Daniel 1997).

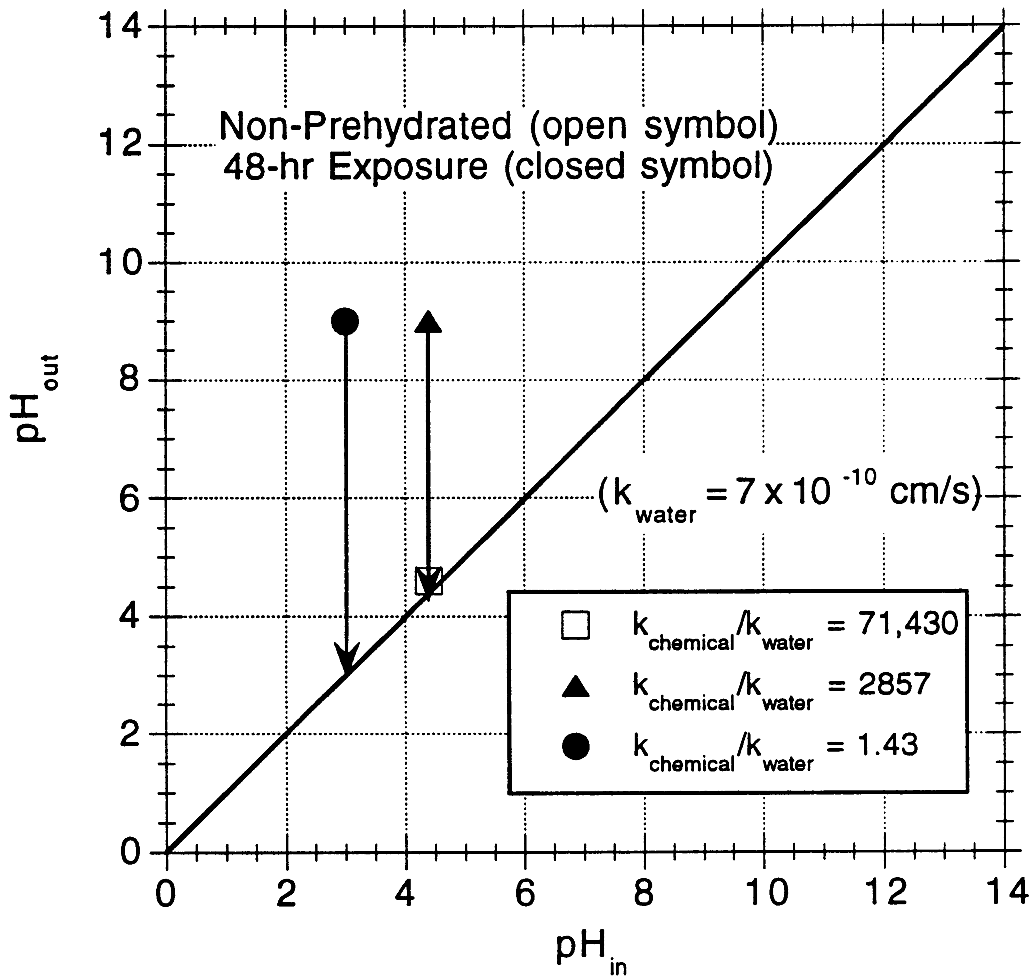

Figure 11 - Inflow pH (pH_{in}) versus outflow pH (pH_{out}) for permeation of Bentofix® with different permeant liquids (data from Ruhl 1994, and Ruhl and Daniel 1997).

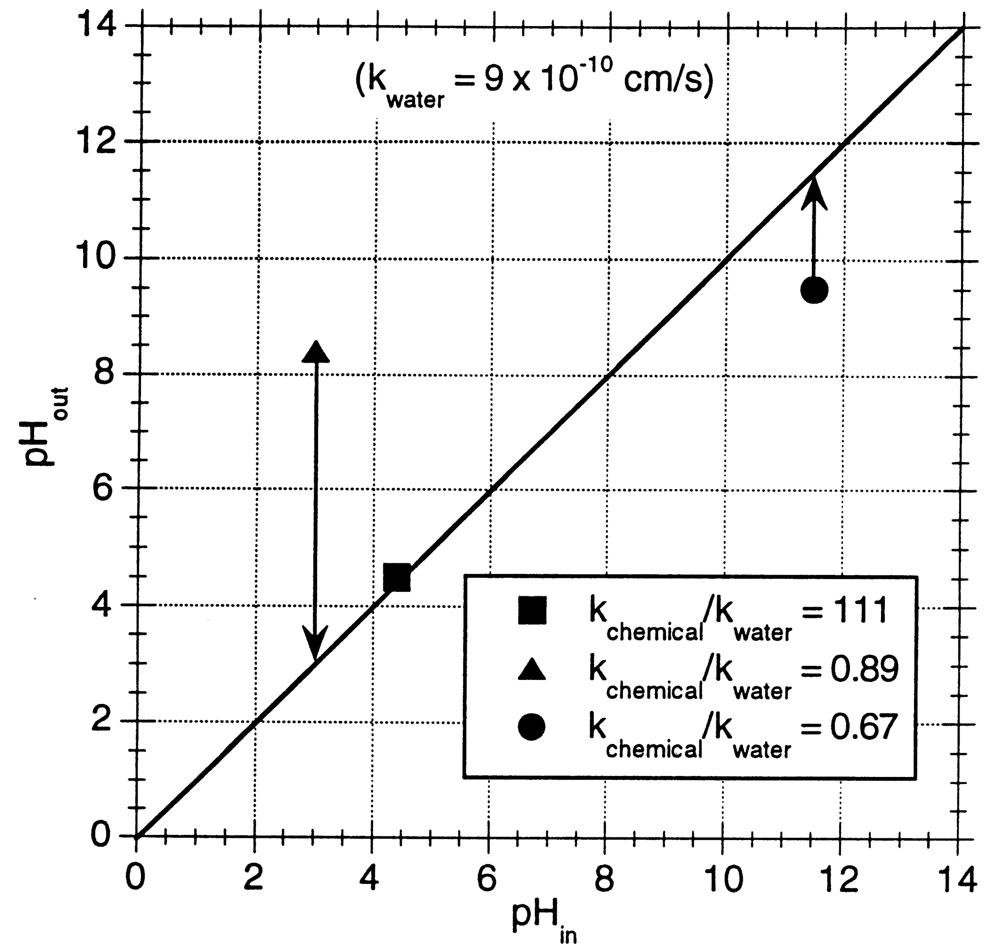

Figure 12 - Inflow pH (pH_{in}) versus outflow pH (pH_{out}) for permeation of Bentomat® specimens exposed to the permeant liquid for 48 hours before permeation (data from Ruhl 1994, and Ruhl and Daniel 1997).

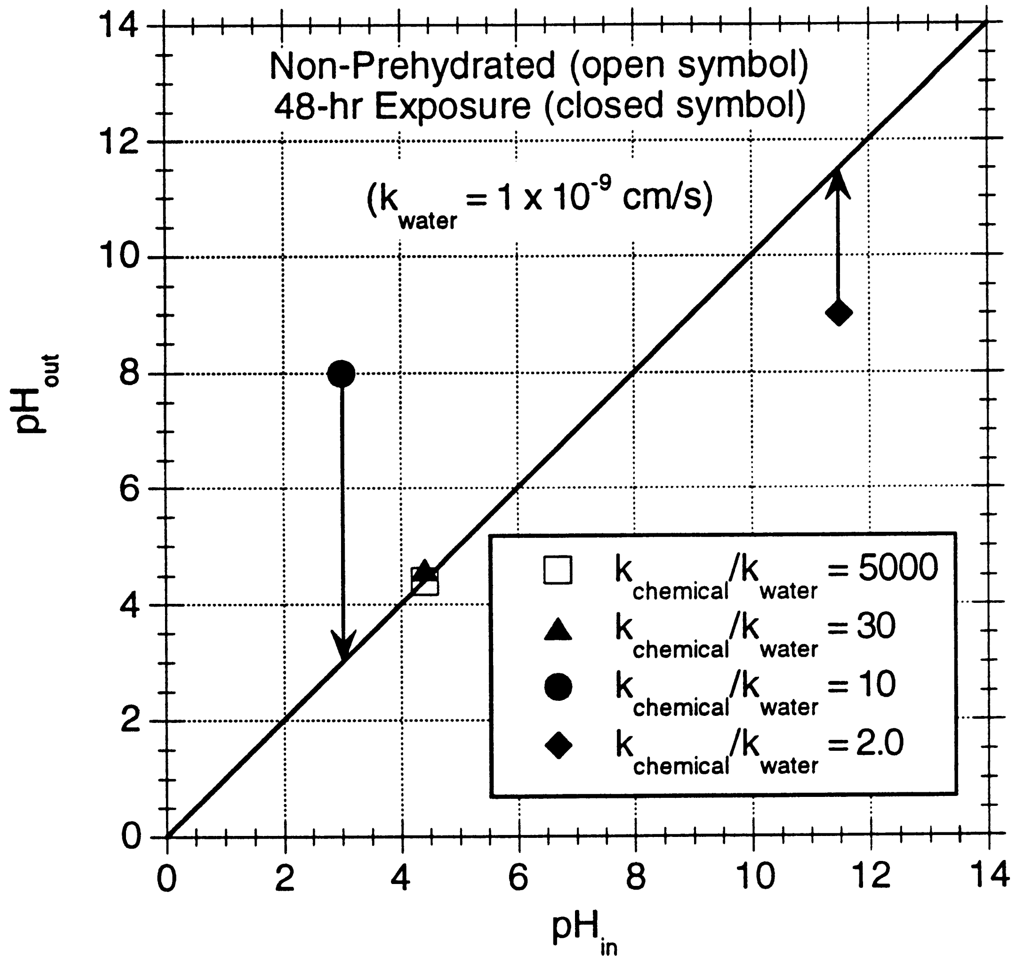

Figure 13 - Inflow pH (pH_{in}) versus outflow pH (pH_{out}) for permeation of Claymax® with different permeant liquids (data from Ruhl 1994, and Ruhl and Daniel 1997).

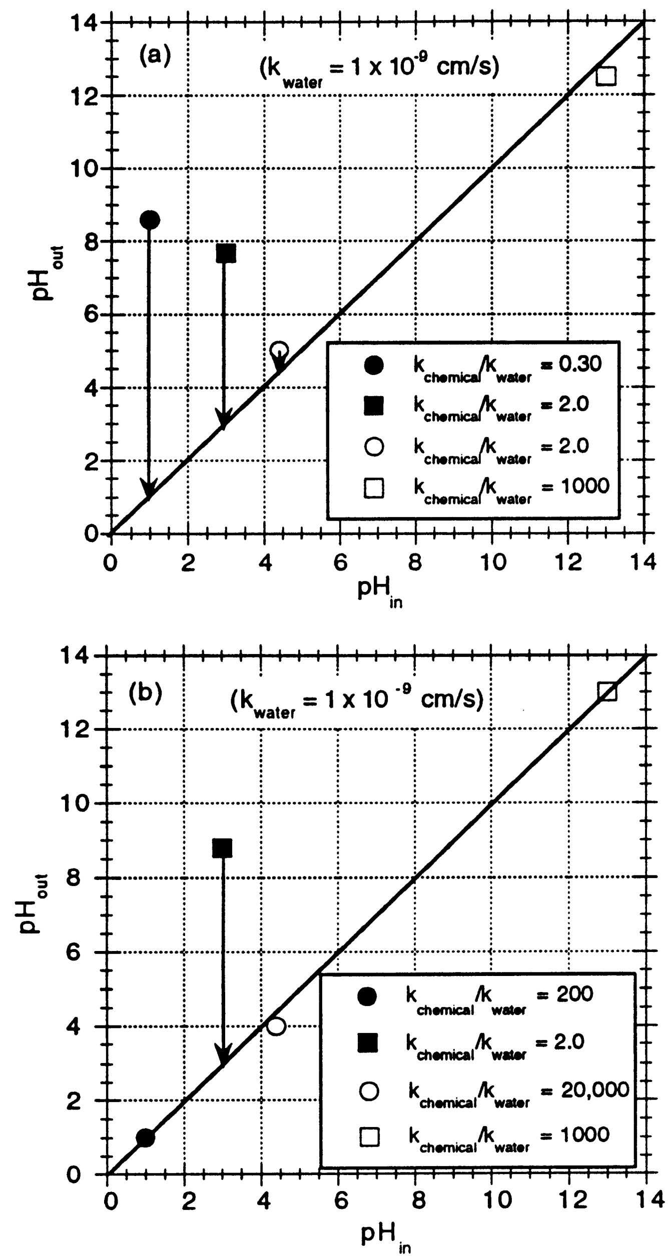

Figure 14 - Inflow pH (pH_{in}) versus outflow pH (pH_{out}) for permeation of Gundseal® with different permeant liquids: (a) prehydrated specimens; (b) non-prehydrated specimens (data from Ruhl 1994, and Ruhl and Daniel 1997).

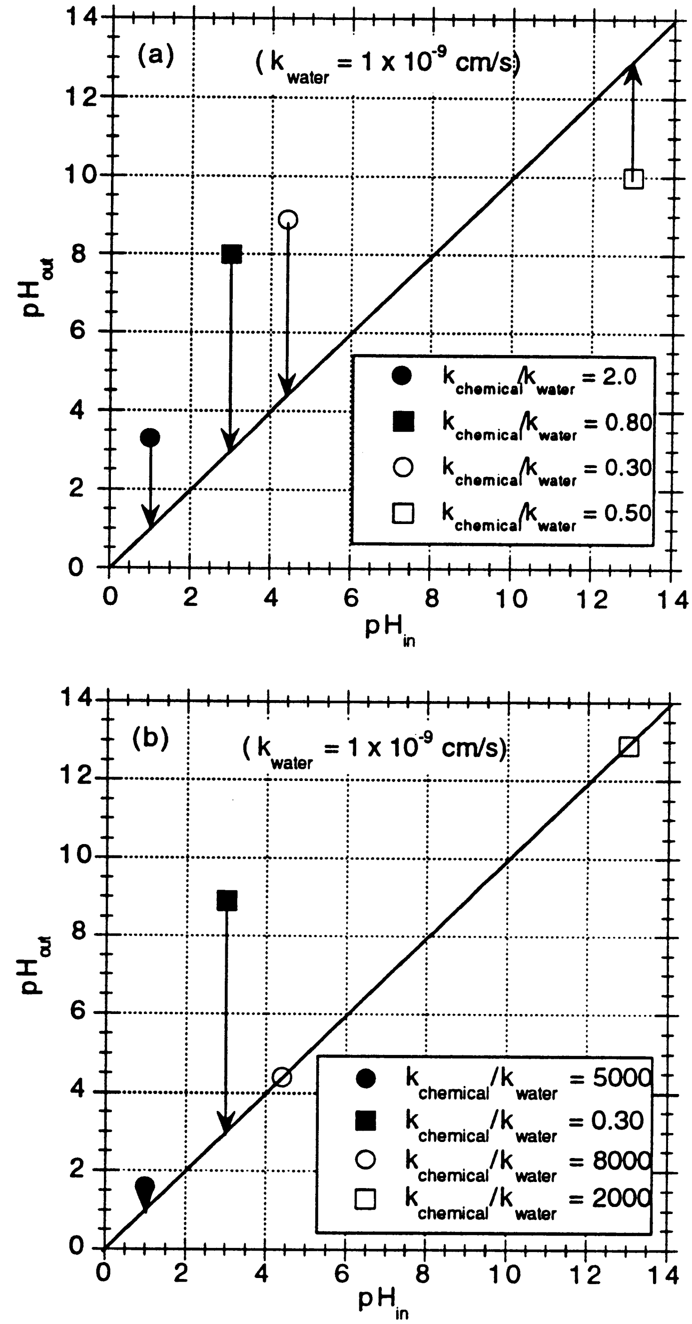

Figure 15 - Inflow pH (pH_{in}) versus outflow pH (pH_{out}) for permeation of contaminant resistant Gundseal® with different permeant liquids: (a) prehydrated specimens; (b) non-prehydrated specimens (data from Ruhl 1994, and Ruhl and Daniel 1997).

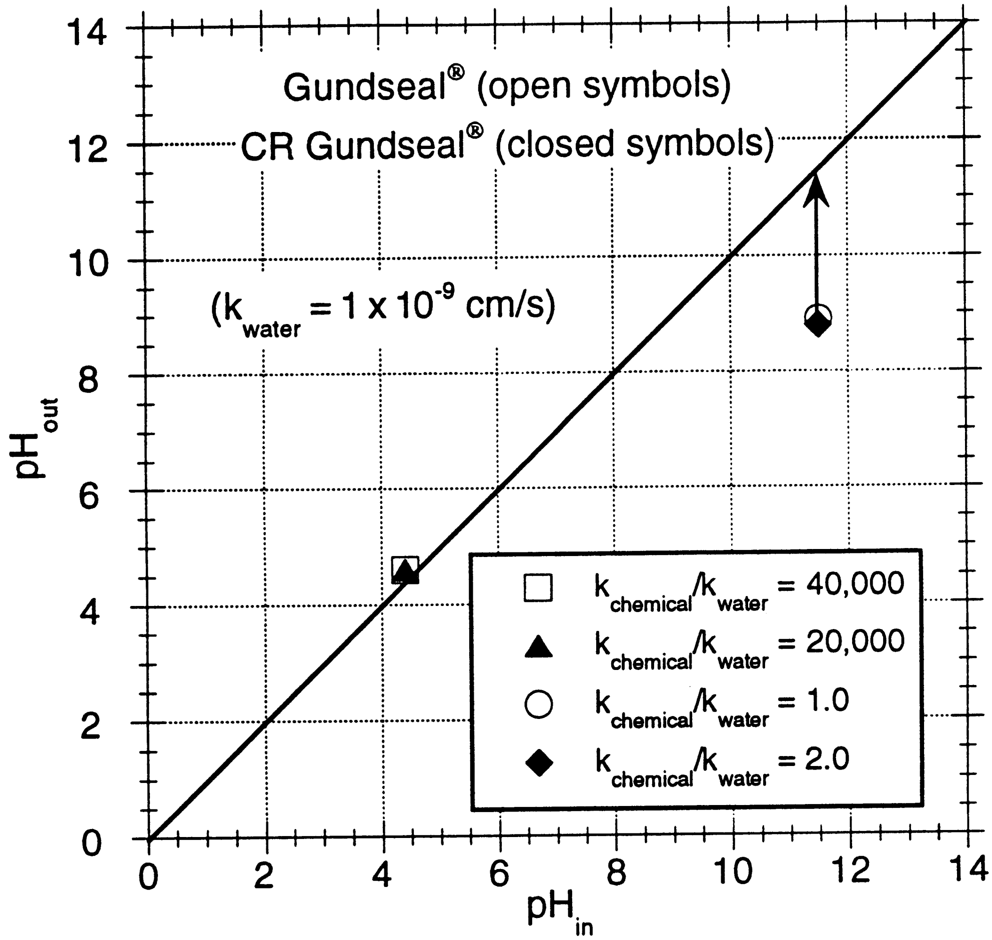

Figure 16 - Inflow pH (pH_{in}) versus outflow pH (pH_{out}) for permeation of non-prehydrated Gundseal® and contaminant resistant (CR) Gundseal® GCL specimens exposed to different permeant liquids for a 48-hour period before permeation (data from Ruhl 1994, and Ruhl and Daniel 1997).

(4) a simulated fly ash leachate (pH_{in} = 11.5), and (5) 0.1 M NaOH (pH_{in} = 13). The arrows shown in Figs. 11-16 indicate the direction and extent of change in pH_{out} required to achieve chemical equilibrium with respect to pH_{in}, and are shown only for tests where the final pH_{out} was not within 10 percent of pH_{in} (i.e., $pH_{out}/pH_{in} = 1.0 \pm 0.1$) indicating the pH equilibrium had not been established before the test was terminated.

An overview of all of the data presented in Figs. 11-16 indicates that $k_{chemical}/k_{water}$ ranges from 30 to 71,430 in all tests where $pH_{out}/pH_{in} = 1.0 \pm 0.1$, whereas $k_{chemical}/k_{water} \leq 2.0$ in 15 of 18 tests where pH equilibrium has not been established (i.e., $pH_{out}/pH_{in} \neq 1.0 \pm 0.1$). In the three tests where $pH_{out}/pH_{in} \neq 1.0 \pm 0.1$, $k_{chemical}/k_{water}$ values of 10, 2857, and 5000 were observed indicating that significant incompatibility between the permeant liquids and the GCLs had been observed before pH equilibrium was established. Thus, a strong correlation between the establishment of pH equilibrium and the measurement of high $k_{chemical}$ values relative to k_{water} values is apparent regardless of GCL type or test conditions. On the contrary, failure to establish pH equilibrium typically results in the measurement of low $k_{chemical}$ values relative to k_{water} values regardless of GCL type or test conditions.

Another interesting aspect of the data shown in Figs. 11-16 is that the majority of prehydrated GCL specimens (7 of 8) were not permeated until pH equilibrium was achieved, whereas the majority of non-prehydrated specimens (7 of 10) were permeated until pH equilibrium was achieved. However, only 5 of 12 GCL specimens that were exposed to the permeant liquid for 48 hours prior to permeation (i.e., 48-hour exposed specimens) without prehydration were permeated until pH equilibrium was achieved.

The potential importance of these trends becomes apparent in Fig. 17 where the data in Figs. 11 - 16 are plotted as $k_{chemical}/k_{water}$ values versus pH_{out}/pH_{in} values in terms of each of the three categories of specimen preparation. As shown in Fig. 17, all of the specimens that were permeated until pH equilibrium was achieved indicated significant incompatibility with the permeant liquid (i.e., $k_{chemical}/k_{water} > 30$), whereas none of the prehydrated GCL specimens

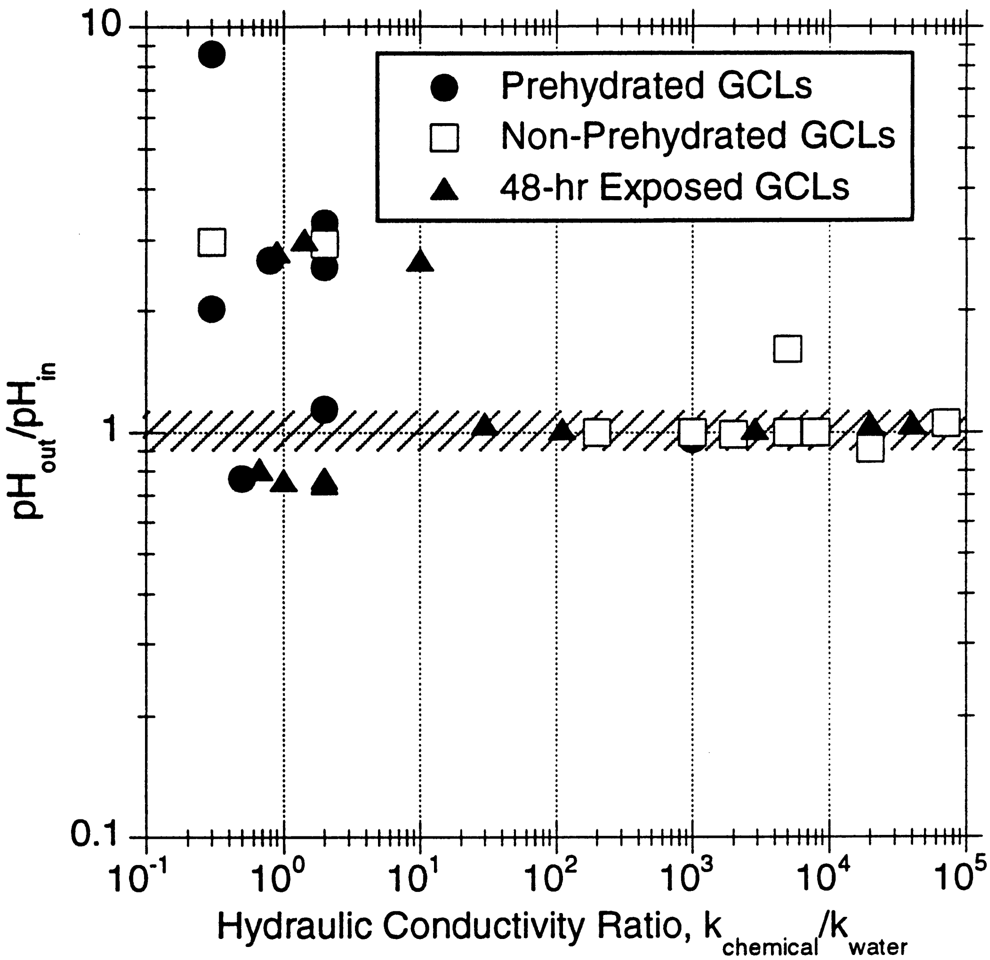

Figure 17 - Correlation between hydraulic conductivity ratio and pH ratio for different GCLs permeated with different liquids (data from Ruhl 1994, and Ruhl and Daniel 1997).

indicated significant incompatibility with the permeant liquid. Thus, the inability to permeate prehydrated specimens until pH equilibrium was established apparently resulted in the measurement of unrepresentative final hydraulic conductivity ($k_{chemical}$) values. This conclusion is consistent with statements made by Ruhl and Daniel (1997).

CORRELATION BETWEEN PH EQUILIBRIUM AND PORE VOLUMES OF FLOW

The pH_{out}/pH_{in} values for the data in Figs. 11-17 are plotted as a function of pore volumes of flow in Fig. 18 in terms of each of the three categories of specimen preparation previously described. Although significant scatter is apparent in the data in Fig. 18, GCLs that either were prehydrated prior to permeation with the chemical solution or were exposed to the permeant liquid prior to permeation with the permeant liquid typically would have required significantly greater numbers of PVF to establish pH equilibrium than were required in the case where the GCL was permeated directly with the permeant liquid.

APPLICABILITY OF ELECTRICAL CONDUCTIVITY (EC)

Fundamental Basis for Use of EC

The electrical conductivity (EC), or specific conductance (κ), of a solution is a measure of the ability of the solution to carry an electrical current, and varies both with the number and type of ions present in the solution (Sawyer and McCarty 1978). As a result, EC measurements frequently are used in water analysis to obtain a rapid estimate of the dissolved solids content of a water sample through the use of an EC electrode and conductivity meter. This ability of EC to provide a rapid estimate of dissolved solids content also can be used as a basis for evaluating the breakthrough of ions contained in the permeant liquid during compatibility testing.

For example, consider the simple case where a calcium chloride ($CaCl_2$) solution is permeated through a GCL that contains a sodium (Na) saturated bentonite. In this case, the Ca^{2+} cations resulting from dissolution of $CaCl_{2(s)}$ will exchange during permeation with the Na^+ ions that are held electrostatically to the clay minerals (e.g., montmorillonite) comprising the bentonite

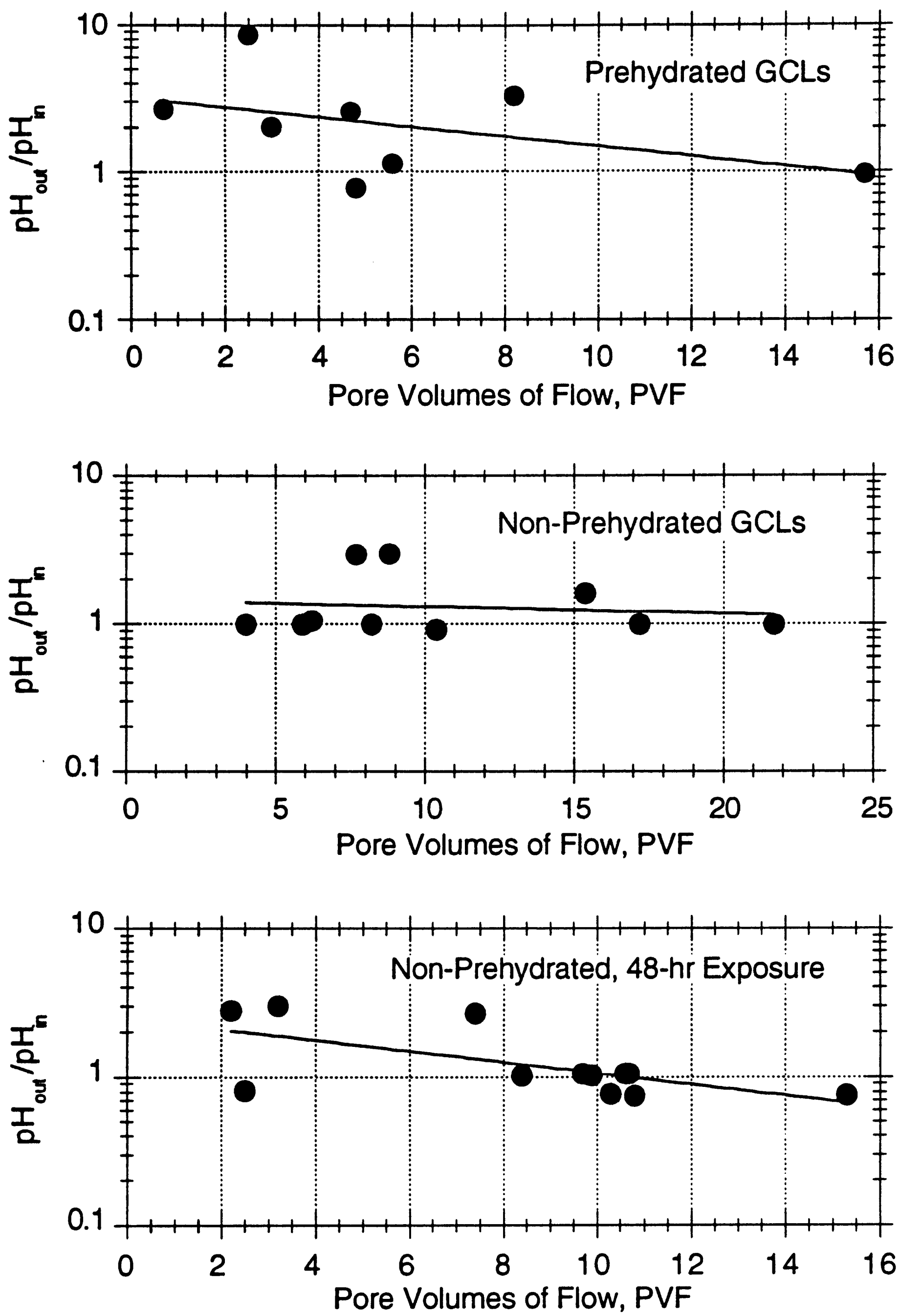

Figure 18 - Correlation between the pore volumes of flow and the ratio of the outflow-to-inflow pH for permeation of several GCLs with several permeant liquids (data from Ruhl and Daniel 1997).

particles. In accordance with the requirement for electroneutrality of the exchange complex of the bentonite as well as electroneutrality in solution, an equal number of equivalents of Ca^{2+} and Na^{+} will exchange. Thus, the outflow solution will consist of chloride (Cl^{-}) anions as well as a mixture of Ca^{2+} and Na^{+} ions that will satisfy the following relationship for electroneutrality in solution:

$$c^{-} = c_1^{+} + c_2^{+} \tag{7}$$

where c^{-}, c_1^{+}, and c_2^{+} represent the Cl^{-}, Ca^{2+}, and Na^{+} concentrations in terms of normality (equivalents/liter) in the outflow solution at any time. Each of these ions carries current such that the electrical conductivity at any time at the effluent end of the GCL of thickness L, or EC(L,t), is given as follows:

$$EC(L,t) = EC^{-}(L,t) + EC_1^{+}(L,t) + EC_2^{+}(L,t) \tag{8}$$

where $EC^{-}(L,t)$, $EC_1^{+}(L,t)$, and $EC_2^{+}(L,t)$ are the contributions of EC attributed to the Cl^{-}, Ca^{2+}, and Na^{+} ions, respectively. For the assumption of infinite dilution, Eq. 8 may be written as follows:

$$EC(L,t) = \lambda_o^{-} c^{-}(L,t) + \lambda_{o1}^{+} c_1^{+}(L,t) + \lambda_{o2}^{+} c_2^{+}(L,t) \tag{9}$$

where λ_o^{-}, λ_{o1}^{+}, and λ_{o2}^{+} represent the *equivalent ionic conductivities* for Cl^{-}, Ca^{2+}, and Na^{+} ions, respectively. The values for equivalent ionic conductivities for several different ions are given in Table 1. Substitution of Eq. 7 for c_2^{+} in Eq. 9 results in the following expression for the electrical conductivity in the outflow solution:

$$EC(L,t) = \left(\lambda_o^{-} + \lambda_{o2}^{+}\right) c^{-}(L,t) + \left(\lambda_{o1}^{+} - \lambda_{o2}^{+}\right) c_1^{+}(L,t) \tag{10}$$

Table 1 - Equivalent ionic conductivities at infinite dilution (λ_0) in aqueous solutions at 25°C (modified after Sawyer and McCarty 1978, and Bard and Faulkner 1980).

Anions		Cations	
Ion	λ_o^- (S-cm²/equivalent)	Ion	λ_o^+ (S-cm²/equivalent)
OH^-	198.0	H^+	349.82
$0.5SO_4^{2-}$	79.8	K^+	73.52
Br^-	78.4	NH_4^+	73.4
I^-	76.85	$0.5Ca^{2+}$	59.50
Cl^-	76.34	Na^+	50.11
NO_3^-	71.44	Li^+	38.69
HCO_3^-	44.48		
OAc^-	40.9		

The outflow electrical conductivity given by Eq. 10 may be normalized with respect to the inflow electrical conductivity, EC_o, for the calcium chloride solution which may be represented as follows:

$$EC_o = \Lambda_o c_o \qquad (11)$$

where Λ_o is the *equivalent conductance* given as follows:

$$\Lambda_o = \lambda_o^- + \lambda_{o1}^+ \qquad (12)$$

and c_o is the normality of the calcium chloride solution since both the inflow chloride and calcium concentrations are equal when expressed in normality (i.e., equivalents/liter), or

$$c_o = c_o^- = c_{o1}^+ \qquad (13)$$

where c_o^- is the initial chloride concentration in the permeant liquid and c_{o1}^+ is the initial calcium concentration in the permeant liquid. Thus, the relative electrical conductivity in the outflow solution is given as follows:

$$\frac{EC(L,t)}{EC_o} = \frac{EC^-(L,t) + EC_1^+(L,t) + EC_2^+(L,t)}{EC_o} \qquad (14)$$

or, after substitution of Eqs. 10 and 11 into Eq. 14, by

$$\frac{EC(L,t)}{EC_o} = \frac{\left(\lambda_o^- + \lambda_{o2}^+\right)c^-(L,t) + \left(\lambda_{o1}^+ - \lambda_{o2}^+\right)c_1^+(L,t)}{\Lambda_o c_o} \qquad (15)$$

Equation 15 also may be written in terms of the chloride and calcium relative concentrations as follows:

$$\frac{EC(L,t)}{EC_o} = \left(\frac{\lambda_o^- + \lambda_{o2}^+}{\Lambda_o}\right)\left(\frac{c^-(L,t)}{c_o}\right) + \left(\frac{\lambda_{o1}^+ - \lambda_{o2}^+}{\Lambda_o}\right)\left(\frac{c_1^+(L,t)}{c_o}\right) \tag{16}$$

Thus, as indicated by Eq. 16, the relative electrical conductivity in the outflow solution, or EC breakthrough curve (BTC), essentially represents weighted contributions from the chloride and calcium ion BTCs appearing in the outflow solution that have been corrected for the existence of the exchanged sodium resulting from the requirement to maintain electrical neutrality in the solution.

An example of an EC BTC based on Eq. 16 for permeation of a GCL containing a sodium-saturated bentonite with a calcium chloride solution is shown in Fig. 19. The parameter values required to perform the solute transport analysis are shown in Fig. 19. These values are considered to be within the range of values commonly reported for GCL compatibility testing. Also, retardation factors of 1.0 and 3.0 were assumed for Cl^- and Ca^{2+}, respectively, in performing the solute transport analysis. Three observations are apparent from the curves shown in Fig. 19.

First, the electrical conductivity (EC) breakthrough curve (BTC) is very close to the BTC for chloride. An EC BTC that is more intermediate between the chloride and calcium BTCs would have resulted had the effect of exchanged sodium not been included in the analysis. Second, although three different ionic species (Cl^-, Ca^{2+}, and Na^+) contribute to EC(L,t) in accordance with Eq. 8, whereas only two ionic species (Cl^-, Ca^{2+}) contribute to EC_o (Eqs. 11 and 12), complete breakthrough of electrical conductivity still is not achieved until both of the inflow ionic species also have reached complete breakthrough due to the requirement for electroneutrality in solution. Thus, the establishment of EC breakthrough in this case reflects exactly the establishment of chemical breakthrough. Third, the BTCs for Cl^-, Ca^{2+}, and EC exhibit extended tailing that is characteristic of diffusion-dominated transport even though a relatively high hydraulic gradient (i =

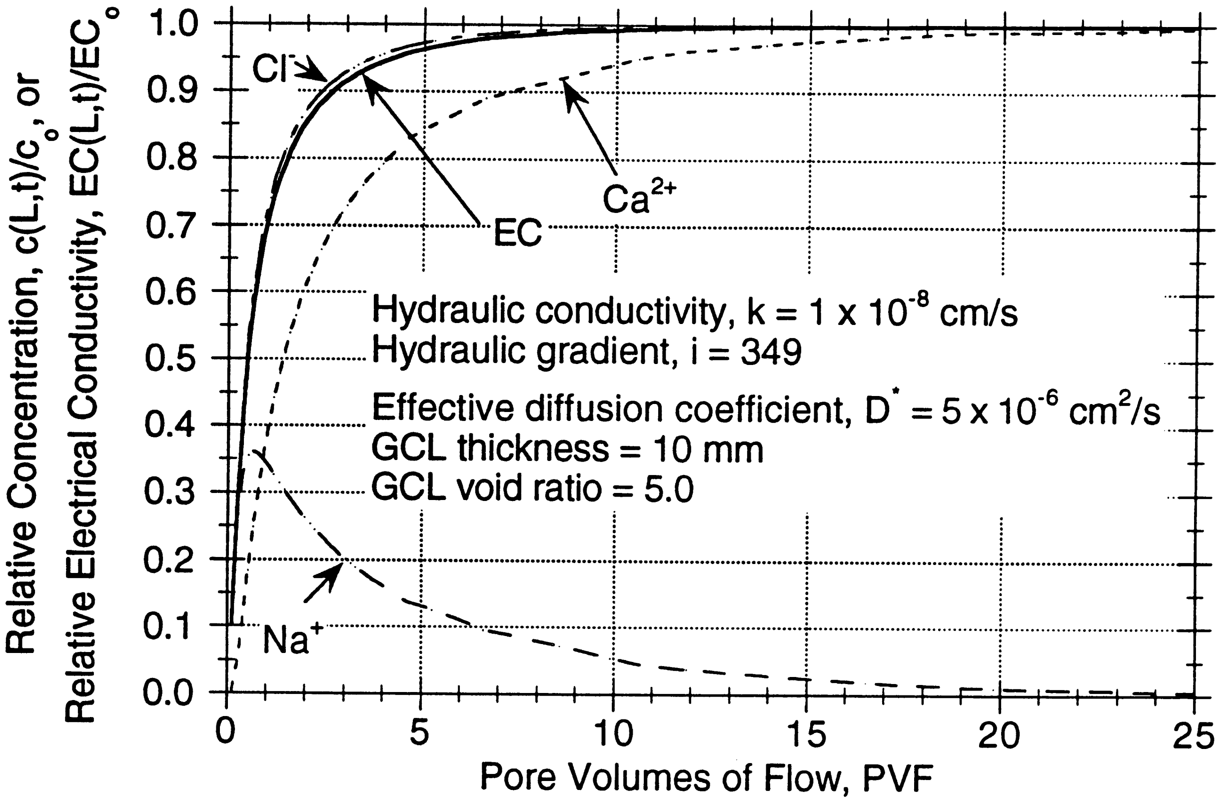

Figure 19 - Example of the relative electrical conductivity breakthrough curve associated with Ca^{2+} and Cl^- transport through a sodium saturated GCL.

349) was used in the analysis. This observation is consistent with that of Petrov et al. (1997a) who concluded that diffusion likely was responsible for the premature arrival of a salt (NaCl) front at the outflow end of a needle-punched GCL.

Other Considerations in Interpreting Electrical Conductivity Breakthrough Curves

Several assumptions, such as infinite dilution, the existence of only ionic solutes, and a restricted number of ions, were made in the analysis that culminated in Eq. 16 and Fig. 19. In general, these assumptions are valid only in extreme cases. Therefore, some consideration must be given to the potential effect on the EC BTC arising from variations in these assumptions.

Infinite Dilution

Infinite dilution refers to the idealized case where the concentrations of solutes in solution are sufficiently low such that no interaction among the solutes occurs. In practice, such dilute conditions rarely, if ever, exist, particularly with respect to the situation where compatibility is a concern. For the more typical case where more concentrated solutions are used, the values for the equivalent ionic conductivities given in Table 1 are expected to be somewhat lower, and the solute are expected to behave as if lower concentrations were present (i.e., the activity effect). Since both of these factors tend to result in the measurement of EC that is lower at a given time relative to the idealized case, the estimate of chemical equilibrium based measurement of EC likely will be somewhat delayed relative to the idealized case.

Ionic Species

Since only ionic species contribute to the conductivity of solution, the measurement of EC does not include non-ionic species. As a result, EC cannot be used as a measure of chemical equilibrium for permeant liquids that consist mainly of non-ionic chemicals, such as non-polar organic compounds. Fortunately, most inorganic chemical solutions contain significant concentrations of ions such that a reasonable estimate of chemical breakthrough should be possible provided the outflow EC is normalized with respect to the inflow EC. However, the EC of the permeant liquid in the inflow also should be measured periodically to evaluate changes in solution chemistry.

Other Ions

In practice, more than three ionic species generally will be present in most chemical solutions. As a result, the analysis of the EC BTC becomes more complicated since all ionic species contribute to EC. In this case, the Eq. 14 must be modified as follows:

$$\frac{EC(L,t)}{EC_o} = \frac{\sum_{i=1}^{m} EC_i^-(L,t) + \sum_{j=1}^{n} EC_j^+(L,t)}{\sum_{i=1}^{M} EC_{oi}^- + \sum_{j=1}^{N} EC_{oj}^+} \qquad (17)$$

where

EC_{oi}^- = the electrical conductivity of anionic species i in the inflow solution (permeant liquid),

EC_{oj}^+ = the electrical conductivity of cationic species j in the inflow solution (permeant liquid),

$EC_i^-(L,t)$ = the electrical conductivity of anionic species i in the outflow solution,

$EC_j^+(L,t)$ = the electrical conductivity of cationic species j in the outflow solution,

M,N = the number of anionic and cationic species, respectively in the inflow solution (permeant liquid), and

m,n = the number of anionic and cationic species, respectively in the outflow solution.

Effect of pH on EC

Changes in the pH of the chemical solution can result in changes in the EC through precipitation/dissolution reactions. Also, as shown in Table 1, the equivalent ionic conductivity's of the proton (H^+) and hydroxide (OH^-) ions are the highest equivalent ionic conductivities associated with cations and anions, respectively. As a result, changes in proton and hydroxide concentrations potentially can result in significant changes in the electrical conductivity of the solution. For example, the dissociation of water (H_2O) results in the generation of protons and hydroxides in accordance with the ion product for water ($K_w = 10^{-14}$ @ 25°C). This dissociation reaction may be written in terms of the concentrations of H^+ and OH^- as follows:

$$[H^+][OH^-] = 10^{-14} \tag{18}$$

where the brackets represent concentrations and the activities have been neglected for convenience. The expression given by Eq. 18 also may be written in terms of the p-scale notation as follows:

$$pH + pOH = 14 \tag{19}$$

where

$$pH = -\log[H^+] \tag{20}$$

and

$$pOH = -\log[OH^-] \tag{21}$$

The electrical conductivity of water, therefore, is a function of the concentrations of protons and hydroxides, or

$$EC = \lambda_o^-[H^+] + \lambda_o^+[OH^-] \tag{22}$$

where λ_0^- is the equivalent ionic conductivity of H^+ and λ_0^+ is the equivalent ionic conductivity of OH^-. The EC of water also may be written in terms of pH and pOH by substitution of Eqs. 20 and 21 into Eq. 22, or

$$EC = \lambda_o^-\left(10^{-pH}\right) + \lambda_o^+\left(10^{-pOH}\right) \tag{23}$$

which upon substitution of the equivalent ionic conductivities for H^+ and OH^- from Table 1 paying attention to units results in the following expression for EC of water:

$$EC(S/cm) = 0.34982\left(10^{-pH}\right) + 0.198\left(10^{-pOH}\right) \tag{24}$$

where pOH = 14 - pH in accordance with Eq. 19. The EC based on Eq. 24 has been plotted as a function of pH and pOH in Fig. 20.

As shown in Fig. 20, the contribution of H^+ (or OH^-) to the EC of a solution increases as extremes in pH (or pOH) are approached. Thus, changes in pH can affect significantly the EC of the solution, especially when the H^+ or OH^- concentration represents a significant component of the overall EC of the solution. As a result, pH also should be measured whenever EC is used as a measure of chemical equilibrium in GCL compatibility testing.

Effect of Electrical Conductivity of Bentonite Portion of GCL

In general, the EC of the bentonite portion of the GCL is not zero, as previously assumed, due to the existence of soluble salts in the pore water of the bentonite. The existence of these soluble salts in ionic form can radically affect the observed trends in EC BTCs, as illustrated schematically in Fig. 21. For example, in the case where the electrical conductivity of the GCL (EC_{GCL}) is significantly higher than electrical conductivity of the permeant liquid (EC_0), or $EC_{GCL} > EC_0$, $EC(L,t)/EC_0$ values greater than one may be observed.

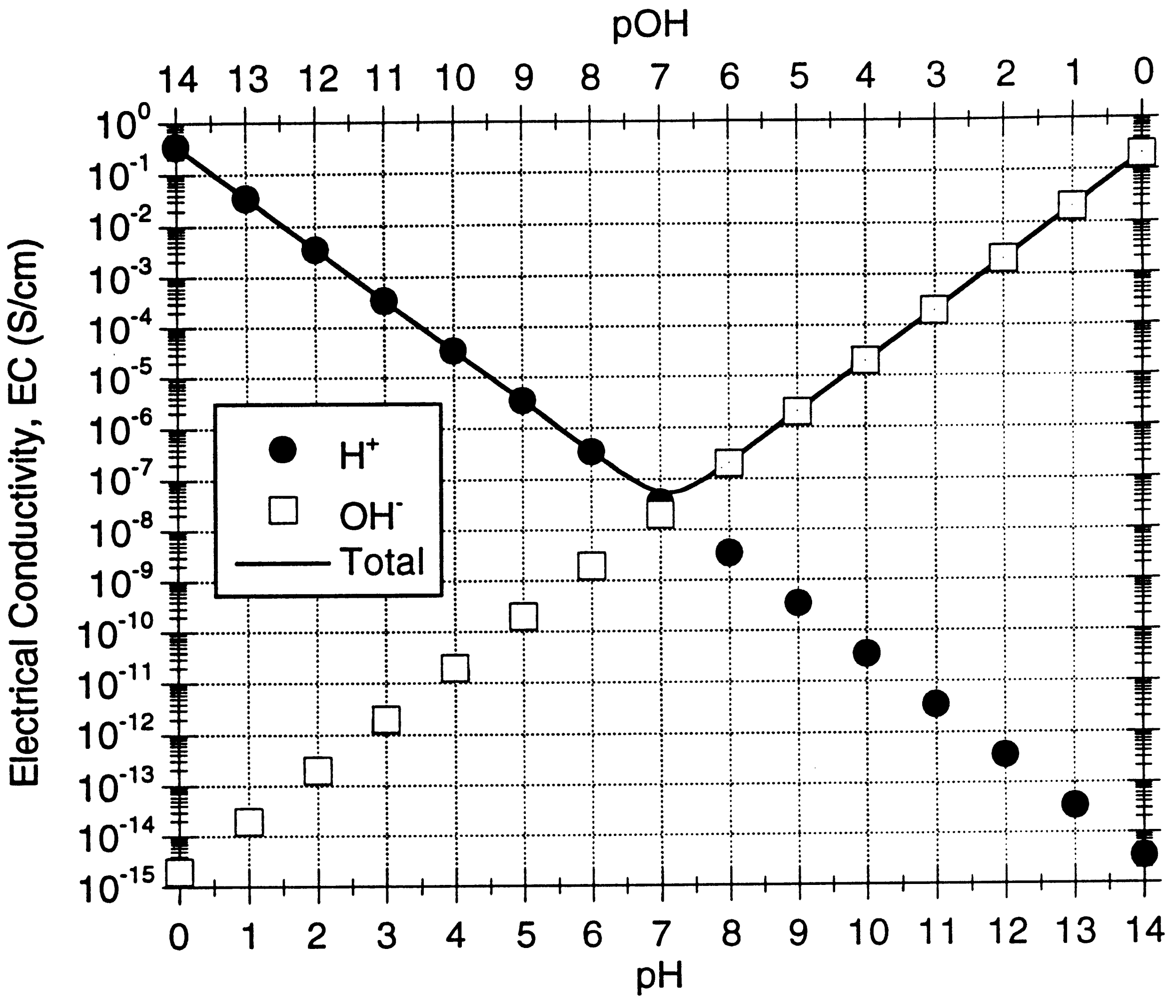

Figure 20 - Electrical conductivity of H^+ and OH^- at 25°C and infinite dilution as a function of pH.

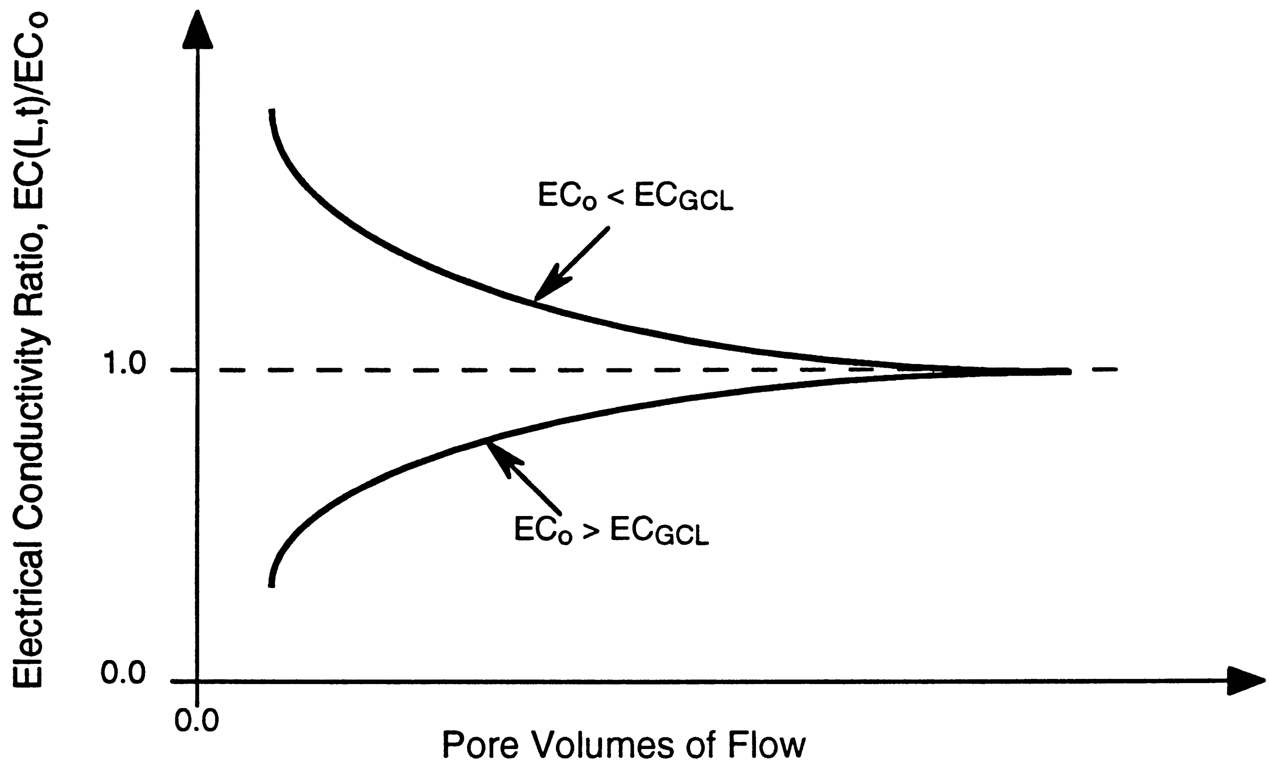

Figure 21 - Expected trends in relative electrical conductivity breakthrough curves (EC_0 = electrical conductivity of permeant liquid; EC_{GCL} = electrical conductivity of GCL).

For example, consider the EC BTCs shown in Fig. 22. For the test where the electrical conductivity of the permeant liquid was relatively high (Fig. 22a), the EC BTC follows the traditional trend presumably because EC_{GCL} is relatively low. However, for the test where the electrical conductivity of the permeant liquid was relatively low (Fig. 22b), the EC_{GCL} apparently was significantly greater than EC_o. Thus, in this latter case, the EC(L,t)/ECo values initially are greater than one and approach one with increased pore volumes of flow as the soluble salts are flushed from the GCL and the permeant liquid reaches the outflow end of the GCL.

In tests where $EC_{GCL} > EC_o$, undetected precipitation of ionic chemical species in the inflow solution (permeant liquid) during permeation results in measured $EC(L,t)/EC_o$ values that are lower than the actual $EC(L,t)/EC_o$ values due to the decrease in EC_o. In this case, measurement of the EC of the permeant liquid may be critical in preventing premature termination of the test since the measured EC BTC arrives earlier at the outflow end of the GCL than the actual EC BTC.

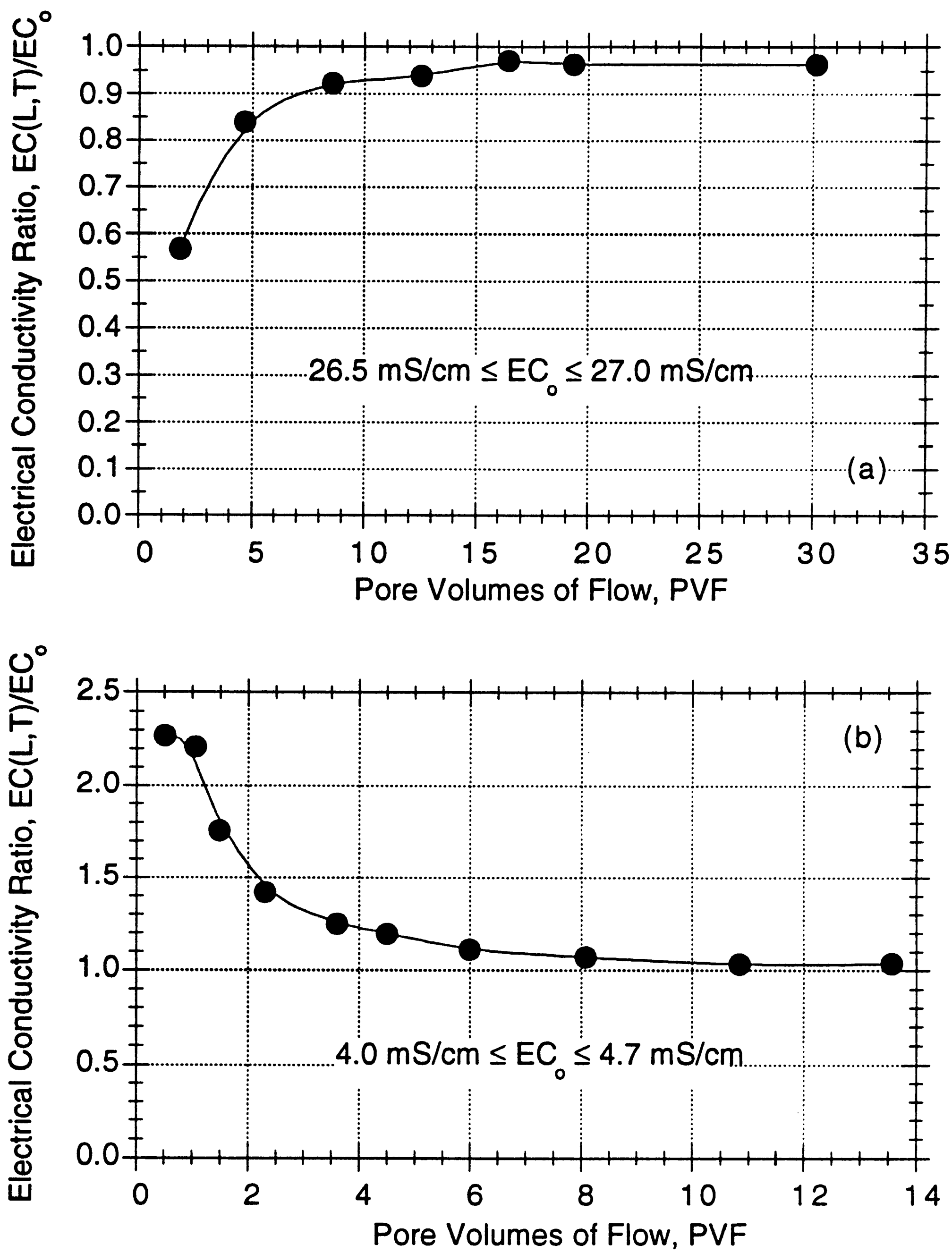

Figure 22 - Effect of electrical conductivity of GCL, EC_{GCL}, on electrical conductivity breakthrough curves for CETCO Bentomat® DN GCL permeated with two different permeant liquids: (a) $EC_0 > EC_{GCL}$; (b) $EC_0 < EC_{GCL}$.

INTERPRETATION OF TEST RESULTS

Applicability of Diffuse Double Layer Theory

The Gouy-Chapman, or diffuse double layer (DDL), theory from colloidal chemistry often is used to explain the effects of various permeant liquids on the fabric and, therefore, hydraulic conductivity of fine-grained soils (e.g., Mitchell 1993, Daniel 1994, Shackelford 1994). Based on this theory, increases in the cation valence and/or concentrations of ions in the pore water as well as a decrease in the dielectric constant of the pore water result in compression of the DDL surrounding clay particles leading to the formation of a relatively flocculated microfabric and an consequent increase in the hydraulic conductivity of the soil. Although these trends have been observed in several studies involving the compatibility of soils based on permeation with chemical solutions, Shackelford (1994) notes that the DDL theory was developed to describe the behavior of particle suspensions and, as a result, may not accurately represent the volume changes that have been observed in compatibility tests that involve compacted or natural clay soils that typically are subjected to some applied stress conditions. For example, particle re-arrangement and flocculation tends to result in an increase in the volume of the solid mass in suspensions, but several studies have indicated the permeation with low dielectric constant solutions containing organic solvents tends to result in shrinkage and cracking of clay soil. Such behavior is consistent with incomplete particle re-arrangement upon collapse of the DDL.

Regardless of the differences between the assumptions inherent in the DDL theory and the conditions typically prevalent in compatibility testing, studies have indicated that increases in hydraulic conductivity values observed during permeation of sand-bentonite mixtures with calcium dominated solutions are consistent with the changes that would be predicted based on the DDL theory (e.g., Gleason et al. 1997, Stern and Shackelford 1998). Thus, the DDL theory seems to be applicable in terms of interpreting changes in hydraulic conductivity of bentonite dominated materials, such as GCLs. Some examples of the relevance of DDL theory in describing the effects of permeant liquids on the hydraulic conductivity of GCLs are discussed in the remainder of this section.

Effect of Valence

James et al. (1997) investigated the cause of leakage through GCLs that were used in a cover system for brick arches that served to protect water reservoirs. The GCL consisted of a granular bentonite sandwiched between a woven polypropylene geotextile and a perforated sheet of polypropylene held together by a lightly applied adhesive. The initial water content of the GCL was 19 %. After correction for the presence of calcite in the bentonite, which contributed to the measurement of elevated calcium concentrations, the composition of the exchange complex of the bentonite consisted of 65.0 meq/100 g of sodium (Na), 2.0 meq/100 g of potassium (K), 10.9 meq/100 g of calcium (Ca), and 12.3 meq/100 g of magnesium (Mg). Thus, the bentonite was sodium dominated with a cation exchange capacity (CEC) of 90.2 meq/100 g.

After leakage was observed at several sites where the GCL had been placed, samples of the GCL were exhumed from 6 sites and returned to the laboratory. The average water contents of the samples from 5 of the 6 sites ranged from 89.2 % to 138 %. The 6th sample had an average water content of 488 % due to flooding of the site prior to sample recovery. Subsequent measurement of the exchangeable metals portion of the bentonite indicated that the average Ca concentrations on the exchange complex had increased to values ranging from 76.9 meq/100 g to 85.8 meq/100 g in the first 5 samples and to a value of 42.5 meq/100 g in the 6th sample, whereas the average Na concentrations on the exchange complex had decreased to values ranging from 2.6 meq/100 g to 15.3 meq/100 g in the first 5 samples and to a value of 47.6 meq/100 g in the 6th sample. Based primarily on the comparison of the initial and final exchangeable metals composition of the bentonite, James et al. (1997) concluded that calcium from the foundation soil had migrated into the GCL and displaced the sodium from the exchange complex resulting in subsequent shrinkage and cracking of the bentonite. This explanation is consistent with the DDL theory in that the replacement of a monovalent cation on the exchange complex (e.g., Na^{+}) with divalent cation (e.g., Ca^{2+}) is expected to result in compression of the DDL and a subsequent increase in hydraulic conductivity. This explanation also is consistent with the test results reported by Shan and Daniel (1991) in which the hydraulic conductivity of Claymax® GCL permeated with 24.2 pore volumes of a 0.5 N $CaCl_2$ solution was ~ 9 times greater than the hydraulic conductivity based on permeation with water (see Fig. 9a).

Effect of Concentration

The effect of an increase in salt concentration on the hydraulic conductivity of a needle-punched GCL is illustrated by the results reported by Petrov et al. (1997a) and shown in Fig. 23. All of the results shown in Fig. 23 are for tests performed using similar hydraulic gradients ($144 \leq i \leq 162$) and the same static confining stress of 3-4 kPa (0.4 - 0.6 psi). Although all of the GCL specimens tested by Petrov et al. (1997a) were prehydrated without back-pressure, some of the specimens were permeated first with distilled water (DW) prior to permeation with the NaCl solutions whereas other specimens were permeated only with the NaCl solutions. Thus, two sets of data are shown in Fig. 23.

In general, an increase in the NaCl concentration in the permeant liquid resulted in an increase in the hydraulic conductivity of the GCL. This trend is consistent with the expected effect of concentration based on the DDL theory. However, as shown in Fig. 24, initial permeation with the NaCl results in from 9 to 10 times greater increase in the hydraulic conductivity relative to the hydraulic conductivity observed for the specimens initially permeated with DW for NaCl concentrations ranging from 0.6 N to 2.0 N. Thus, the effect of degree of prehydration is evident in the test results shown in Figs. 23 and 24.

Effect of Dielectric Constant

In some cases, shrinkage of clay soils and significant increases in hydraulic conductivity have resulted upon permeation with solutions containing aqueous miscible organic solvents (Shackelford 1994). Since the dielectric constant of most pure phase organic compounds is less than ~ 40, whereas the dielectric constant of water is ~ 80, this effect is consistent with a decrease in the DDL due to a decrease in the dielectric constant of the permeant liquid. However, significant

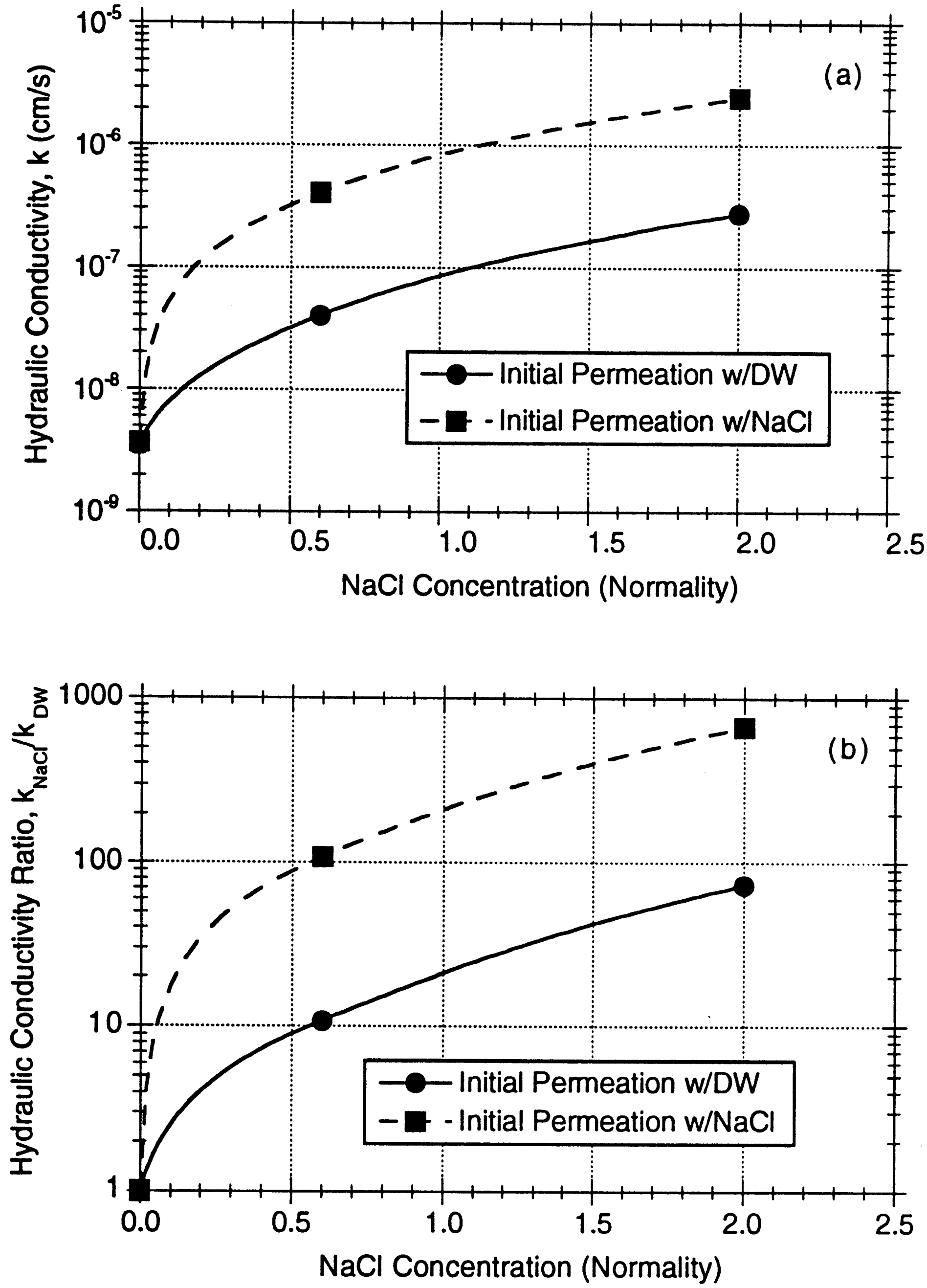

Figure 23 - Effect of concentration of NaCl solutions on the hydraulic conductivity of a needle-punched GCL: (a) hydraulic conductivity versus NaCl concentration; (b) hydraulic conductivity ratio versus NaCl concentration (data from Petrov et al. 1997a; DW = distilled water).

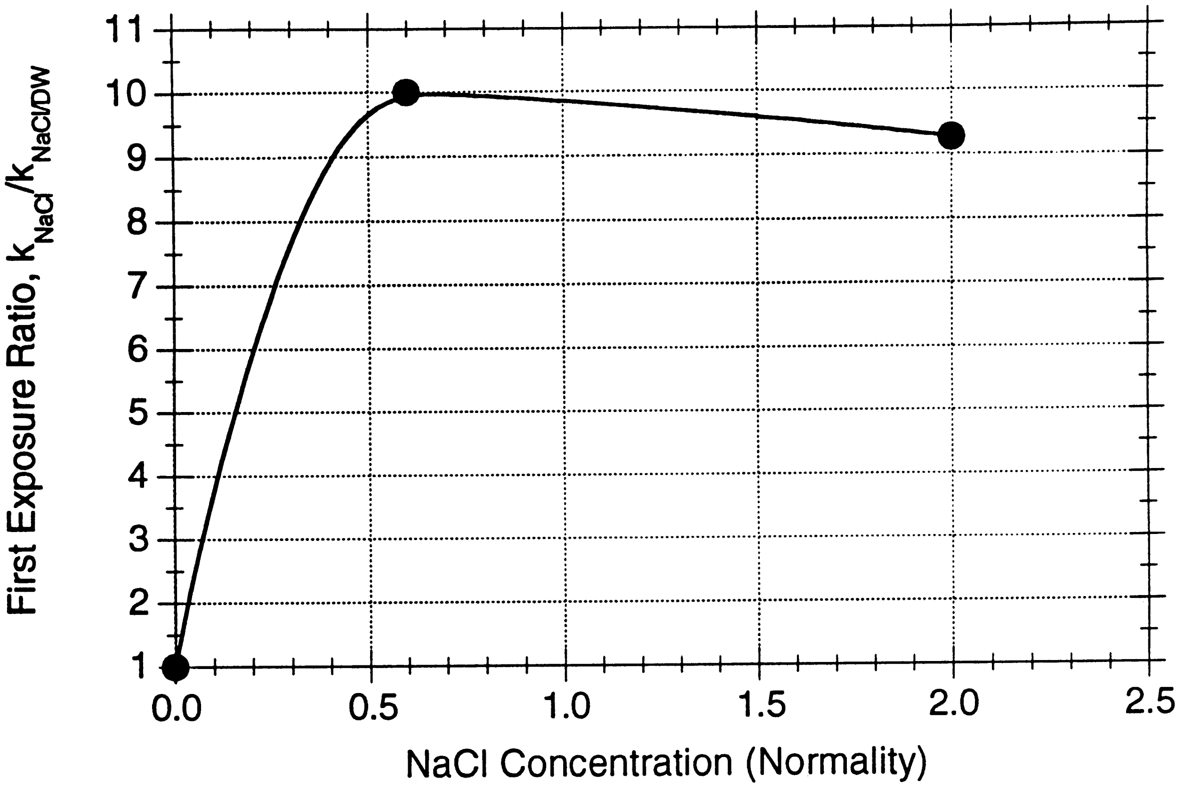

Figure 24 - First exposure ratio for permeation of a needle-punched GCL with NaCl solutions either with or without initial permeation using distilled water (DW) (data from Petrov et al. 1997a).

increases in hydraulic conductivity typically have been observed only in cases where the organic compound concentration in the solution is ≥ approximately 80 % since dilution of the solution with water results in an increase in the dielectric constant of the solution.

For example, Petrov et al. (1997b) evaluated the effect of ethanol concentration on the hydraulic conductivity of a needle-punched GCL. Their results are reproduced in Fig. 25. For ethanol concentration ≤ 50 % the hydraulic conductivity of the GCL actually decreased, whereas progressively greater increases in hydraulic conductivity as the ethanol concentration increased above 50 %. This behavior was explained on the basis of the contrasting effects of viscosity and DDL control.

For example, the hydraulic conductivity, k, is a product of the properties of both the porous medium and the permeant liquid in accordance with the following equation (e.g., Shackelford 1994):

$$k = K\frac{\gamma}{\mu} \tag{25}$$

where K is the intrinsic, absolute, or specific permeability of the porous medium, γ is the unit weight of the permeant liquid, and μ is the absolute or dynamic viscosity of the permeant liquid. For permeation with water, Eq. 25 is written as follows:

$$k_{water} = K_{water}\left(\frac{\gamma_{water}}{\mu_{water}}\right) \tag{26}$$

whereas, for permeation with a chemical solution, Eq. 25 becomes

$$k_{chemical} = K_{chemical}\left(\frac{\gamma_{chemical}}{\mu_{chemical}}\right) \tag{27}$$

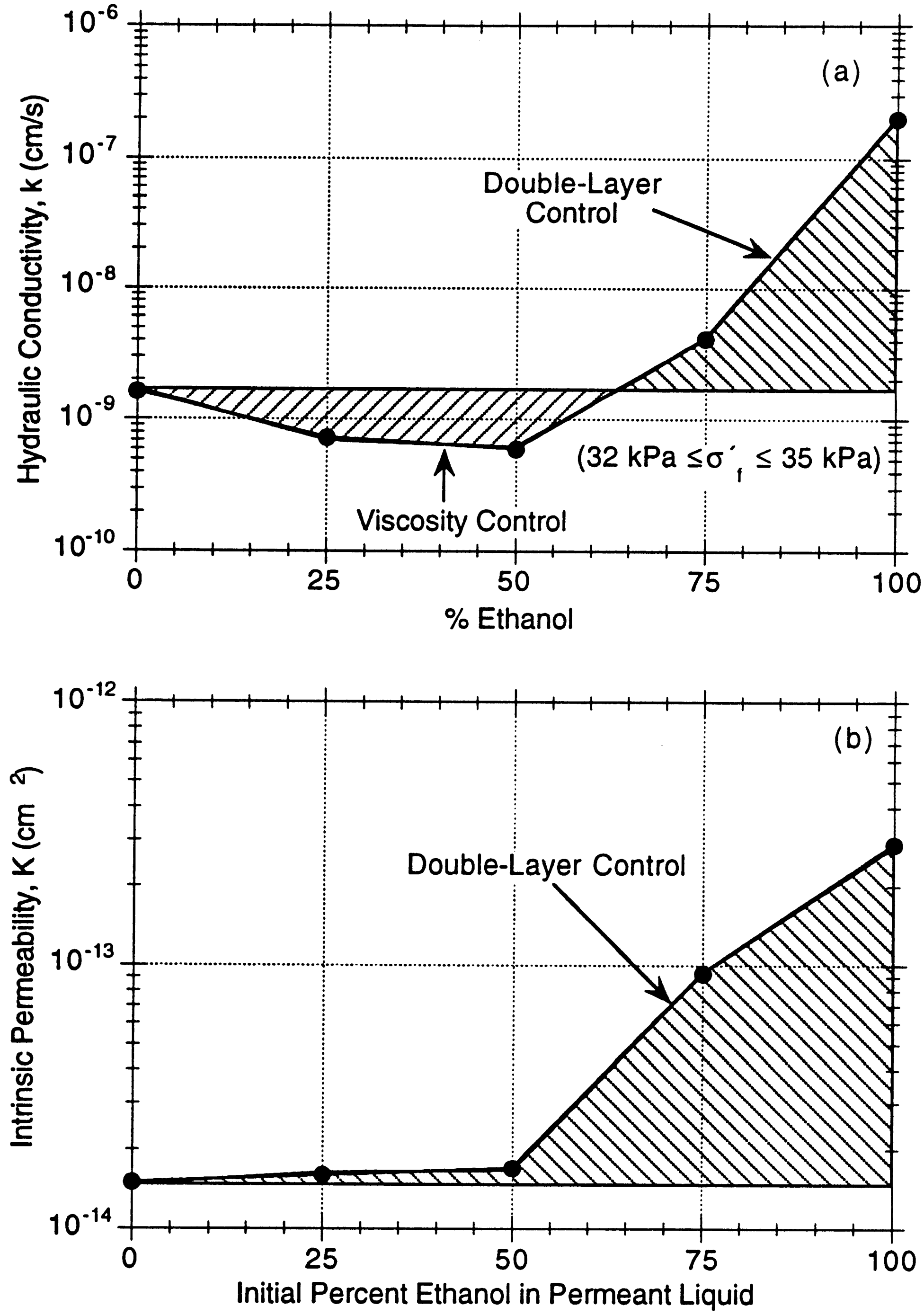

Figure 25 - Viscosity and double layer effects for GCL permeated with ethanol solutions: (a) effect on hydraulic conductivity; (b) effect on intrinsic permeability (data from Petrov et al. 1997b).

A qualitative evaluation of the relative effects of the properties of the two permeant liquids in terms of changes in the hydraulic conductivity of the porous medium can be ascertained by dividing Eq. 27 by Eq. 26, or

$$\frac{k_{chemical}}{k_{water}} = \left(\frac{K_{chemical}}{K_{water}}\right)\left(\frac{\mu_{water}}{\mu_{chemical}}\right)\left(\frac{\gamma_{chemical}}{\gamma_{water}}\right) \tag{28}$$

Based on the assumption that the ratio of $\gamma_{chemical}/\gamma_{water} \approx 1$, the relative effect of the chemical on the hydraulic conductivity of the porous medium is proportional to the ratio of the intrinsic permeability based on permeation with the chemical solution relative to permeation with water, and the ratio of the viscosity of water relative to the viscosity of the permeant liquid, or

$$\frac{k_{chemical}}{k_{water}} \propto \left(\frac{K_{chemical}}{K_{water}}\right)\left(\frac{\mu_{water}}{\mu_{chemical}}\right) = \left(\frac{K_{chemical}}{K_{water}}\right)\left(\frac{\mu_{chemical}}{\mu_{waterl}}\right)^{-1} \tag{29}$$

As shown in Fig. 25b, permeation with the solutions containing ≤ 50 % ethanol resulted in essentially no change in the intrinsic permeability of the GCL indicating that the interaction between the ethanol solution and the GCL was negligible. Thus, $K_{chemical}/K_{water} \approx 1$ for solutions containing ≤ 50 % ethanol. However, the hydraulic conductivity of the GCL actually decreases upon permeation with the solutions containing ≤ 50 % ethanol (Fig. 25a) apparently due to the increase in viscosity with increase in ethanol concentration in accordance with Eq. 29. As the ethanol concentration in the permeant liquid increases beyond 50 %, the decrease in the dielectric constant of the solution apparently results in flocculation and shrinkage of the bentonite such that $K_{chemical}/K_{water} > 1$, and the increase in $K_{chemical}/K_{water}$ apparently is greater than the increase in $\mu_{chemical}/\mu_{water}$ (i.e., $K_{chemical}/K_{water} > \mu_{chemical}/\mu_{water}$ such that $k_{chemical}/k_{water}$ increases with increasing ethanol concentration for ethanol concentrations > 50 %.

Petrov et al. (1997b) noted that their results in Fig. 25 tended to counter the results of previously published studies. For example, Petrov et al. (1997b) noted that Shan and Daniel

(1991) observed a slight decrease in the hydraulic conductivity of Claymax® GCL after permeating with 100 % methanol for about 0.6 pore volumes (e.g., see Fig. 9a). However, Petrov et al. (1997b) hypothesized the decrease in hydraulic conductivity reported by Shan and Daniel (1991) was due to the increased viscosity of the methanol solution and, therefore, that the test probably was terminated before chemical equilibrium had been achieved. Petrov et al. (1997b) suspect that the hydraulic conductivity probably would have increased eventually had the test conducted by Shan and Daniel (1991) for methanol permeation been allowed to reach chemical equilibrium (i.e., more pore volumes of flow). Thus, the results reported by Petrov et al. (1997b) illustrate further the importance of achieving chemical equilibrium in compatibility testing.

CONCLUSIONS

Prehydration of GCLs is a significant factor both in terms of the hydraulic conductivity values of GCLs permeated with chemical solutions as well as in the interpretation of the hydraulic conductivity test results. Reported hydraulic conductivity values for non-prehydrated GCLs permeated directly with chemical solutions have been found to range from one to five orders of magnitude higher than the hydraulic conductivity values for same specimens prehydrated prior to permeation with the same chemical solutions, with different results depending on the properties of the permeant liquids, the type of GCL, the specimen preparation procedure, and the degree of prehydration achieved prior to permeation. In addition, failure to achieve chemical equilibrium in tests that involve prehydrated GCL specimens due to swelling of the bentonite against a confining stress is a major factor contributing to the measurement of relatively low hydraulic conductivity values upon subsequent permeation with the chemical solution.

Relatively high hydraulic gradients (e.g., $\sim 50 \leq i \leq \sim 200$) commonly are reported in conjunction with hydraulic conductivity testing of GCLs. In some cases, hydraulic gradients ranging from 100 to ~ 900 have been reported. However, no significant effect on the hydraulic conductivity of selected GCLs permeated with hydraulic gradients less than about 590 generally has been reported in the case where the stress conditions in the tests are maintained constant. This trend is supported by an analysis illustrating that hydraulic gradients ranging from 233 to 700 for GCL thicknesses ranging from 15 mm to 5 mm, respectively, result in the same stress (boundary) conditions that are imposed on a standard (Proctor mold) compacted specimen subjected to a constant hydraulic gradient of 30. Thus, higher hydraulic gradients in the case of GCLs do not necessarily result in significant differences in stress conditions relative to permeation of thicker compacted clay soils at lower hydraulic gradients.

On the other hand, the hydraulic conductivity of selected GCLs based on permeation with distilled water (DW) is shown to decrease approximately an order of magnitude as the effective stress of the GCLs increases from ~ 3.5 kPa (0.5 psi) to 138 kPa (20 psi) regardless of hydraulic gradient used in the tests. In addition, a 10-fold increase in static confining stress from ~ 3.5 kPa (0.5 psi) to ~ 34.5 kPa (5.0 psi) of a needle-punched GCL permeated with 0.6 N NaCl solution resulted in an decrease in the hydraulic conductivity by ~ 8 times. Therefore, consideration of the stress conditions imposed on the GCL during hydraulic conductivity testing apparently is more important than the use of relatively high hydraulic gradients.

The single most important criterion for terminating a GCL compatibility tests is the establishment of chemical equilibrium between the outflow solution and the inflow solution (permeant liquid). Failure to ensure that chemical equilibrium has been established may lead to premature termination of the test and the measurement of hydraulic conductivity values that are too low relative to the actual hydraulic conductivity of the GCL.

The results of several tests performed on five different GCLs using several different permeant liquids with pH values ranging from 1 to 13 were evaluated in terms of establishment of pH equilibrium between the outflow solution and the inflow solution (permeant liquid). The results indicate that significant increases in the hydraulic conductivity of the GCLs upon permeation with the chemical solution relative to permeation with water (i.e., $30 \leq k_{chemical}/k_{water} \leq 71{,}430$) occurred in all 12 tests where the ratio of the pH in the outflow solution relative to the pH in the inflow solution, or pH_{out}/pH_{in}, was 1.0±0.1. However, $k_{chemical}/k_{water} \leq 2.0$ in 15 of 18 tests where pH equilibrium was not established (i.e., $pH_{out}/pH_{in} \neq 1.0 \pm 0.1$), with $k_{chemical}/k_{water}$

values of 10, 2857, and 5000 resulting for the 3 tests that were terminated before pH equilibrium was established. In addition, prehydration of the GCL specimens was a significant hindrance to the ability to establish pH equilibrium. As a result, failure to establish pH equilibrium probably will result in the measurement of hydraulic conductivity values that are too low relative to the actual hydraulic conductivity of the GCL.

An analysis of the use of electrical conductivity, EC, as an indicator of chemical equilibrium was presented. Based on several simplifying assumptions, the analysis indicated that EC breakthrough reflected exactly the breakthrough of the chemical species in the inflow solution (permeant liquid). However, several complicating aspects of the use of EC as a measure of chemical breakthrough, such as the dependence of EC on pH and the fact that EC only reflects the existence of ionic chemical species, also were identified. As a result, the use of EC as a measure chemical breakthrough may be beneficial in cases where the permeant liquid is expected to consist primarily of ionic species, such as dissolved salt concentrations, but the measurement of EC should be complemented by the measurement of pH, and the EC of the inflow solution (permeant liquid) should be measured each time the EC of the outflow solution is measured.

The results from several studies were evaluated in terms of the applicability of the diffuse double layer (DDL) theory in explaining the effects of cation valence, solute concentration, and solution dielectric constant on the hydraulic conductivity of GCLs permeated with chemical solutions. In general, a strong correlation exists between the principal parameters affecting the DDL and the hydraulic conductivity of GCLs, with higher cation valence, higher solute concentration, and lower dielectric constant resulting in decreases in, or compression of, the thickness of the DDL and increases in hydraulic conductivity due to partial or complete particle re-arrangement resulting in the formation of a relatively flocculated microfabric and shrinkage of the bentonite. However, failure to achieve chemical equilibrium in the tests may mask the relationship between the DDL theory and the expected results of the compatibility test when the properties of the permeant liquid include a low dielectric constant solutions and a high viscosity relative to water.

Neither ASTM D 5084 nor GRI GCL2 require an evaluation of chemical equilibrium as a criterion for terminating the hydraulic conductivity test. In addition, the back-pressure saturation procedures in both of these standards will result in prehydration of the GCL that may radically influence the test results, particularly if the test is not continued until chemical equilibrium has been established. Other aspects of each standard, such at the recommended maximum hydraulic gradients in ASTM D 5084 or the application of the initial effective stress of 69 kPa (10 psi) in GRI GCL2, may not be appropriate in the case of GCL compatibility testing. As a result, performance of GCL compatibility testing soley in accordance with the procedures contained in these two standards is not recommended, particularly given the importance of chemical equilibrium in compatibility testing.

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Appendix B

Comparison of HELP Model and Giroud-Bonaparte Equations

(Reproduced from Appendix G in TMA Addendum No. 3)

Foth & Van Dyke	Client: Crandon Mining Co Scope I.D.: 93C049 Project: Crandon TMA Page: 1 of 4 Prepared by: NxP Date: 7-16-96 Checked by: PAG Date: 7/17/96

LEAKAGE RATES USING GIROUD-BONAPARTE EQUATIONS

Purpose: To compare percolation through TMA liner using HELP model and Giroud-Bonaparte equations

Scope: For the cases of TMA conditions used in the HELP model studies, compare the results with calculated results using Giroud-Bonaparte equations. Employ the head on the liner as the average annal head obtained from the HELP model runs.

References. Schroeder, P.R et al (1994) "The Hydrologic Evaluation of Landfill Performance (HELP) model, Engineering Documentation for Version 3" EPA/600/R-94/168b, September 1994.

Giroud J.P and Bonaparte R (1989) "Leakage through liners Constructed with Geomembranes - Part II. Composite Liners" Geotextiles and Geomembranes, Elsevier Applied Science, Vol 8. p71-111

Limitations: Giroud and Bonaparte equations as used here are obtained from Schroeder et al, who had used Giroud and Bonaparte (1989) and Giroud et al (1992) to develop the equations used in these calculations

HELP model

Interfacial $$Q = K_s \, i_{av} \, n \, \pi R^2 \left(\eta_{20}/\eta_{15}\right) \qquad — (1)$$

K_s = hyd. Con m/sec

i_{av} : hydraulic gradient

n = density of flaws /m^2

R = Radius of wetted area

η_{20}, η_{15} viscosity at 20 and 15°

$$i_{av} = 1 + \frac{h_g}{2 T_s \ln \frac{R}{r_o}} \qquad — (2)$$

h_g = total hydraulic head - m

T_s Thickness of controlling soil layer

r_o = radius of geomembrane flaw
= 0.0113 m for defects; 0.001 m for pinholes

For Good contact

$$R = 0.26 \, a_o^{0.05} \, h_g^{0.45} \, K_s^{-0.13} \qquad — (3)$$

where a_o = Geomembrane flaw area .0001 m^2 for installation defects and 0.000000784 m^2 for pinholes

K_s = 3×10^{-11} m/sec for GCL

$$R = 0.26(.0001)^{.05} \times (3\times10^{-11})^{-.13} h_g^{.45} \quad \text{for defects}$$

$$= 3.828\, h_g^{0.45} \checkmark$$

$$R = 0.26(.000000784)^{.05} (3\times10^{-11})^{-.13} h_g^{.45} \quad \text{for pinholes}$$

$$= 3.003\, h_g^{0.45} \checkmark$$

$$i_{av} = 1 + \frac{h_g}{2(.0061)\ln\frac{R}{.0113}} \quad \text{for defects}$$

$$= 1 + \frac{h_g}{2(.0061)\ln\frac{R}{.001016}} \quad \text{for pinholes}$$

$$Q = k_s\, i_{av} \cdot n\, \pi R^2 (n_{20}/n_{15}) \qquad \underline{\text{defects}}$$

$$= 3\times10^{-11} \times \frac{1}{4046} \times 4 \times \pi \times \frac{.001}{.00114} \quad i_{av} R^2 \quad m/s$$

1 acre = 4046 m^2

$$= \frac{3\times10^{-11}}{4046} \times \pi \times (.8772)\, 60\times1440\times365\times\frac{100}{2.54} \quad i_{av} R^2 \times n$$

$(n = 4)$ $$= 1.015\times10^{-4}\, i_{av} R^2 \quad \text{for defects} \checkmark$$

$(n = 1)$ $$2.537\times10^{-5}\, i_{av} R^2 \quad \text{for pinholes} \checkmark$$

RESULTS

CASE	Av. Head on Liner m	Q from Giroud + Bonaparte in/yr			Q from HELP in/yr
		defect	pinholes	total	
1. Sideslope 1st stage	.0001524	5.48×10^{-7}	8.48×10^{-8}	6.33×10^{-7}	3.8×10^{-8}
2 Base 1st stage	.0.03	1.0×10^{-4}	1.35×10^{-5}	1.14×10^{-4}	1.9×10^{-4}
3 Sideslope 2nd stage (with Geocomposite)	.0001778	6.32×10^{-7}	9.7×10^{-8}	7.29×10^{-7}	4.6×10^{-8}
4. Sideslope 2nd stage (without Geocomposite)	4.051	.276	.032	.308	.399
5 Base 2nd stage	.0322	1.09×10^{-4}	1.46×10^{-5}	1.23×10^{-4}	1.9×10^{-4}
6. Base - Post Closure Monitoring Period	.0163	4.88×10^{-5}	6.9×10^{-6}	5.57×10^{-5}	1×10^{-4}
7 Base - Leachate System shutoff	.0162	4.84×10^{-5}	6.8×10^{-6}	5.52×10^{-5}	1×10^{-4}
8 Sideslope (without GeoComposite) Post Closure Monitoring Period	0.083	3.88×10^{-4}	4.85×10^{-5}	4.37×10^{-4}	5.5×10^{-3}