APPENDIX A

ALTERNATIVE LINER FLOW COMPARISON

APPENDIX A

ALTERNATIVE LINER FLOW COMPARISON

Analyses were conducted using the method proposed by Giroud et al. (1997) to demonstrate that the secondary composite liner system consisting of a 60 mil high density polyethylene (HDPE) geomembrane overlying a geosynthetic clay liner (GCL) has equivalent or improved fluid migration characteristics when compared to a secondary composite liner system consisting of a 60 mil HDPE geomembrane overlying the prescriptive compacted clay liner (i.e., 3 feet of 10^{-7} cm/sec soil, per 40 CFR 264.221). The liner flow comparison calculation is provided in Appendix A-1.

Compatibility testing was conducted to evaluate the potential for the GCL to increase in permeability when exposed to the synthetic tailings solution chemistry. The results of the compatibility testing are presented in Appendix B. The certified hydraulic conductivity of the proposed GCL material is $5x10^{-9}$ centimeters per second (cm/sec) when tested with deaired/distilled/deionized water. Testing of a polymer-treated GCL in contact with the synthetic leachate indicated no increase in hydraulic conductivity. However, the standard GCL exhibited an increase in permeability when tested with the synthetic leachate to approximately $1.1x10^{-8}$ cm/sec.

Based on this site-specific analysis, which accounts for the loading conditions and anticipated head on the secondary liner system, as well as the potential for an increase in the GCL hydraulic conductivity when exposed to the tailings leachate, the amount of flow through the secondary liner system with the prescriptive compacted clay liner was evaluated to be nearly 5 times greater than the flow through the secondary liner system with a standard GCL underliner, and more than 8 times greater than the flow through the secondary liner system with a polymer-treated GCL underliner. Therefore, in terms of limiting fluid flow through the composite secondary liner system, the secondary liner system containing a GCL performs better than the secondary liner system containing the prescriptive clay liner.

REFERENCES

40 CFR Part 264 – "*Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities*", Subpart K (Surface Impoundments).

Giroud, J.P., Badu-Tweneboah, K., and Soderman, K.L. 1997. "Comparison of leachate flow through compacted clay liners and geosynthetic clay liners in landfill liner systems." *Geosynthetics International*, 4 (3-4), 391-431.

APPENDIX A-1

FLOW COMPARISON CALCULATION

OBJECTIVE:

Evaluate the use of a geosynthetic clay liner (GCL) as the underliner in the secondary liner system to demonstrate equivalent or better fluid migration resistance when compared to a prescriptive compacted clay liner (CCL) for design of the tailings cells.

GIVEN:

- The tailings cells will be designed with a double composite liner system which meets the requirements of 40 CFR Part 264, Subpart K (EPA).
- Results of GCL compatibility testing with a synthetic tailings leachate (see GCL compatibility testing appendix).

GEOMETRY:

- Base lining system configuration alternatives shown in Figure 1.

MATERIAL PROPERTIES:

Table 1 summarizes the hydraulic conductivity properties for the considered materials in this analysis:

Table 1. Material Hydraulic Properties

Material	Hydraulic Conductivity / *Transmissivity		Thickness (in)	Notes
	(cm/sec) / *(m^2/sec)	(ft/sec) / *(gal/min/ft)		
CCL	$1x10^{-7}$	$3.28x10^{-9}$	36	Prescriptive liner 40 CFR §264.221
GCL[1,2]	(a) $5x10^{-9}$ (b) $3x10^{-9}$ (c) $1.1x10^{-8}$	(a) $1.6x10^{-10}$ (b) $9.8x10^{-11}$ (c) $3.6x10^{-10}$	0.4	i.e., CETCO Bentomat ST, or equivalent
Geonet[1]	*$6x10^{-3}$	*29	0.28	i.e., HyperNet HS geonet manufactured by GSE or equivalent

[1] See Attachment 2.
[2] Range of GCL hydraulic conductivity values obtained from: (a) published values as tested with water; (b) polymer-treated GCL tested with synthetic leachate; and (c) standard GCL tested with synthetic leachate.

ASSUMPTIONS:

- A good contact exists between the secondary geomembrane and the underliner in the secondary composite liner system;
- According to the EPA, common practice is to assume a circular defect with a diameter equal to the thickness of the geomembrane (Giroud and Bonaparte 1989). Accordingly, these calculations assume circular defects with a diameter of 60 mil (0.005 ft, or 0.06 inches);
- A frequency of 1 defect per acre is assumed, which reflects good to excellent installation quality of the geomembrane installation (Giroud and Bonaparte 1989);
- The flow is assumed to be steady state;
- The flow in the leakage collection layer is laminar;

- It is assumed that flows through various defects do not interfere with each other; and
- The maximum height of liquid above the primary geomembrane is conservatively assumed to be equal to the ultimate height of the tailings in the cells (e.g. 76 ft).

METHOD:

In this analysis the method proposed by Giroud et al. (1997a) is used to compare the leachate flow through a GCL to the prescriptive CCL liner. The comparison between the GCL alternative liner and a CCL prescribed liner is performed by calculating the ratio between the rates of leachate flow through these composite liner systems. The following equation can be used to calculate the advective flow rate ratios.

$$\frac{q_{comp\ CCL}}{q_{comp\ GCL}} = qratio = \left(\frac{k_{CCL}}{k_{GCL}}\right)^{0.74} \frac{1 + 0.1(\frac{h}{t_{CCL}})^{0.95}}{1 + 0.1(\frac{h}{t_{GCL}})^{0.95}}$$

where:

$q_{comp\ CCL}$ = unit rate of flow through a composite liner where the soil component is a CCL;
$q_{comp\ GCL}$ = unit rate of flow through a composite liner where the soil component is a GCL;
k_{CCL} = hydraulic conductivity of the CCL;
k_{GCL} = hydraulic conductivity of the GCL;
t_{CCL} = thickness of the CCL in the composite liner;
t_{GCL} = thickness of the GCL in the composite liner; and
h = maximum head of liquid above the geomembrane.

The maximum liquid head on the secondary geomembrane (h) is calculated by assuming that a pinhole in the primary geomembrane exists to allow liquids to flow through and reach the leak collection and recovery system and create a potential head on the secondary geomembrane. According to Giroud et al. (1997b) the flow rate through a geomembrane defect is given by the following equation:

$$Q = \frac{2}{3} d^2 \sqrt{g\, h_{prim}}$$

where:

Q = flow rate through one geomembrane defect;
d = defect diameter;
g = acceleration due to gravity; and
h_{prim} = head of liquid on top of primary liner.

The head of liquid above the secondary lower geomembrane in the double composite liner system is calculated by the method proposed by (Giroud et al. 1997b):

$$t_o = \sqrt{\frac{Q}{k}}$$ for the case where the leakage collection layer is not full.

where:

t_o = thickness of leachate in the leakage collection layer;

Q = steady-state rate of leachate flow in the leakage collection layer, which results from a defect in the primary geomembrane liner; and
k = hydraulic conductivity of the leakage collection layer material.

The calculated head of liquid above the secondary lower geomembrane (t_o) represent the maximum head of liquid above the geomembrane (h), which allows us to calculate the advective flow rate ratio.

The geonet for the leak collection and recovery system layer was selected to drain the maximum flow rate through a defect in the primary upper geomembrane liner.

CALCULATIONS:

Calculations are provided in Attachment 1.

RESULTS:

Table 2 summarizes the results obtained from the calculations provided in Attachment 1.

Table 2. Calculation Results

Parameter	Value	Notes
Q	8.4×10^{-4} ft^3/sec	Maximum flow rate through a defect in the primary upper geomembrane liner.
k	2.8 ft/sec	Minimum required geonet hydraulic conductivity.
Q_{full}	1.5×10^{-3} ft^3/sec	Maximum flow in the minimum leak collection and recovery system layer.
t_o	0.017 ft (0.20 in, 5.2 mm)	Liquid build-up on the secondary geomembrane.
$q_{comp\ CCL}$/ $q_{comp\ GCL}$	Ranges from 4.9 to 12.8, depending on GCL used.	Ratio between the rates of leachate flow.

CONCLUSIONS:

According to the calculations, the amount of liquid head over the secondary geomembrane is 0.20 inches (i.e., 0.017 ft) due to a circular defect in the primary geomembrane with a diameter equal to 0.005 ft. For this liquid head, the flow through the secondary liner system with a standard GCL underliner exposed to the tailings leachate was evaluated to be nearly 5 times less than the flow rate through a secondary liner system with a CCL underliner. If a polymer-treated GCL is used instead, the flow through the secondary liner system may be reduced up to nearly 13 times less than a secondary liner system with a CCL underliner. Conservatively, however, the polymer-treated GCL was assumed to result in no change in permeability from the manufacturer-specified permeability, and therefore the flow is more than 8 times less than the flow through a secondary liner system with a CCL underliner.

In conclusion, a double composite liner system comprised of a geomembrane/geonet/geomembrane/GCL (option B) performs better than a double composite liner system comprised of a geomembrane/geonet/geomembrane/CCL (option A) for the assumed conditions.

In order to prevent liquid build-up above the secondary geomembrane that could fill the leak collection and recovery system layer, the properties for the geonet should be equal to or greater than those assumed in these calculations (see Table 1).

REFERENCES:

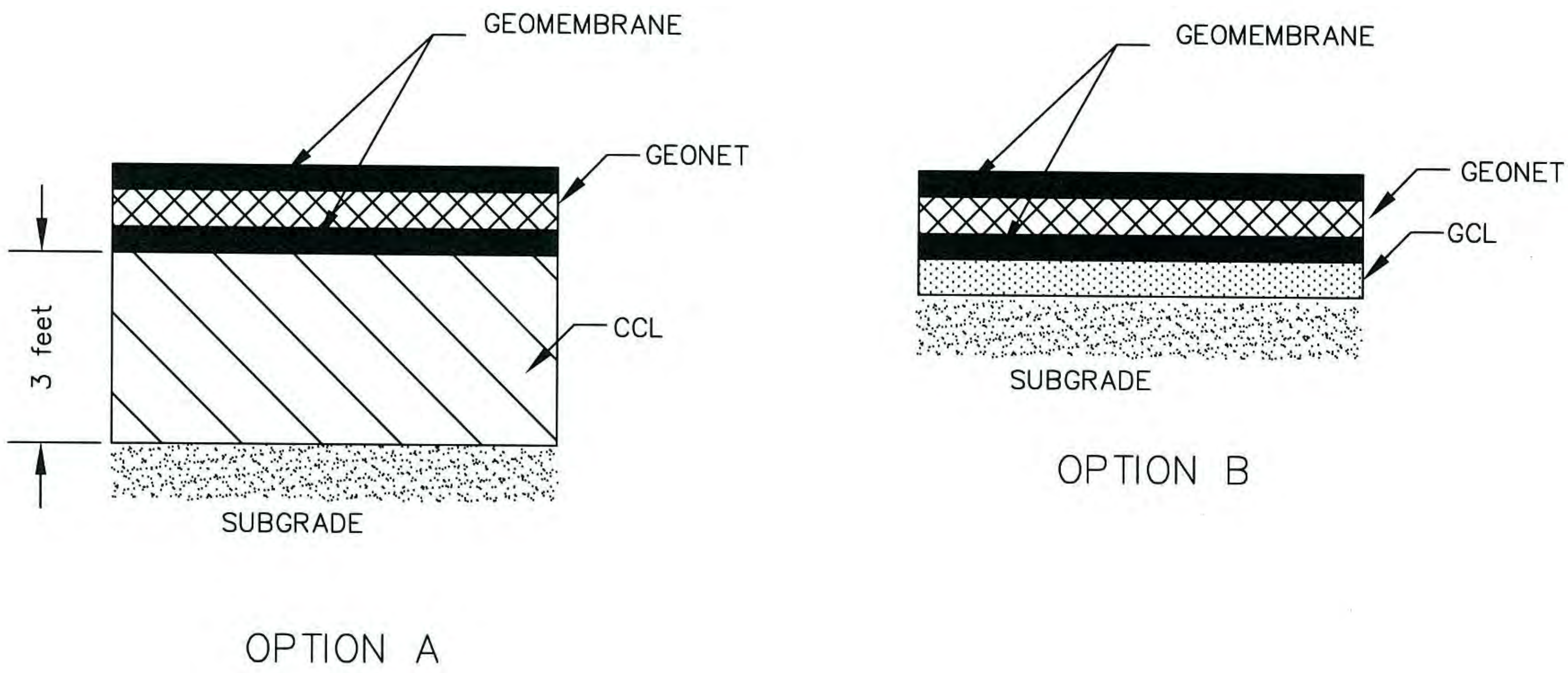
Environmental Protection Agency (EPA), 40 CFR Part 264 - "Standards for Owners and Operators of Hazardous Waste Treatment, storage, and Disposal Facilities", Subpart K (Surface Impoundments).

Giroud, J. P., Badu-Tweneboah, K., and Soderman, K. L. (1997a). "Comparison of leachate flow through compacted clay liners and geosynthetic clay liners in landfill liner systems." *Geosynthetics International*, 4(3-4), 391-431.

Giroud, J. P., and Bonaparte, R. (1989). "Leakage through liners contructed with geomenbranes-Part I geomembranes liners." *Geotextiles and Geomembranes*, 8, 27-67.

Giroud, J. P., Gross, B. A., Bonaparte, R., and McKelvey, J. A. (1997b). "Leachate flow in leakage collection layers due to defects in geomembrane liners." *Geosynthetics International*, 4(3-4), 215-292.

FIGURES



Golder Associates Denver, Colorado

TITLE
LINER SYSTEM CONFIGURATION ALTERNATIVES

CLIENT/PROJECT ENERGY FUELS RESOURCES CORPORATION PIÑON RIDGE PROJECT - TAILINGS CELL DESIGN MONTROSE COUNTY, COLORADO	DRAWN EF	DATE FEBRUARY 15, 2008	JOB NO. 073-81694
	CHECKED KFM	SCALE N.T.S.	DWG. NO.
	REVIEWED KFM	FILE NO. Figures CCL-GCL.dwg	FIGURE NO. 1

ATTACHMENT 1
LINER COMPARISON CALCULATIONS

COMPARISON OF FLOW THROUGH CCL AND GCL LINER CALCULATIONS

The ratio between the rates of leachate flow through a composite liner with compacted clay (CCL) underliner and a composite liner with a goesynthetic clay (GCL) underliner is given by (Giroud et al. 1997a):

$$q_{ratio} = \left(\frac{k_{CCL}}{k_{GCL}}\right)^{0.74} \cdot \frac{\left[1 + 0.1\cdot\left(\frac{h}{t_{CCL}}\right)^{0.95}\right]}{\left[1 + 0.1\cdot\left(\frac{h}{t_{GCL}}\right)^{0.95}\right]}$$

In order to solve the above equation, the maximum height of liquids above the secondary geomembrane liner must be evaluated. The maximum head on the secondary liner is derived by assuming that a defect in the primary geomembrane liner exists to allow liquids to flow through the primary geomembrane to the leak detection system. The flow rate through the geomembrane defect is calculated by conservatively assuming a maximum height of liquid above the primary geomembrane to be equal to the ultimate height of the tailings in the cells (e.g. 76 ft).

The flow rate through a defect in the geomembrane is given by the following equation (Giroud et al. 1997b):

$d := 0.005$ ft — defect diameter

$h_{prim} := 78$ ft — total liquid head over primary geomembrane

$g := 32.2$ ft / sec^2 — gravity

$$Q := \frac{2}{3}d^2\cdot\sqrt{g\cdot h_{prim}}$$

where the maximum flow rate through the primary liner geomembrane is:

$Q = 8.35 \times 10^{-4}$ ft^3/sec

The permeability of the geonet can be defined by:

$t_{LCL} := 0.023$ ft — thickness of the geonet

$\theta := 0.0646$ ft^2 / sec — geonet transmissivity

$$k := \frac{\theta}{t_{LCL}}$$ geonet hydraulic conductivity

$k = 2.81$ ft / sec

The maximum steady-state rate of leachate migration through a defect in the primary liner that a leakage collection layer can accommodate without being filled with leachate (Giroud et al. 1997b):

$$Q_{full} := k \cdot t_{LCL}^{2}$$

$$Q_{full} = 1.49 \times 10^{-3} \quad \text{ft}^3/\text{sec}$$

The liquid head build-up on the secondary geomembrane liner can be calculated by using the following equation (Giroud et al. 1997b):

$$to := \sqrt{\frac{Q}{k}}$$

$$to = 0.017 \quad \text{ft}$$

Since the flow rate through a defect in the geomembrane (Q) is lower than the maximum flow rate that the leakage collection layer can accommodate (Qfull), and the estimated liquid head build-up (to) is less than the thickness of the geonet (tLCL), the use of the Hyper Net HS Geonet is validated.

The ratio between the rates of leachate flow through a composite liner with CCL underliner and a composite liner with a GCL underliner is:

$$k_{CCL} := 3.28 \times 10^{-9} \quad \text{ft / sec}$$

(a) Published GCL Value:

$$k_{GCL} := 1.64 \cdot 10^{-10} \quad \text{ft / sec}$$

$$t_{CCL} := 3 \quad \text{ft}$$

$$t_{GCL} := 0.033 \quad \text{ft}$$

$$h := to$$

$$h = 0.017 \quad \text{ft}$$

$$qratio := \left(\frac{k_{CCL}}{k_{GCL}}\right)^{0.74} \cdot \frac{\left[1 + 0.1 \cdot \left(\frac{h}{t_{CCL}}\right)^{0.95}\right]}{\left[1 + 0.1 \cdot \left(\frac{h}{t_{GCL}}\right)^{0.95}\right]}$$

$$qratio = 8.71$$

(b) Polymer-treated GCL: $k_{GCL} := 9.8 \cdot 10^{-11}$ ft / sec

$$qratio := \left(\frac{k_{CCL}}{k_{GCL}}\right)^{0.74} \cdot \frac{\left[1 + 0.1 \cdot \left(\frac{h}{t_{CCL}}\right)^{0.95}\right]}{\left[1 + 0.1 \cdot \left(\frac{h}{t_{GCL}}\right)^{0.95}\right]}$$

$qratio = 12.76$

(c) Standard GCL: $k_{GCL} := 3.6 \cdot 10^{-10}$ ft / sec

$$qratio := \left(\frac{k_{CCL}}{k_{GCL}}\right)^{0.74} \cdot \frac{\left[1 + 0.1 \cdot \left(\frac{h}{t_{CCL}}\right)^{0.95}\right]}{\left[1 + 0.1 \cdot \left(\frac{h}{t_{GCL}}\right)^{0.95}\right]}$$

$qratio = 4.87$

References

Giroud, J. P. (1997). "Equations for calculating the rate of liquid migration through composite liners due to geomembrane defects." *Geosynthetics international*, 4(3-4), 335-348.

Giroud, J. P., Badu-Tweneboah, K., and Soderman, K. L. (1997a). "Comparison of lechate flow through compacted clay liners and geosynthetic clay liners in landfill liner systems." *Geosynthetics International*, 4(3-4), 391-431.

Giroud, J. P., Gross, B. A., Bonaparte, R., and McKelvey, J. A. (1997b). "Leachate flow in leakage collection layers due to defects in geomembrane liners." *Geosynthetics International*, 4(3-4), 215-292.

ATTACHMENT 2
PRODUCT DATA SHEETS

GSE

GSE STANDARD PRODUCTS

Product Data Sheet

GSE HyperNet Geonets

GSE HyperNet geonets are synthetic drainage materials manufactured from a premium grade high density polyethylene (HDPE) resin. The structure of the HyperNet geonet is formed specifically to transmit fluids uniformly under a variety of field conditions. HDPE resins are inert to chemicals encountered in most of the civil and environmental applications where these materials are used. GSE geonets are formulated to be resistant to ultraviolet light for time periods necessary to complete installation. GSE HyperNet geonets are available in standard, HF, HS, and UF varieties.

The table below provides index physical, mechanical and hydraulic characteristics of GSE geonets. Contact GSE for information regarding performance of these products under site-specific load, gradient, and boundary conditions.

Product Specifications

TESTED PROPERTY	TEST METHOD	FREQUENCY	MINIMUM AVERAGE ROLL VALUE[c]			
			HyperNet	HyperNet HF	HyperNet HS	HyperNet UF
Product Code			XL4000N004	XL5000N004	XL7000N004	XL8000N004
Transmissivity[a], gal/min/ft (m^2/sec)	ASTM D 4716-00	1/540,000 ft^2	9.66 (2 x 10^{-3})	14.49 (3 x 10^{-3})	28.98 (6 x 10^{-3})	38.64 (8 x 10^{-3})
Thickness, mil (mm)	ASTM D 5199	1/50,000 ft^2	200 (5)	250 (6.3)	275 (7)	300 (7.6)
Density, g/cm^3	ASTM D 1505	1/50,000 ft^2	0.94	0.94	0.94	0.94
Tensile Strength (MD), lb/in (N/mm)	ASTM D 5035	1/50,000 ft^2	45 (7.9)	55 (9.6)	65 (11.5)	75 (13.3)
Carbon Black Content, %	ASTM D 1603, modified	1/50,000 ft^2	2.0	2.0	2.0	2.0
Roll Width, ft (m)			15 (4.6)	15 (4.6)	15 (4.6)	15 (4.6)
Roll Length, ft (m)[b]			300 (91)	250 (76)	220 (67)	200 (60)
Roll Area, ft^2 (m^2)			4,500 (418)	3,750 (348)	3,300 (305)	3,000 (278)

NOTES:

- [a]Gradient of 0.1, normal load of 10,000 psf, water at 70° F (20° C), between steel plates for 15 minutes.
- [b]Please check with GSE for other available roll lengths.
- [c]These are MARV values that are based on the cumulative results of specimens tested by GSE.

DS017 R07/07/03

Americas	GSE Lining Technology, Inc.	Houston, Texas	800-435-2008	281-443-8564	Fax: 281-230-8650
Europe/Middle East/Africa	GSE Lining Technology GmbH	Hamburg, Germany		49-40-767420	Fax: 49-40-7674233
Asia/Pacific	GSE Lining Technology Company Ltd.	Bangkok, Thailand		66-2-937-0091	Fax: 66-2-937-0097

This product data sheet is also available on our website at:

www.gseworld.com

CETCO LINING TECHNOLOGIES

Certified Properties

BENTOMAT® ST CERTIFIED PROPERTIES

MATERIAL PROPERTY	TEST METHOD	TEST FREQUENCY $ft^2(m^2)$	REQUIRED VALUES
Bentonite Swell Index[1]	ASTM D 5890	1 per 50 tonnes	24 ml/2g min.
Bentonite Fluid Loss[1]	ASTM D 5891	1 per 50 tonnes	18 ml max.
Bentonite Mass/Area[2]	ASTM D 5993	40,000 ft^2 (4,000 m^2)	0.75 lb/ft^2 (3.6 kg/m^2) min
GCL Grab Strength[3]	ASTM D 4632 ASTM D 6768	200,000 ft^2 (20,000 m^2)	90 lbs (400 N) MARV 22.5 lbs/in (40 N/cm) MARV
GCL Peel Strength[3]	ASTM D 4632 ASTM D 6496	40,000 ft^2 (4,000 m^2)	15 lbs (65 N) min 2.5 lbs/in (4.4 N/cm) min
GCL Index Flux[4]	ASTM D 5887	Weekly	1 x 10^{-8} m^3/m^2/sec max
GCL Hydraulic Conductivity[4]	ASTM D 5887	Weekly	5 x 10^{-9} cm/sec max
GCL Hydrated Internal Shear Strength[5]	ASTM D 5321 ASTM D 6243	Periodic	500 psf (24 kPa) typ @ 200 psf

Bentomat ST is a reinforced GCL consisting of a layer of sodium bentonite between a woven and a nonwoven geotextiles, which are needlepunched together.

Notes

[1] Bentonite property tests performed at a bentonite processing facility before shipment to CETCO's GCL production facilities.
[2] Bentonite mass/area reported at 0 percent moisture content.
[3] All tensile strength and peel strength testing is performed in the machine direction using 4 inch grips per modified ASTM D 4632. Results are reported as minimum average roll values unless otherwise indicated. Upon request, tensile strength can be reported per ASTM D 6768 and peel strength can be reported per ASTM D 6496.
[4] Index flux and permeability testing with deaired distilled/deionized water at 80 psi (551kPa) cell pressure, 77 psi (531 kPa) headwater pressure and 75 psi (517 kPa) tailwater pressure. Reported value is equivalent to 925 gal/acre/day. This flux value is equivalent to a permeability of 5×10^{-9} cm/sec for typical GCL thickness. Actual flux values vary with field condition pressures. The last 20 weekly values prior the end of the production date of the supplied GCL may be provided.
[5] Peak values measured at 200 psf (10 kPa) normal stress for a specimen hydrated for 48 hours. Site-specific materials, GCL products, and test conditions must be used to verify internal and interface strength of the proposed design.

CETCO has developed an edge enhancement system that eliminates the need to use additional granular sodium bentonite within the overlap area of the seams. We call this edge enhancement, SuperGroove™, and it comes standard on both longitudinal edges of Bentomat® ST. It should be noted that SuperGroove™ does not appear on the end-of-roll overlaps and recommend the continued use of supplemental bentonite for all end-of-roll seams.

CETCO® LINING TECHNOLOGIES

1500 W. Shure Drive Arlington Heights, IL 60004 USA 800.527.9948 Fax 847.577.5571
For the most up-to-date information please visit our website, www.cetco.com
A wholly owned subsidiary of AMCOL International