9 April 2010 Project No. 073-81694.022.1

Mr. Frank Filas, Environmental Manager
Energy Fuels Resources Corporation
44 Union Blvd., Suite 600
Lakewood, Colorado 80228

RE: TAILINGS CELL FOUNDATION AND CLOSURE COVER SYSTEM SETTLEMENT ANALYSES ADDENDUM, PIÑON RIDGE PROJECT, MONTROSE COUNTY, COLORADO

Dear Frank:

Golder Associates Inc. (Golder) has prepared this Tailings Cell Foundation and Closure Cover System Settlement Analyses Addendum for Energy Fuels Resources Corporation (EFRC) for the Piñon Ridge Project located in Montrose County, Colorado. This addendum augments information included in EFRC's Radioactive Material License Application (EFRC 2009) submitted to the Colorado Department of Public Health and Environment (CDPHE) on the 18th of November 2009. Specifically, this report serves as an Addendum to the Tailings Cell Design Report (Golder 2008) for the project. The application was found substantially complete by CDPHE (2009) in mid-December, and CDPHE has begun the adequacy review process. On the 26th of February, CDPHE issued their first formal Request for Additional Information (RAI) (CDPHE 2010).

1.0 SCOPE OF THIS REPORT

This report provides responses to a portion of the geotechnical consideration comments, relating to tailings cell settlement, from CDPHE's RAI (CDPHE, 2010), where CDPHE has reviewed documentation for completeness in accordance with Section 2.0 of NUREG 1620 (NRC 2003) (Geotechnical Stability). The following comment received from CDPHE (2010) is addressed in this report:

> *"The other…area requiring additional information concerns the settlement properties of the foundation, tailings, cover system, and overall cell. Section 2.3 of NUREG 1620 presents the complete guidance needed for settlement evaluation. In general, both total and differential settlement should be analyzed and evaluated with respect to the cracking potential of the radon barrier and the other engineering components of the cell (e.g., GCL, geomembrane, leachate collection and recovery system, entire cover system, etc.). The analysis should verify that the components can maintain their integrity when subjected to the induced strain associated with the calculated settlement"*

2.0 APPROACH

Foundation settlements were calculated using the elastic half-space model and the material parameters selected based on the results of the geotechnical investigation performed by Golder (2008a). Settlement analyses were performed on Tailings Cell A, the southernmost tailings cell, which is proposed for construction first, at the time of mill construction. The settlement values for Cell A are considered conservative due to the fill height and the underlying geology. Cell A is generally underlain by the thickest alluvial deposits, which are more compressible than the underlying bedrock, and will produce the greatest strains on the liner system due to deformation. The maximum height of embankment fill required for

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Cell A construction is approximately 25 feet, which is considered representative of typical conditions. Although there are local areas constructed with as much as 35 feet of fill, the majority of the perimeter berms for Cells A, B, and C will be constructed with 20 to 25 feet of fill.

It was assumed that the foundation for portions of the tailings cell constructed in cut will not settle due to the net unloading of the foundation soil. The tailings cells will be constructed primarily below grade in excavations extending approximately 70 feet below the ground surface, in general accordance with the regulatory statement (per 6 CCR 1007-1 Part 18, Appendix A, Criterion 3) that "*the 'prime option' for disposal of tailings is placement below grade*," but that "*flexibility is provided in the criteria to allow achieving an optimum tailings disposal program on a site-specific basis*". Refer to the Tailings Cell Design Report (Golder 2008b) for additional information on the specifics of the design.

The laboratory test results presented in Golder (2008a) indicate the native soil deposits consist primarily of compact to dense wind-blown silty sand deposits (loess) and have the potential to collapse if loaded and then saturated with water. The decrease in height of the soil samples taken from the Cell A foundation area ranges from 3.9 to 9.2 percent upon saturation, and when under loads between 2,000 and 8,000 pounds per square foot (psf). Because the tailings and water storage facilities at the mill will be lined with a double composite geomembrane liner system and intervening leak collection and recovery system (refer to Golder 2008b; Golder 2008c), significant changes in soil moisture content are not anticipated, and little risk of soils becoming saturated due to milling activities exists. Nevertheless, Golder calculated the potential strains on the foundation liner system for the unlikely extreme condition of foundation soils becoming saturated.

Tailings and closure cover system settlements were calculated using the large strain consolidation model in order to account for the non-linear material properties. Tailings properties selected for this study were based on the laboratory data for uranium tailings produced at two nearby facilities (the Cotter Mill and Moab Mill) with similar ore and processing methods. The Cotter Mill, located near Cañon City, Colorado processes the same geological unit (the Salt Wash member of the Morrison formation) as is proposed for the Piñon Ridge Project. The Moab Mill was the second analogue used to develop tailings properties. These tailings were produced from the Salt Wash member and the similar Chinle formation. Tailings and closure cover deformations were estimated based on the proposed average production rate of 500 tons per day (tpd) and employing the Tailings Cell A geometry as discussed in Golder (2008b). The geometries of Cells A, B, and C are very similar, and the closure cover deformations calculated based on tailings consolidation and settlement will be essentially equal for all three cells. For conservatism, analyses were conducted assuming an impervious bottom boundary (i.e., assuming the underdrain system is not in-use or ineffective), which results in a single drained situation and prolongs consolidation. Tailings and closure cover system settlements were calculated in four stages:

- Stage 1 – Impoundment Filling. This stage consists of the tailings deposition with the influx of 500 tpd of dry tailings at an initial slurry density of 27.3 percent solids. During this phase, tailings are assumed to be fully submerged with the phreatic surface coinciding with the tailings surface.

- Stage 2 – Impoundment Drying. This stage follows the impoundment filling (i.e. there is no influx of tailings) with the intent to allow drying of the tailings surface in order to achieve sufficient strength prior to placement of the interim cover. Drying of the tailings surface was modeled by imposing an average evaporation rate of 0.014 ft/day (e.g., 5 inch/month) at the top boundary for a duration of 60 days. The adopted evaporation rate was selected based on the climatic parameters discussed in Golder (2008b).

- Stage 3 – Interim Cover Placement. The tailings impoundment surface will be loaded with 240 psf, assuming placement of the interim cover with a thickness of approximately 2 feet and an average density of 120 pounds per cubic foot (pcf).

- Stage 4 – Closure Cover Placement. Placement of the final closure cover will not begin until 90 percent of total settlements have occurred, as discussed in the Reclamation Specifications for the project (Golder, 2009). The tailings impoundment surface will be loaded with 1,620 psf (i.e., interim cover is loaded with an additional 1,380 psf). This scenario assumes that the tailings impoundment surface is loaded with an approximately 13.5 foot thick cover system with an average material density of 120 pcf. The proposed cover system (Kleinfelder, 2009) consists of the following layers (from top to bottom): 1) Rock Mulch = 0.5 ft, 2) Native Soil = 1.5 ft, 3) Bio-Intrusion Layer = 1 ft, 4) Filter Layer = 0.5 ft, 5) Capillary Break = 1 ft, 6) Radon Barrier = 7 ft, and 7) Interim Cover = 2 ft.

3.0 TAILINGS CELL SETTLEMENT ANALYSES

3.1 Criteria for Determining Acceptable Settlements

The maximum allowable strain on the liner system is controlled by the strain tolerance of the high density polyethylene (HDPE) and geosynthetic clay liner (GCL) components. Although specific suppliers and products have not yet been selected, minimum yield strains for HDPE materials are included in the project specifications (Golder, 2008c). According to the specifications, the minimum yield strain for HDPE geomembrane is 12 percent, and the minimum elongation of HDPE geomembrane at break is 700 percent. There is additional concern when a geomembrane is exposed to tension perpendicular to seams. In these cases, a general rule-of-thumb is that the allowable strain on the geomembrane is about half the value for the un-seamed sheet material (Giroud et al, 1995). For this reason, horizontal seams are not allowed on side slopes (Golder, 2008c). Tensile stresses applied to a geomembrane parallel to the seams are generally not a large concern, provided that the seams are good quality, and were installed in accordance with the specifications. For these reasons, strains of up to 12 percent will be considered acceptable for HDPE geomembrane components.

For GCL materials, the yield strain is not typically included on standard specification sheets. For these materials, the yield strain is typically controlled by the geotextile layers on the top and bottom of the clay. Geotextiles generally have yield strains in excess of 50 percent. For reference, we have attached standard specifications for GCL and geotextile materials produced by the Geosynthetic Institute (GSI) (refer to Attachment B). The GSI is a highly respected organization that is involved in developing industry guidelines for geosynthetic materials.

The bentonite component of GCLs also has a high strain tolerance, and can heal cracks (if they occur) over time. If the GCL were to experience such large strains, thinning of the bentonite layer (and a corresponding increase in permeability) would likely be the primary concern. A second concern would be the GCL panel overlap. To avoid separation of panels caused by strain on the liner system, project specifications (Golder, 2008c) include required overlaps twice as large as typical manufacturer recommended overlaps.

In summary, the least strain-tolerant component of the liner system is the HDPE geomembrane. Accordingly, the maximum acceptable strain on the liner system is 12 percent, the yield strain of the HDPE component.

3.2 Settlements From Embankment Fill Placement

Based on the results of the geotechnical investigation (Golder, 2008a), foundation soils are expected to consist primarily of compact to dense wind-blown silty sand deposits (loess) with an elastic modulus on the order of 1000 ksf (Bowles, 1996). In addition, Golder modeled the underlying bedrock with an elastic modulus of 10,000 ksf. Because the bedrock is much stiffer, the majority of the elastic compression can be expected to occur in the soil deposits. This analysis conservatively assumes a uniform soil thickness of 70 feet, which corresponds with the deepest deposits in the Cell A foundation area (the average depth is approximately 55 to 60 feet). Figure 1 shows the proposed grading plan for Cell A, the locations of the borings (with depth to bedrock indicated), and a cut/fill isopach for Cell A construction.

Based on the tailings cell design geometry (Golder, 2008b), the maximum foundation loading is expected to occur on the north side of Tailings Cell A, which is to be constructed with a maximum of approximately 25 feet of fill. Golder assumed the embankment fill will have an average density of approximately 126 pcf. This value assumes that the fill is placed at 95 percent of the maximum dry density at the optimum moisture content, as determined by the standard Proctor test results contained in Golder (2008a). Golder also assumed that no settlements will occur in areas constructed in cut.

The strains on the foundation liner system were calculated using the following steps:

- Step 1 - Use the Boussinesq solution to calculate the increase in vertical stress in the soils beneath the fill zones. Calculate the stress changes at the point expected to experience the most settlement (point A, located at the inside edge of the berm crest) and at the point expected to experience the least settlement (point B, located at the cut/fill interface).
- Step 2 - Use the increase in stress calculated in step one and the elastic modulus to calculate the change in height of the soil columns beneath points A and B.
- Step 3 - Determine the differential settlement between points A and B.
- Step 4 - Calculate the change in the length of the liner system caused by the differential settlement between points A and B.
- Step 5 - Calculate the strain on the liner system by dividing the change in the liner length by the initial, pre-settlement liner (slope) length between point A and point B. This calculation assumes that the strain will be uniformly distributed across the liner.

The above calculation shows that the differential settlement on the foundation liner system caused by embankment fill placement will be approximately 0.14 feet over a slope length of 79 feet. This differential settlement will produce a decrease in the slope (liner system) length of 0.05 feet, which is equivalent to a strain of 0.06 percent. Therefore, according to the criteria set forth in Section 3.1, the liner system will not be damaged by settlements induced by embankment construction. A schematic showing the pre- and post-settlement slope configuration is shown below as Figure 2.

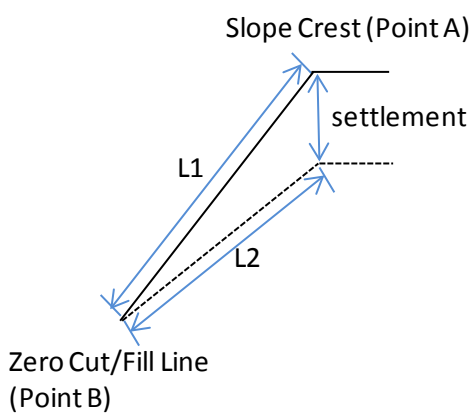

Figure 2 - Foundation strains caused by embankment construction.

3.3 Settlements From Tailings Placement

Golder used the procedure described above for calculating foundation settlements due to filling of Cell A with tailings. Golder conservatively assumed that the average density of the tailings will be 125 pcf. Based on the Cell A grading plan presented in Golder (2008b), the maximum depth of tailings within the

cell will be approximately 85 feet. For this case, the differential settlement was calculated between a soil column located beneath the Cell A berm crest and a soil column located at the toe of the slope (at the base of the impoundment). Based on the calculation, the differential settlement will be approximately 0.76 feet over a slope length of 269 feet. This differential settlement will produce an increase in the slope (liner system) length of 0.24 feet, which is equivalent to a strain of 0.09 percent. Therefore, according to the criteria described in Section 3.1, the liner system will not be damaged by settlements induced by filling Cell A with tailings and constructing the cover system. A schematic showing the pre- and post-settlement slope configuration is shown below as Figure 3.

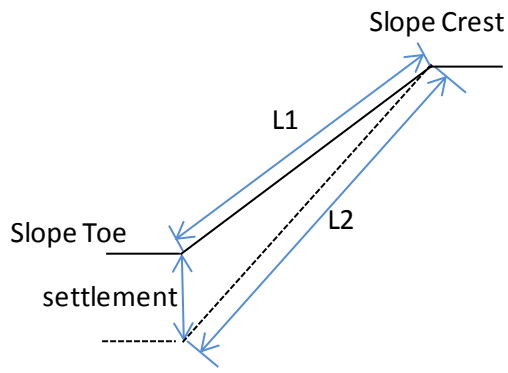

Figure 3 - Foundation strains caused by tailings placement.

3.4 Potential Settlements From Foundation Soil Collapse

Although Golder considers it extremely unlikely that milling activity will saturate native soils beneath the tailings storage facilities due to the proposed liner systems, Golder calculated the liner strains that would occur if the soils beneath Cell A become saturated and collapse. Golder (2008a) previously performed a series of consolidation/collapse tests on undisturbed samples of foundation soils. In the Cell A footprint, the minimum collapse potential found was 3.9 percent (at boring GA-BH-40). The maximum collapse potential found was 7.4 percent (average of tests performed on samples from GA-BH-41).

Within the Cell A footprint, the thickness of soil appears to range from approximately 48 to 70 feet. Golder assumed that the maximum differential settlement will occur between a location with deep soil deposits with high collapse potential and a location with shallow soil deposits and low collapse potential. The majority of Cell A will be constructed in cuts of up to 70 feet deep. It is possible, therefore, that there will be no remaining native soils at the base of the impoundment in some areas (which is highly likely for portions of Cell B and C). It is also possible that at the top of the Cell A slopes, a native soil column as much as 70 feet in height may exist. The maximum possible differential settlement will be between a 70 foot native soil column with a collapse potential of 7.4 percent and a column with no native soils. Under this worst-case condition, the maximum differential settlement is 5.2 feet. These assumptions indicate that complete collapse of the foundation soils beneath the Cell A foundation would produce strains on the liner of approximately 0.72 percent. Therefore, according to the criteria described in Section 3.1, the liner system will not be damaged by settlements induced by collapse of foundation soils beneath Cell A. A schematic showing the pre- and post-settlement slope configuration is shown below as Figure 4.

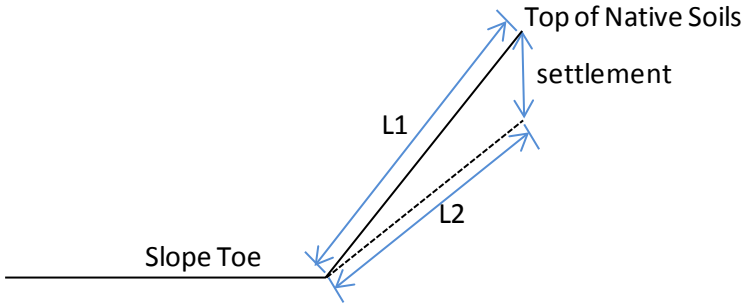

Figure 4 - Potential foundation strains from native soil collapse.

4.0 TAILINGS AND CLOSURE COVER SYSTEM SETTLEMENTS

4.1 Rationale

There are three purposes for conducting settlement analysis on the tailings and closure cover system:

- It is important to verify that the post-settlement cover system will maintain adequate drainage grades.
- Large strains may have an adverse affect on the integrity of the radon barrier. The results of the settlement analysis can be used to verify that the cover placement schedule is adequate to minimize the risk of cracking the radon barrier.
- The settlement analysis can be used to estimate the density of the tailings at the end of placement. The calculated density can then be used to verify the impoundment has the required storage capacity.

4.2 Inputs and Assumptions

Based on the tailings cell design reports (Golder, 2008b; Kleinfelder, 2009) and the available uranium tailings properties (taken from laboratory tests performed on the Cotter and Moab Mill tailings), tailings and closure cover settlement analyses were conducted using the following assumptions and material parameters:

- Tailings production rate is 500 tpd of solids;
- Tailings solids specific gravity is 2.8;
- Tailings exhibit non-liner compressibility and permeability relationships. Hence, the large-strain consolidation numerical code *CONDES* was employed to calculate tailings settlements utilizing the following material models (see e.g. Abu-Hejleh and Znidarcic, 1994; Abu-Hejleh and Znidarcic,1996):

$$e = A(\sigma' + Z)^B \qquad \text{Compressibility}$$

$$k = C\,e^D \qquad \text{Permeability}$$

where *e* denotes the void ratio, σ' stands for the effective stress and *k* is hydraulic conductivity functionally dependent on void ratio. In the above equations, the constants *A, B, C, D, and Z* are material parameters discussed in more detail in Attachment A.

- Uranium tailings parameters assumed for the settlement analyses are summarized in Table 4.1, with a detailed discussion of the material parameter development provided in Attachment A.

TABLE 4.1

COMPRESSION AND PERMEABILITY PARAMETERS

A ($1/psf^B$)	B (-)	Z (psf)	C (ft/day)	D (-)
2.014	-0.131	49.963	1.64×10^{-2}	3.97

- A simplified stage elevation-area-volume curve (see Table 4.2) was employed for the tailings deposition modeling based on the Golder (2008b) Tailings Cell Design Report.

TABLE 4.2

STAGE ELEVATION-AREA-VOLUME CURVE FOR TAILINGS DEPOSITION ANALYSIS

Stage	Start Elev. (ft)	Stop Elev. (ft)	Area (ft2)	Volume (ft3)
1	5440	5460	272,937	5,458,749
2	5460	5485	561,248	19,489,947
3	5485	5500	877,930	32,658,890
4	5500	5520	1,118,859	55,036,068

- Maximum tailings height is 80 feet (see Table 4.2).
- A piece-wise constant filling rate was determined based on the adopted material parameters and the simplified stage elevation-area-volume relationship (Table 4.2). The calculated filling rates used for Stage 1 settlement analysis are summarized Table 4.3.

TABLE 4.3

FILLING RATES FOR TAILINGS DEPOSITION ANALYSIS

Stage	Max. Column Height (ft)	Avg. Area (ft2)	Filling rate (ft/day)
1	20	272,937	4.63E-2
2	45	561,248	2.25E-2
3	60	877,930	1.44E-2
4	80	1,118,859	1.13E-2

- Minimum dry freeboard of the tailings cell is 5.0 feet.
- The tailings slurry will be deposited with an initial solids content of 27.3%.
- Tailings will exhibit relatively fast initial settlement associated with the release of water to the tailings pool until reaching the solids content of approximately 70%. At this point, the dry density of tailings will be 79.2 pcf with a corresponding void ratio of approximately 1.2.
- At the end of deposition (end of Stage 1), the tailings surface will be exposed to an average evaporation rate of 0.014 ft/day (e.g., 5 inch/month) for 60 days to achieve sufficient strength for the interim cover placement.

4.3 Model Code for Large Strain Consolidation Analyses

To account for the non-linearity in the tailings material properties, the computer program *CONDES* was used to simulate the accretion and consolidation processes. *CONDES* is a one-dimensional large-strain finite difference computer program used to model impoundment filling, consolidation and desiccation using large-strain consolidation theory (Gibson et al., 1967). It solves a non-linear second order partial differential equation formulated for one-dimensional compression, three-dimensional shrinkage and propagation of vertical cracks in soft fine-grained soils. It provides the one-dimensional time-dependent solutions of void ratio distribution (solid content distributions), layer thickness, and gives information on propagation and volume of cracks (Yao and Znidarcic, 1997). Governing equations used to calculate the one-dimensional tailings compression can be summarized as follows:

Velocity Function:

$$v_u = \frac{k \cdot (G_s - 1)}{1+e} + \frac{k \cdot (1+e_o)}{\gamma_w (1+e)} \frac{d\sigma_v'}{de} \frac{\partial e}{\partial a}$$

Conservation of mass:

$$\frac{\partial v_u}{\partial a} = \frac{-1}{1+e} \frac{\partial e}{\partial t}$$

Where:

t	=	time
e	=	void ratio
σ_v'	=	vertical effective stress
a	=	elevation in the Lagrangian coordinate system
k	=	hydraulic conductivity
e_o	=	void ratio at zero effective stress
G_s	=	specific gravity of soil particles
v_u	=	velocity function
γ_s, γ_w	=	unit weights of soil solids and water, respectively

4.4 Results

A three-dimensional tailings deposition analysis using the approach by Gjerapic et al. (2008) indicates an average tailings dry density of approximately 97.7 pcf at the end of the deposition cycle. The corresponding Tailings Cell A capacity is approximately 2.7 million tons (Mt) of dry tailings, as presented in Table 4.4. These results indicate the proposed Cell A geometry will have the required storage capacity.

TABLE 4.4

FILLING TIMES FOR 1D AND 3D TAILINGS DEPOSITION ANALYSES

Filling Time (days)		Impoundment Capacity (Mt)	
1D Method	3D Method	1D Method	3D Method
5,589	5,375	2.79	2.69

Due to a relatively small difference between the three-dimensional model (Gjerapic et al., 2008) and a conventional equivalent one-dimensional model [see e.g. GWP Software (1999)], as demonstrated by the calculated filling times and impoundment capacities in Table 4.4, a one-dimensional model approach using the deepest tailings column with a thickness of 80 feet was used to calculate the interim cover and closure cover settlements. Calculated heights of the tailings column and the corresponding settlements are summarized in Table 4.5.

TABLE 4.5

CALCULATED TAILINGS COLUMN SETTLEMENTS

Stage	Description	Max Column Height (ft)	Cumulative Settlement (ft)	Incremental Settlement (ft)
1	Impoundment Filling	80.00	n/a	n/a
2	Surface Evaporation	79.15	0.85	0.85
3	Interim Cover Placement	78.81	1.19	0.34
4	Closure Cover Placement 60-day*	77.99	2.01	0.82
4	Closure Cover Placement - final	76.49	3.51	1.50

* Tailings column height approximately 60 days after starting final closure cover placement

For the purposes of determining changes in post-settlement cover grades, we have assumed that the placement of final closure cover materials will require at least 60 days. Because the top of cover will be constructed to a fixed elevation, any settlement that occurs over these 60 days will be compensated for by the placement of additional cover materials, and will therefore not affect the post closure grades. The amount of settlement that will affect the post closure grades was calculated to be 1.5 feet (refer to Table 4.5).

The calculated total settlement values can now be used to evaluate the influence on the post-closure grades. The largest differential settlement will occur between the edge of the tailings cell (zero settlement) and the base of the embankment slope where the thickness of tailings is 80 feet (1.5 feet of settlement). Noting that the tailings cell is designed with internal slopes of 3H:1V, the "flattening" of the closure grades can be estimated as:

$$\text{Grade Loss}\,(\%) = \frac{1.5\ ft}{3.0 \times 80\ ft} \times 100\% = 0.625\%$$

Similarly, it was assumed that settlements occurring during final cover placement will not affect the integrity of the radon barrier. It was assumed that the continuing compaction of the cover soils will heal soils and eliminate the effects of settlements occurring during construction. Therefore, the amount of differential settlement causing strains in the radon barrier was assumed to be 1.5 feet. This amount of differential settlement will cause strains of less than 0.1% in the radon barrier. This small amount of strain will not adversely affect the radon barrier. A schematic showing the pre- and post-settlement cover configuration is shown below as Figure 5.

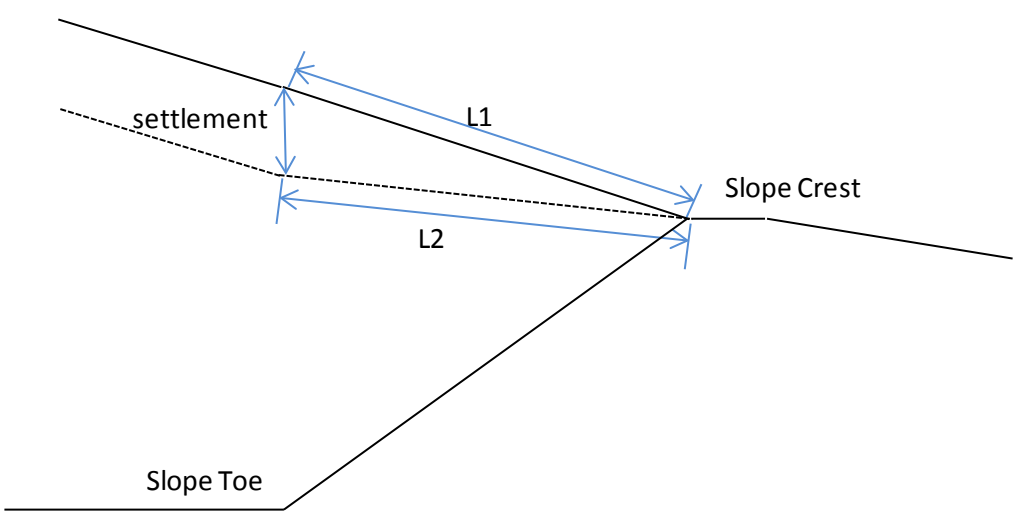

Figure 5 - Cover system strains caused by tailings consolidation.

5.0 CONCLUSIONS

Based on the estimated subsoil elastic properties, the maximum calculated differential foundation settlement will be caused by filling of the impoundment and placement of cover soils. Expected differential settlements result in less than 0.1 percent strain in the foundation liner system. Strains on the tailings cell liner system caused by embankment fill placement are expected to be even less (i.e., 0.06% strain). In the unlikely event that foundation soils become saturated, the differential settlements caused by soil collapse are expected to cause strains on the liner system of less than 1 percent.

Maximum tailings settlement is expected to occur over the tailings cell area where the majority of tailings consist of tailings slimes. Noting that the interim cover construction may start only after the tailings achieve sufficient surface strength, the consolidation analyses presented assume a 60 day drying period after cessation of tailings deposition and prior to interim cover placement. Cover grades are expected to experience slight "flattening" between the time of construction and the end of consolidation. The tailings settlement calculations indicate that the final cover grades are expected to lose approximately 0.6 percent of the original slope. Therefore, assuming construction cover grades of 2 percent (Kleinfelder, 2009), the final cover grades after consolidation might exhibit slopes of 1.4% over the deepest parts of the tailings impoundment. In addition, settlement of the tailings is expected to cause only small strains within the radon barrier (less than 0.1%), which will not adversely impact the function of the radon barrier.

6.0 CLOSING

Golder appreciates the opportunity to provide continued engineering services to EFRC for the Piñon Ridge Project. If you have any questions or comments, please contact the undersigned via phone at 303-980-0540, or via e-mail at kmorrison@golder.com.

Sincerely,

GOLDER ASSOCIATES INC.

David Geier
Senior Project Engineer

Gordan Gjerapic, Ph.D., P.E.
Geotechnical Engineer

Kimberly Finke Morrison, P.E., R.G.
Associate, Senior Project Manager

cc: James Johnson, Bob Monok

ATTACHMENTS

Figure 1 – Tailings Cell A Excavation Grading Plan and Isopach
Attachment A – Material Properties Evaluation for Piñon Ridge Tailings
Attachment B – GSI Standard Specifications for GCL and Geotextile Materials

7.0 REFERENCES

6 CCR 1007-1, Part 18 – "*State Board of Health Licensing Requirements for Uranium and Thorium Processing*," specifically Appendix A (Criteria relating to the operation of mills and the disposition of the tailings or wastes from these operations).

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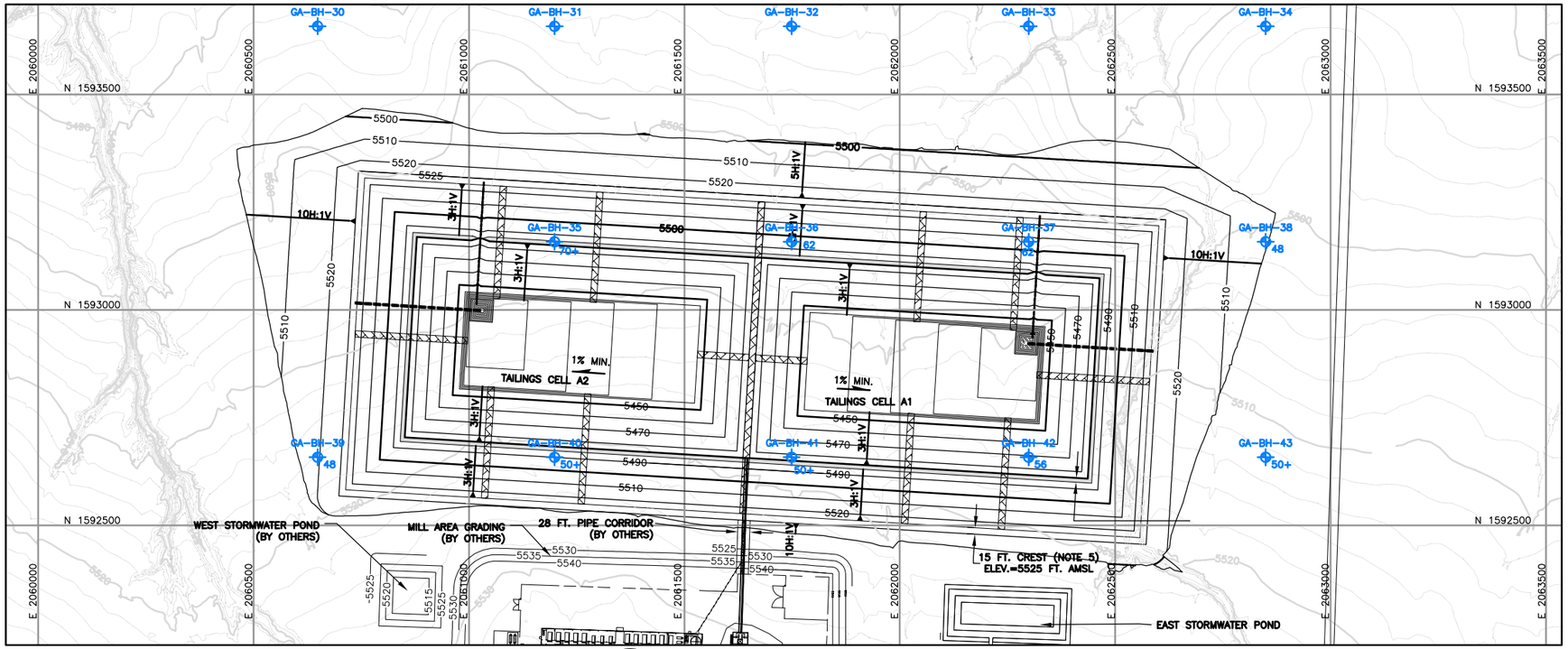
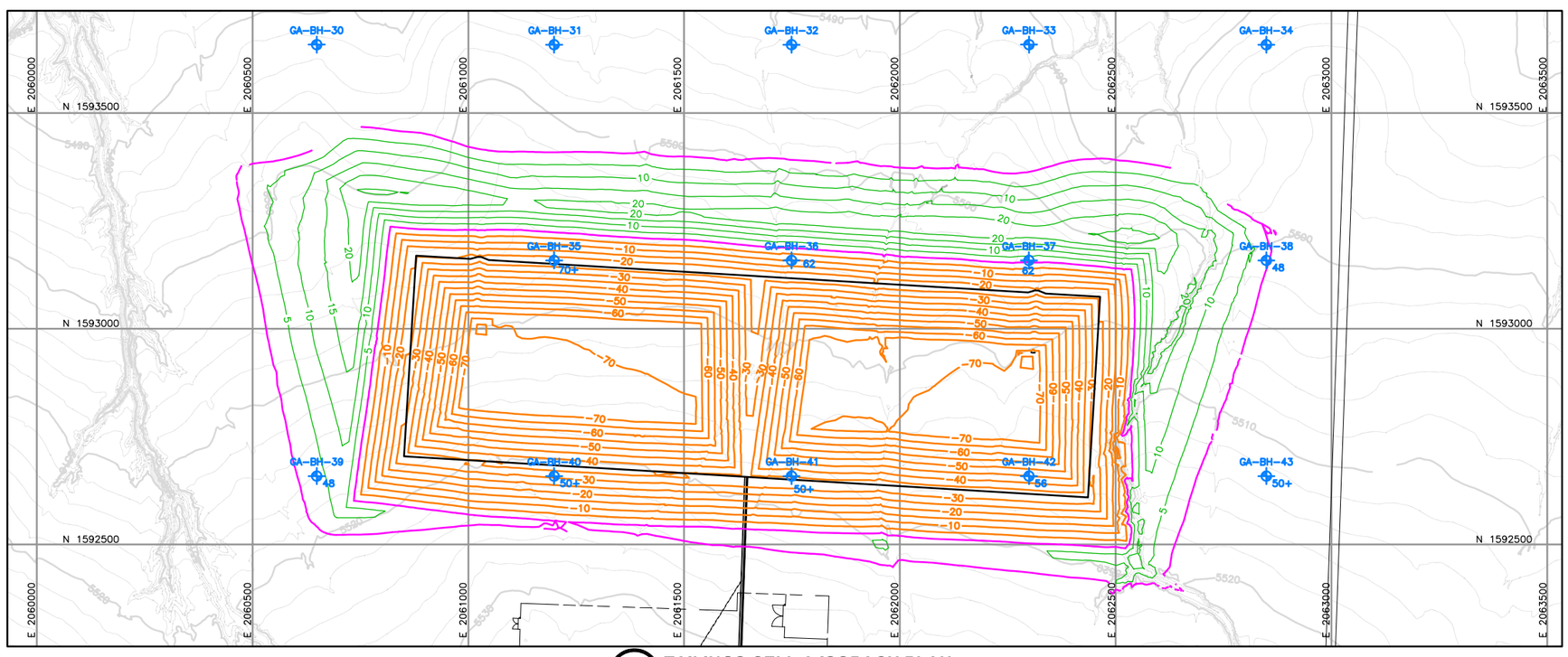
Yao, D.T.C. and Znidarcic, D.Z., 1997, "*User's Manual for Computer Program CONDES*". Florida Institute of Phosphate Research Publication No. 04-055-134.

FIGURES



1/1 TAILINGS CELL A GRADING PLAN

SCALE: 1 IN. = 150 FT.



2/1 TAILINGS CELL A ISOPACH PLAN

SCALE: 1 IN. = 150 FT.

LEGEND

- EXISTING GROUND TOPOGRAPHY (SEE REFERENCE 1)
- PROPOSED FINISHED GRADE TOPOGRAPHY
- RUB SHEET (NOTE 4)
- ANCHOR BENCH
- LCRS RISER PIPES
- UNDERDRAIN RISER PIPES
- ISOPACH CUT CONTOUR
- ISOPACH FILL CONTOUR
- ISOPACH ZERO CONTOUR
- TOE / CREST — SLOPE DIRECTION
- GA-BH-44 70+ — GOLDER 2007 GEOTECHNICAL PHASE 2 BORING LOCATIONS WITH DEPTH TO BEDROCK INDICATED IN LOWER RIGHT

NOTES

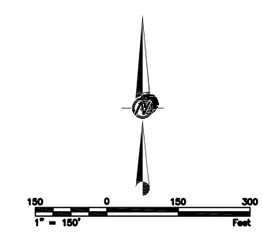
1. EACH TAILINGS CELL IS DESIGNED FOR A MINIMUM CAPACITY OF 2.45 MILLION TONS ASSUMING A DRY DENSITY OF 95 PCF.
2. GRADING PLAN DEVELOPED TO PROVIDE EXCESS MATERIAL FOR FUTURE USE AS CLOSURE COVER BORROW. MATERIAL TO BE STOCKPILED ON SITE WITH MAXIMUM SLOPES OF 3H:1V.
3. GRADING PLAN CONTOURS REPRESENT TOP OF UPPER GEOMEMBRANE WITHIN TAILINGS CELL, AND TOP OF STRUCTURAL FILL OUTSIDE THESE LIMITS.
4. RUB SHEETS PLACED PER CLIENT RECOMMENDATION WHERE NEEDED AROUND TAILINGS CELL PERIMETER TO FACILITATE TAILINGS DELIVERY.
5. EMBANKMENT CREST TO BE SLOPED AT A MINIMUM OF ONE PERCENT INTO THE TAILINGS CELL.

REFERENCES

1. TWO-FOOT CONTOUR BASE MAP PROVIDED BY KLEINFELDER IN JUNE 2008, CREATED FROM DRAWING BY ACCURATE SURVEY & ENGINEERING DATED 9/6/2007.

GRADING QUANTITIES

	CUT (CU. YDS.)	FILL (CU. YDS.)	EXCESS (CU. YDS.)
CELL A	1,713,000	307,000	1,406,000 (CUT)



PROJECT

ENERGY FUELS RESOURCES CORPORATION
PIÑON RIDGE PROJECT - TAILINGS CELL DESIGN
MONTROSE COUNTY, COLORADO

TITLE

TAILINGS CELL A EXCAVATION GRADING PLAN AND ISOPACH

Golder Associates
DENVER, COLORADO

PROJECT No.		073-81694	FILE No.	07381694A039
DESIGN	JWR	02/08	SCALE AS SHOWN	REV. A
CADD	DLG	04/10	FIGURE	1
CHECK	KFM	04/10		
REVIEW	KFM	04/10		

Dwg Name: J:\07JOBS\073-8169 ... DLG\07381694A039-CellA.dwg
Layout Name: 24x36 Landscape (A) Machine: DEN1-L-DGEIER1
Last Updated: Apr 08, 2010 11:23 By: DGEIER
Last Plot: Apr 08, 2010 11:23 By: DGEIER

ATTACHMENT A

MATERIAL PROPERTIES EVALUATION FOR PIÑON RIDGE TAILINGS

OBJECTIVE:

Use existing data to estimate the consolidation properties of the Piñon Ridge tailings. The selected material properties were based on the tailings laboratory results from existing facilities [MFG (2005) and DOE-EM (2008)] provided to Golder by Energy Fuels Resources Corporation (EFRC) on March 22, 2010.

APPROACH:

Tailings laboratory data used to estimate Piñon Ridge properties are summarized in tables 1 and 2.

TABLE 1 – SELECTED COTTER MILL TAILINGS PROPERTIES

Borehole	Depth (ft)	Tailings Type	c_v at 3,200 psf (est) (cm^2/sec)	Cc from 1,600 to 12,800 psf	Void Ratio at 100 psf	Void Ratio at 12800 psf	Void Ratio at 25,600 psf
K	4.0-6.2	Sand Slime - Slime	0.091	0.104	1.22	1.07	1.02
A	8.0-10.0	Slime	0.023	0.317	1.80	1.34	1.25
E	6.0-8.0	Sand Slime	0.142	0.195	1.31	1.01	0.93
Q	22.0-24.0	Sand Slime	0.063	0.278	1.57	1.18	1.10
R	22.0-24.0	Sand Slime	0.063	0.188	1.27	1.02	0.80

Coefficients of consolidation and compression index values in Table 1 were estimated from the consolidation tests performed on tailings samples by Advanced Terra Testing (MFG, 2005).

TABLE 2 – SELECTED MOAB MILL TAILINGS PROPERTIES

Sample No.	Soil Type	Cc	Initial Void Ratio	Ksat (cm/sec)	Dry Density for Ksat prep (pcf)
GABT-03	Sand Tailings	n/a	0.93	9.32E-05	90.5
GABT-04	Sand Tailings	0.15	0.88	3.41E-05	88.2
GABT-05	Sand Tailings	n/a	0.72	2.43E-04	101.7
GABT-06	Sand Tailings	0.07	0.638	n/a	n/a
GABT-07	Transition Tailings	n/a	0.81	1.30E-05	96.3
GABT-08	Sand Tailings	n/a	0.72	3.68E-05	101.4
GABT-09	Transition Tailings	0.2	0.808	6.79E-05	91.8
GABT-10	Transition Tailings	0.17	0.703	n/a	n/a
GABT-11	Slime Tailings	0.38	1.157	n/a	n/a
GABT-12	Slime Tailings	n/a	1.09	9.32E-05	83.6
GABT-13	Slime Tailings	0.34	1.052	n/a	n/a
GABT-14	Slime Tailings	n/a	1.15	9.32E-05	81.2

Unless specified, the void ratios corresponding to the specific permeability value in Table 2 were calculated as

$$e = \frac{\rho_w G_s}{\rho_{dry}} - 1 . \qquad (1)$$

In the above equation ρ_w is the density of water and ρ_{dry} is the dry density of the tailings sample. Specific gravity value was assumed to be equal to Gs=2.8.

The coefficient of volume compressibility was determined as

$$m_v = \frac{1}{1+e_0}\frac{e_0 - e_1}{\sigma'_1 - \sigma'_0} = \frac{1}{1+e_0}\frac{C_c}{0.5(\sigma'_1 + \sigma'_0)\ln(10)} , \qquad (2)$$

where σ'_0 and σ'_1 of 1,600 and 12,800 psf were used to determine m_v values from Table 1 while the reported value of the confining pressure between 2.25 and 2.5 psi (320 to 360 psf) were used to determine m_v values from Table 2.

Saturated permeability values for data in Table 1 were calculated as

$$k = c_v \gamma_w m_v . \qquad (3)$$

Similarly, the coefficient of consolidation was calculated from known k and derived m_v values (using data in Table 2) as

$$c_v = \frac{k}{\gamma_w m_v} \qquad (4)$$

Laboratory measurement values in Table 1 and Table 2, as well as derived compressibility and permeability parameters were used to developed material parameters *A, B, C, D* and *Z* defining the following consolidation relationships (see e.g. Abu-Hejleh and Znidarcic, 1994, 1996):

$$e = A\,(\sigma' + Z)^B \qquad (5)$$

and

$$k = C\,e^D . \qquad (6)$$

In the above relationships, *e* denotes the void ratio, *σ'* stands for the effective stress and *k* is hydraulic conductivity functionally dependent on void ratio. Selected parameters for different systems of units are shown in tables 3 and 4.

TABLE 3 – SELECTED COMPRESSIBILITY PARAMETERS

Units	A	B	Z
(kPa)	1.353	-0.1310	2.393
(psf)	2.014	-0.1310	49.963
(psi)	1.050	-0.1310	0.347

TABLE 4 – SELECTED COMPRESSIBILITY PARAMETERS

Units	C	D
(cm/sec)	5.78E-06	3.973
(ft/day)	1.64E-02	3.973

Selected material properties correspond to an average compression index of approximately C_c=0.23 between 1,000 and 10,000 psf and the coefficient of consolidation of approximately c_v=0.02 cm^2/sec. The permeability and compressibility relationships proposed for the Piñon Ridge project were compared with the laboratory measurements for tailings at existing locations (data in tables 1 and 2) in Figure A-1.

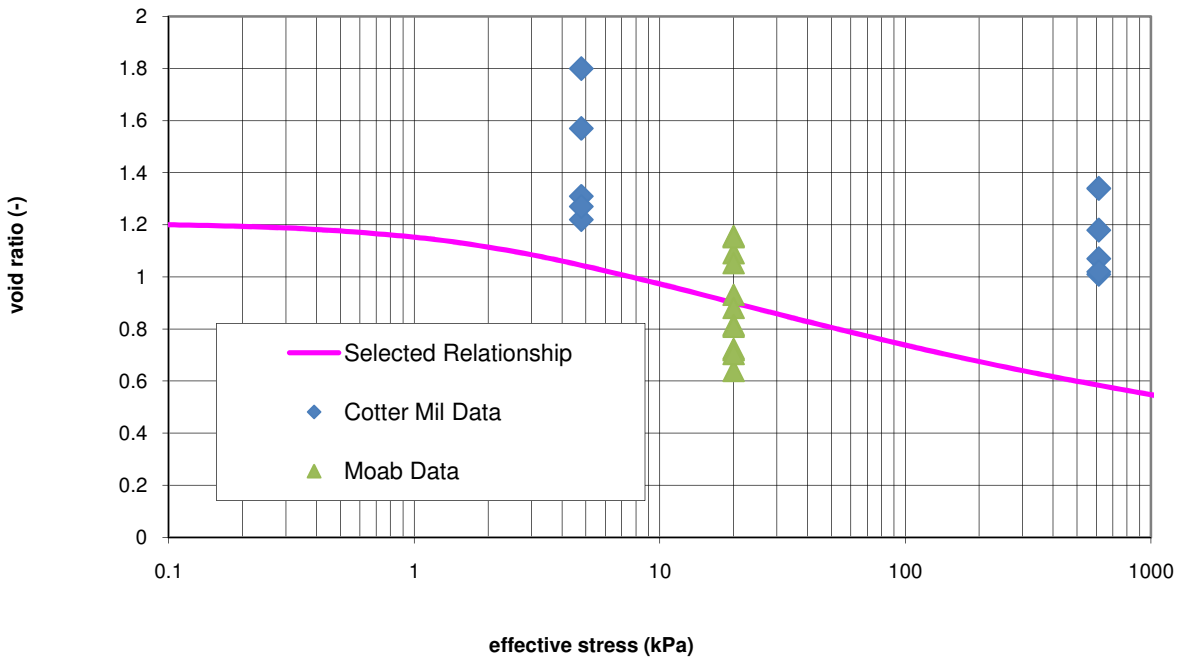
REFERENCES:

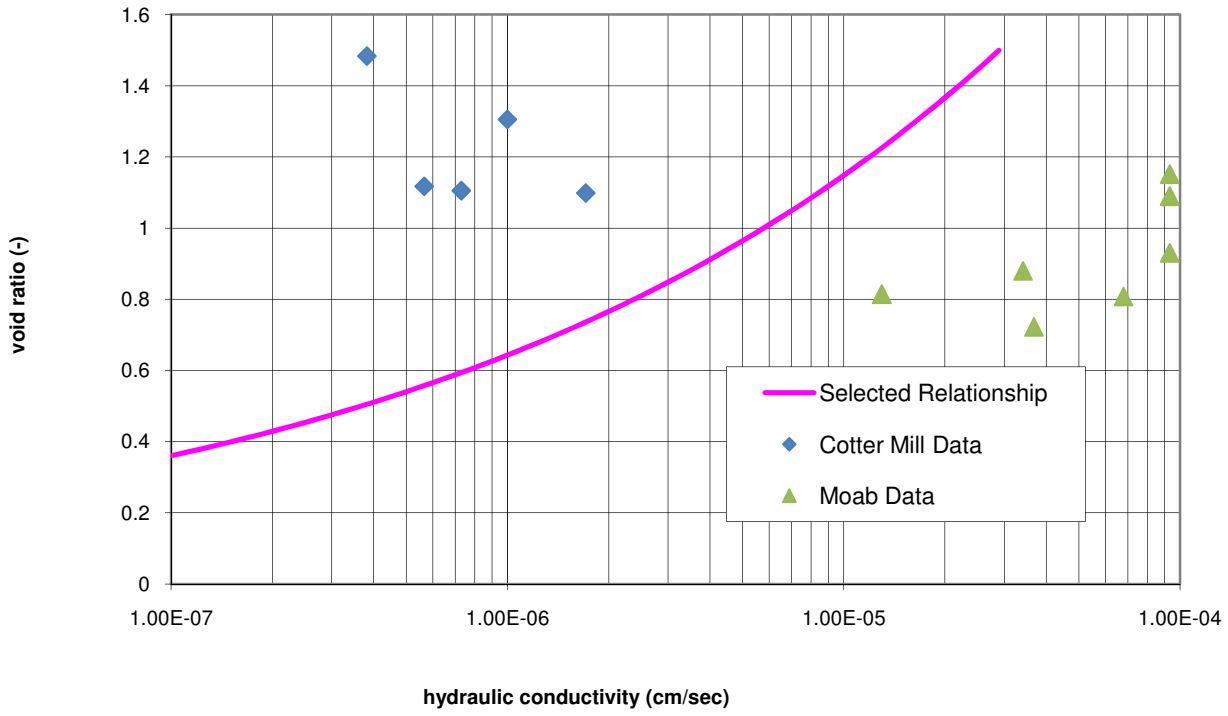
Abu-Hejleh, A.N. and Znidarcic, D., 1994, "Estimation of the Consolidation Constitutive Relations", Computer Methods and Advances in Geomechanics, Siriwardane & Zaman (eds) Balkema, Rotterdam, pp. 499-504.

MFG, 2005, "2005 Update of the Mill Decommissioning and Tailings Reclamation Plan for the Cotter Corporation – Canon City Milling Facility", report prepared for Cotter Corporation, August 2005.

Department of Energy, Environmental Management – Grand Junction Office (DOE-EM), 2008, "Final Remedial Action Plan and Site Design for Stabilization of Moab Title I Uranium Mill Tailings At the Crescent Junction, Utah Disposal Site", remedial action selection report No. DOE-EM/GJ1547, July 2008.

Abu-Hejleh, A. N. and Znidarcic, D., 1996, "Consolidation Characteristics of Phosphatic Clays", Journal of Geotechnical Engineering, ASCE, New-York, Vol. 122, No. 4. pp. 295-301.





Golder Associates	TITLE: MATERIAL PARAMETERS FOR URANIUM TAILINGS		
CLIENT/PROJECT: PINON RIDGE PROJECT	DRAWN: GG	DATE: 4/8/2010	JOB NO. 073-81694
	CHECKED: DLG	SCALE: AS SHOWN	DWG. NO. / REV. NO.
	REVIEWED: KFM	FILE NO. MatProperties.xls	FIGURE A-1

ATTACHMENT B

GSI STANDARD SPECIFICATIONS FOR GCL AND GEOTEXTILE MATERIALS

Geosynthetic Institute
475 Kedron Avenue
Folsom, PA 19033-1208 USA
TEL (610) 522-8440
FAX (610) 522-8441

Original - May 16, 2005
Rev. #1 - March 30, 2009
Revision Schedule on pg. 10

GRI-GCL3*

Standard Specification for

"Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs)"

This specification was developed by the Geosynthetic Research Institute (GRI), with the cooperation of the member organizations for general use by the public. It is completely optional in this regard and can be superseded by other existing or new specifications on the subject matter in whole or in part. Neither GRI, the Geosynthetic Institute, nor any of its related institutes, warrant or indemnifies any materials produced according to this specification either at this time or in the future.

1. Scope

1.1 This specification covers the manufacturing quality control (MQC) of geosynthetic clay liners (GCLs), describing types of tests, the proper test methods, minimum and sometimes maximum values, and the minimum testing frequencies.

Note 1: Geosynthetic Clay Liners (GCLs) are also called Clay Geosynthetic Barriers (GBR-Cs).

1.2 There are two general categories of GCLs covered in this specification: reinforced and nonreinforced. Within each category there are geotextile encased, polymer coated geotextiles, geomembrane related, and geofilm related types.

1.3 This specification is intended to aid manufacturers, suppliers, purchasers and users of GCLs in establishing an acceptable level of effort for manufacturing quality control.

*This GRI standard is developed by the Geosynthetic Research Institute through consultation and review by the member organizations. This specification will be reviewed at least every 2-years, or on an as-required basis. In this regard it is subject to change at any time. The most recent revision date is the effective version.

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1.4 This specification does not address manufacturing quality assurance (MQA), product acceptance testing, or conformance testing. These are independent activities taken by organizations other than the GCL manufacturer.

1.5 The values stated in SI (metric) units are to be regarded as the standard. The U.S. (English) units are calculated values using a "soft" conversion accuracy.

1.6 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards

D 638 Test Method for Tensile Properties of Plastics
D 792 Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement
D 882 Test Method for Tensile Properties of Thin Plastic Sheeting
D 1141 Practice for Preparation of Substitute Ocean Water
D 1505 Test Method for Density of Plastics by the Density-Gradient Method
D 4354 Practice for Sampling of Geosynthetics for Testing
D 4439 Terminology for Geosynthetics
D 4632 Test Method for Grab Breaking Load and Elongation of Geotextiles
D 4759 Practice for Determining the Specification Conformance of Geosynthetics
D 5199 Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
D 5261 Test Method for Measuring Mass per Unit Area of Geotextiles
D 5721 Practice for Air-Oven Aging of Polyolefin Geomembranes
D 5887 Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using Flexible Wall Permeameter
D 5888 Practice for Storage and Handling of Geosynthetic Clay Liners
D 5889 Practice for Quality Control of Geosynthetic Clay Liners
D 5890 Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners
D 5891 Test Method for Fluid Loss of Clay Component of Geosynthetic Clay Liners
D 5993 Test Method for Measuring the Mass Per Unit Area of Geosynthetic Clay Liners
D 5994 Test Method for Measuring the Core Thickness of Textured Geomembrane
D 6102 Guide for Installation of Geosynthetic Clay Liners
D 6141 Guide for Screening the Clay Portion of a GCL for Chemical Compatibility to Liquids

D 6243 Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method
D 6495 Guide for Acceptance Testing Requirements for Geosynthetic Clay Liners
D 6496 Test Method for Determining Average Bonding Peel Strength Between the Top and Bottom Layers of Needle-Punched Geosynthetic Clay Liners
D 6693 Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes
D 6766 Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids
D 6768 Test Method for Tensile Strength of Geosynthetic Clay Liners

2.2 GRI Standards

GM13 Test Properties, Testing Frequency and Recommended Warrant for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes
GM17 Test Properties, Testing Frequency and Recommended Warranty for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes
GM18 Test Properties, Testing Frequency and Recommended Warrant for Flexible Polypropylene (fPP and fPP-R) Nonreinforced and Reinforced Geomembranes (Presently suspended as of May 3, 2004)

2.3 Government Document:

U.S. Environmental Protection Agency Technical Guidance Document "Quality Control Assurance and Quality Control for Waste Containment Facilities," EPA/600/R-93/182, September 1993, 305 pgs.

3. Terminology

3.1 Definition

3.1.1 Geosynthetic Definitions:

3.1.1.1 geotextile, n—a permeability geosynthetic comprised solely of textiles. (ASTM D 4439)
3.1.1.2 geomembrane, n—an essentially impermeable geosynthetic barrier composed of one or more synthetic sheets. (ASTM D 4439)
3.1.1.3 geofilm, n—a thin polymeric film which is essentially impermeable having a thickness no greater than 0.25 mm (10 mils).
3.1.1.4 geotextile-polymer, n—a geotextile which has been coated with, or impregnated by, a polymer such as polypropylene

3.1.1.5 geosynthetic clay liner, n—a manufactured hydraulic barrier consisting of clay bonded to a layer or layers of geosynthetic materials. (ASTM D 4439). Also recall Note 1.

Note 2: Geotextile Related GCL is one in which two geotextiles are used respectively as cap and carrier to the bentonite. Cap and carrier designations in this standard refer to respective orientations during manufacturing. This may or may not be the as-placed orientation in the field. It can be internally reinforced by needle punching or stitching, or be nonreinforced.

Geotextile Polymer Coated GCL is one in which two geotextiles are used respectively as cap and carrier to the encased bentonite, however, one of the geotextiles has been polymer coated in a manner that the permeability and flux are decreased. Within this context a bitumen coated geotextile can be considered as being a polymer. Cap and carrier designations refer to the as manufactured product and not necessarily to the as-placed orientation. It can be internally reinforced by needle punching or stitching, or be nonreinforced.

Geomembrane and Geofilm Related GCLs are those in which a geomembrane or geofilm is included in the cross section either above or below the cap geotextile. It can be internally reinforced needle punching or be nonreinforced. Also in the nonreinforced category is bentonite adhesively bonded to a geomembrane.

3.1.2 Material Definitions

3.1.2.1 bentonite—a distinct type of fine-grained clay soil typically containing not less than 80% montmorillionite clay, usually characterized by high swelling upon wetting.

3.1.2.2 Formulation, n - The mixture of a unique combination of ingredients identified by type, properties and quantity. For geosynthetic materials, a formulation refers to the exact percentages of resin, additives, carbon black and/or other additives. It does not necessarily refer to individual suppliers of each ingredient. The individual suppliers must meet the manufacturer's internal quality control specification.

3.1.3 Organizational Definitions:

3.1.3.1 installer, n—the party who installs, or facilitates installation of, any materials purchased from manufacturers or suppliers.

3.1.3.2 manufacturer, n—the group, corporation, partnership, or individual that manufactures a product.

3.1.3.3 purchaser, n—the person, company, or organization that purchases any materials or work to be performed.

3.1.3.4 supplier, n—the party who supplies material or services.

3.1.4 Quality Definitions:

3.1.4.1 Manufacturing Quality Control (MQC) - A planned system of inspections that is used to directly monitor and control the manufacture of a material which is factory originated. MQC is normally performed by the manufacturer of geosynthetic materials and is necessary to ensure minimum (or maximum) specified values in the manufactured product. MQC refers to measures taken by the manufacturer to determine compliance with the requirements for materials and workmanship as stated in certification documents and contract specifications, ref. EPA/600/R-93/182

3.1.4.2 Manufacturing Quality Assurance (MQA) - A planned system of activities that provides assurance that the materials were constructed as specified in the certification documents and contract specifications. MQA includes manufacturing facility inspections, verifications, audits and evaluation of the raw materials (resins and additives) and geosynthetic products to assess the quality of the manufactured materials. MQA refers to measures taken by the MQA organization to determine if the manufacturer is in compliance with the product certification and contract specifications for the project, ref. EPA/600/R-93/182

3.1.4.3 Construction Quality Control (CQC) - A planned system of inspections that are used to directly monitor and control the quality of a construction project. Construction quality control is normally performed by the geosynthetics manufacturer or installer, or for natural soil materials by the earthwork contractor, and is necessary to achieve quality in the constructed or installed system. Construction quality control (CQC) refers to measures taken by the installer or contractor to determine compliance with the requirements for materials and workmanship as stated in the plans and specifications for the project, ref. EPA/600/R-93/182

3.1.4.4 Construction Quality Assurance (CQA) - A planned system of activities that provide assurance that the facility was constructed as specified in the design. Construction quality assurance includes inspections, verification, audits, and evaluations of materials and workmanship necessary to determine and document the quality of the constructed facility. Construction quality assurance (CQA) refers to measures taken by the CQA organization to assess if the installer or contractor is in compliance with the plans and specifications for a project, ref. EPA.600/R-93/182

4. Significance and Use

4.1 GCLs must be properly manufactured in a manner consistent with a minimum level of quality control as determined by in-house testing of the final product. This specification presents the types of tests, standard methods of the testing, required (usually minimum) test values, and minimum testing frequencies which should be embodied in the manufacturer's quality control documents. The quoted tests, test methods and test values in Table 1 must appear in the MQC plan and the MQC report.

4.2 It should be clearly recognized that manufacturers may perform additional tests or at greater frequency than required in this specification, or both. In this case, the manufacturer's quality control plan will then take precedence over this specification.

4.3 It should also be recognized that purchasers and installers of GCLs may require additional tests or at a great frequency than called for in this specification, or both. The organization(s) producing such project specific specification or quality assurance plan should recognize that such requirements are beyond the current state-of-the-practice. If such a request is made by purchasers or installers, they should clearly communicate the requirements to the manufacturer or supplier during the contract decisions in order that disputes do not arise at a subsequent time.

5. Procedure

5.1 The procedures embodied in this specification are contained in the respective test methods given in Table 1.

5.1.1 The minimum recommended quality control tests for the manufacture of GCLs are given in Table 1. Specific tests are performed on the bentonite, the geosynthetic component materials, and the finished GCL. Table 1(a) is in S.I. (Metric) units and Table 1(b) is in U.S. (English) units.

Note 3: The conversion from S.I. units into U.S. units is soft.

5.1.2 The individual properties in Table 1 are minimum values; except fluid loss, moisture content, and permeability (or flux). They are maximum values. The manner of taking specimens is described in the appropriate test methods. When an average value is indicated, it is listed in the table as "min. ave.", or "max. ave.".

5.2 Bentonite (as received)
Two tests are required; swell index and fluid loss. The latter is a maximum value. These tests should be performed on the bentonite prior to fabrication into a GCL

or on bentonite taken from the manufactured product if the bentonite is modified in any way during manufacturing, e.g., if an adhesive is added.

5.3 Geotextile (as received)
Mass per unit area is required on the as-manufactured cap and carrier fabrics, with different values depending on the fabric being nonwoven or woven.

Note 4: These tests are to be performed on the geotextiles before manufacturing into the final GCL. Removal of the geotextiles from the manufactured product and subsequent testing will give erroneous values and is not an acceptable practice. The exception is polymer coated GCLs where the geotextile must be removed to determine its mass per unit area.

5.4 Geomembrane and Geofilm (as received)
The following tests are required; thickness, density, and tensile strength at break. All are minimum required values. Tensile strength at break is the lowest of machine direction and cross machine direction.

Note 5: These tests are to be performed on the geomembrane or geofilm before manufacturing into the final GCL. Removal of the geomembrane or geofilm from the manufactured product and subsequent testing will give erroneous values and is not an accepted practice.

5.5 GCL (as manufactured)
Six tests are required on the as-manufactured GCL with one having an alternative, i.e., hydraulic conductivity or flux. All are minimum values, with the exception of moisture content and hydraulic conductivity or flux.

5.6 GCL (long-term)
The purpose of these long-term or endurance tests is to provide confidence in the continuing acceptable performance of the bentonite and geosynthetic components of the installed GCL.

5.6.1 The durability of the bentonite is evaluated using a permeant consisting of 0.1 M calcium chloride solution. See ASTM D 6141 which is a guide for this particular aspect of the specification. The GCL is to be hydrated with distilled dionized water prior to conducting the tests with the calcium chloride solution. In this regard, ASTM D6766 Scenario 1 and Method C is the procedure to be used. Furthermore, this test is conducted twice at two different normal pressures, i.e., 35 and 500 kPa. The maximum allowable values are listed in Table 1.

5.6.2 The geotextiles in their as-received condition are evaluated by incubation in a forced air oven per ASTM D5721 set at 60°C for 50 days. The

minimum percent in tensile strength retained at break, as measured by ASTM D6768, is 65%. If individual yarns are used in reinforcing GCLs, they must also meet this same endurance criterion.

5.6.3 The geomembrane in its as-received condition is evaluated for durability via the appropriate GRI Specification. For high density polyethylene (HDPE), the specification is GRI GM13. For linear low density polyethylene (LLDPE), the specification is GRI GM17. For flexible polypropylene (fPP), the specification is GRI GM18.

5.6.4 The geofilm in its as-received condition is evaluated by incubation in a forced air oven per ASTM D5721 set at 60°C for 50 days. The minimum percent tensile strength retained at break for either MD or XMD, as measured by ASTM D882, is reported accordingly and must meet or exceed the specification value.

Note 6: It should be recognized that the above durability criterion for geofilms is not as stringent as the criteria for geomembranes stated in Section 5.6.3.

6. Workmanship and Appearance

6.1 Waterproof ink overlap lines should be printed on both edges of one of the surfaces (geotextile or geomembrane) of the manufactured GCL.

Note 7: The overlap lines are minimally 150 mm (6.0 in.) from the edges of the GCL. Other design-related situations may require greater overlap distances to be printed on the GCLs, e.g., when not backfilled in a timely manner.

6.2 Needle punched and stitch bonded GCLs shall be essentially free of broken needle fragments that would negatively effect the performance of the final product. There must be continuous needle detection and removal devices, e.g., metal detectors and magnets, used during manufacture of GCL products.

6.3 The manufactured GCL shall have good appearance qualities. It shall be free from such defects that would affect the specified properties and integrity of the product.

6.4 General manufacturing procedures shall be performed in accordance with the manufacturer's internal quality control guide and/or documents. ASTM D5888 and D5889 should be followed in this regard.

7. MQC Sampling

7.1 Sampling shall be in accordance with the specific test methods listed in Table 1. If no sampling protocol is stipulated in the particular test method, then test specimens shall be taken evenly spaced across the entire roll width, see ASTM D 4354.

7.2 The number of tests shall be in accordance with the appropriate test methods listed in Table 1.

7.3 The average of the test results should be calculated per the particular standard cited and compared to the minimum value listed in these tables, hence the values listed are the minimum average values and are designated as "min. ave.". When the property is a maximum value, the designation is “max. ave.”.

8. MQC Retest and Rejection

8.1 If the results of any test do not conform to the requirements of this specification, retesting to determine conformance or rejection should be done in accordance with the manufacturing protocol as set forth in the manufacturer's quality manual.

9. Packaging and Marking

9.1 The GCL shall be rolled onto a substantial core, clearly labeled, and enclosed in a waterproof wrapper. Packaging must be adequate for safe transportation to the point of delivery.

9.2 The label should include manufacturer, style, lot and/or roll number, weight, length and width.

10. Conformance and Certification

10.1 Conformance of the manufactured GCL to this specification, or agreed-upon variation thereof, shall be performed by the MQA organization or designated by the purchaser/owner. ASTM D 4759 can be used as a general guide, but individual test methods must be clearly stipulated and communicated to the parties involved.

10.2 Upon request of the purchaser in the contract or order, a manufacturer's certification that the material was manufactured and tested in accordance with this specification, together with a report of the test results, shall be furnished at the time of shipment.

Adoption and Revision Schedule

for

GCL Specification per GRI-GCL3

"Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs)"

Adopted: May 16, 2005

Revision #1: March 30, 2009: Removed permeability testing requirement for GM backed, GF backed, and polymer treated GCLs. Various editorial modifications.

Table 1(a) – Specification for Geosynthetic Clay Liners (GCLs)

Property	ASTM Test Method	Reinforced GCL			Non-Reinforced GCL			Testing Frequency
		GT-Related	GT Polymer Coated	GM-GF Related	GT-Related	GT Polymer Coated	GM-GF Related	
Clay (as received)								
swell index (ml/2g)	D5890	24	24	24	24	24	24	50 tonnes
fluid loss (ml)(1)	D5891	18	18	18	18	18	18	50 tonnes
Geotextiles (as received)								
cap fabric (nonwoven) - mass/unit area (g/m^2)(2)	D5261	200	200	200	70	100	n/a/70	20,000 m^2
cap fabric -(woven) - mass/unit area (g/m^2)	D5261	100	100	100	-	-	-	20,000 m^2
carrier fabric (nonwoven composite) - mass/(g/m^2)(2)	D5261	240	240	240	90	100	n/a/90	20,000 m^2
carrier fabric (woven) - mass/unit area (g/m^2)	D5261	100	100	100	-	-	-	20,000 m^2
coating - mass/unit area (g/m^2)(3)	D5261	n/a	100	n/a	n/a	100	n/a	4,000 m^2
Geomembrane/Geofilm (as received)								
thickness(5) (mm)	D5199/D5994	n/a	n/a	0.40/0.50/0.10	n/a	n/a	0.40/0.75/0.10	20,000 m^2
density (g/cc)	D1505/D792	n/a	n/a	0.92	n/a	n/a	0.92	20,000 m^2
break tensile strength, MD&XMD (kN/m)	D6693	n/a	n/a	n/a	n/a	n/a	6.0	20,000 m^2
break tensile strength, MD (kN/m)	D882	n/a	n/a	2.5	n/a	n/a	2.5	20,000 m^2
GCL (as manufactured)								
mass of GCL (g/m^2)(6)	D5993	4000	4050	4100	4000	4050	4100	4,000 m^2
mass of bentonite (g/m^2)(6)	D5993	3700	3700	3700	3700	3700	3700	4,000 m^2
moisture content(1) (%)	D5993	(4)	(4)	(4)	(4)	(4)	(4)	4,000 m^2
tensile str., MD (kN/m)	D6768	4.0	4.0	4.0	4.0	4.0	4.0	20,000 m^2
peel strength (N/m)	D6496	360	360	360	n/a	n/a	n/a	4,000 m^2
permeability(1) (m/sec), "or"	D5887	5×10^{-11}	n/a	n/a	5×10^{-11}	n/a	n/a	25,000 m^2
flux(1) (m^3/sec-m^2),	D5887	1×10^{-8}	n/a	n/a	1×10^{-8}	n/a	n/a	25,000 m^2
GCL permeability(1),(7) (m/sec) (max. at 35 kPa)	D6766	1×10^{-8}	n/a	n/a	1×10^{-8}	n/a	n/a	yearly
GCL permeability(1),(7) (m/sec) (max. at 500 kPa)	D6766 mod.	5×10^{-10}	n/a	n/a	5×10^{-10}	n/a	n/a	yearly
Component Durability								
geotextile and reinforcing yarns (8) (% strength retained)	See § 5.6.2	65	65	n/a	65	65	n/a	yearly
geomembrane	See § 5.6.3	n/a	n/a	GM Spec(9)	n/a	n/a	GM Spec(9)	yearly
geofilm/polymer treated(8) (% strength retained)	See § 5.6.4	n/a	85	80	n/a	85	80	yearly

n/a = not applicable with respect to this property :

(1) These values are maximum (all others are minimum)
(2) For both cap and carrier fabrics for nonwoven reinforced GCLs; one, or the other, must contain a scrim component of mass ≥ 100 g/m^2 for dimensional stability
(3) Calculated value obtained from difference of coated fabric to as-received fabric
(4) Value is both site-specific and product-specific and is currently being evaluated
(5) First value is for smooth geomembrane; second for textured geomembrane; third for geofilm
(6) Mass of the GCL and bentonite is measured after oven drying per the stated test method
(7) Value represents GCL permeability after permeation with a 0.1 M calcium chloride solution (11.1 g CaCl2 in 1-liter water)
(8) Value represents the minimum percent strength retained from the as-manufactured value after oven aging at 60°C for 50 days
(9) Durability criteria should follow the appropriate specification for the geomembrane type used; i.e., GRI GM-13 for HDPE, GRI GM-17 for LLDPE or GRI GM-18 for fPP

Table 1(b) – Specification for Geosynthetic Clay Liners (GCLs)

Property	ASTM Test Method	Reinforced GCL			Non-Reinforced GCL			Testing Frequency
		GT-Related	GT Polymer Coated	GM-GF Related	GT-Related	GT Polymer Coated	GM-GF Related	
Clay (as received)								
swell index (ml/2g)	D5890	24	24	24	24	24	24	50 tonnes
fluid loss (ml)(1)	D5891	18	18	18	18	18	18	50 tonnes
Geotextiles (as received)								
cap fabric (nonwoven) - mass/unit area (oz/yd^2)(2)	D5261	5.8	5.8	5.8	2.1	2.9	n/a/2.1	25,000 yd^2
cap fabric (woven) - mass/unit area (oz/yd^2)	D5261	3.0	3.0	3.0	-	-	-	25,000 yd^2
carrier fabric (nonwoven composite) - mass/(oz/yd^2)(2)	D5261	7.1	7.1	7.1	2.7	2.9	n/a/2.7	25,000 yd^2
carrier fabric (woven) - mass/unit area (oz/yd^2)	D5261	3.0	3.0	3.0	-	-	-	25,000 yd^2
coating - mass/unit area (oz/yd^2)(3)	D5261	n/a	2.9	n/a	n/a	2.9	n/a	5,000 yd^2
Geomembrane/Geofilm (as received)								
thickness(5) (mils)	D5199/D5994	n/a	n/a	15/20/4	n/a	n/a	15/30/4	25,000 yd^2
density (g/cc)	D1505/D792	n/a	n/a	0.92	n/a	n/a	0.92	25,000 yd^2
break tensile strength, MD&XMD (lb/in.)	D6693	n/a	n/a	n/a	n/a	n/a	34	25,000 yd^2
break tensile strength, MD & XMD (lb/in.)	D882	n/a	n/a	14	n/a	n/a	14	25,000 yd^2
GCL (as manufactured)								
mass of GCL (lb/ft^2)(6)	D5993	0.82	0.83	0.84	0.82	0.83	0.84	5,000 yd^2
mass of bentonite (lb/ft^2)(6)	D5993	0.75	0.75	0.75	0.75	0.75	0.75	5,000 yd^2
moisture content(1) (%)	D5993	(4)	(4)	(4)	(4)	(4)	(4)	5,000 yd^2
tensile str., MD (lb/in.)	D6768	23	23	23	23	23	23	25,000 yd^2
peel strength (lb/in.)	D6496	2.1	2.1	2.1	n/a	n/a	n/a	5,000 yd^2
permeability(1) (cm/sec), "or"	D5887	5×10^{-9}	n/a	n/a	5×10^{-9}	n/a	n/a	30,000 yd^2
flux(1) (cm^3/sec-cm^2),	D5887	1×10^{-6}	n/a	n/a	1×10^{-6}	n/a	n/a	30,000 yd^2
GCL permeability(1),(7) (cm/sec) (max. at 5 lb/in.^{2})	D6766	1×10^{-6}	n/a	n/a	1×10^{-6}	n/a	n/a	yearly
GCL permeability(1),(7) (cm/sec) (max. at 70 lb/in.^{2})	D6766 mod.	5×10^{-8}	n/a	n/a	5×10^{-8}	n/a	n/a	yearly
Component Durability								
geotextile and reinforcing yarns(8) (% strength retained)	See § 5.6.2	65	65	n/a	65	65	n/a	yearly
geomembrane	See § 5.6.3	n/a	n/a	GM Spec(9)	n/a	n/a	GM Spec(9)	yearly
geofilm/polymer treated(8) (% strength retained)	See § 5.6.4	n/a	85	80	n/a	85	80	yearly

n/a = not applicable with respect to this property :

(1) These values are maximum (all others are minimum)
(2) For both cap and carrier fabrics for nonwoven reinforced GCLs; one, or the other, must contain a scrim component of mass > 2.9 oz/yd^2 for dimensional stability
(3) Calculated value obtained from difference of coated fabric to as-received fabric
(4) Value is both site-specific and product-specific and is currently being evaluated
(5) First value is for smooth geomembrane; second for textured geomembrane; third for geofilm
(6) Mass of the GCL and bentonite is measured after oven drying per the stated test method
(7) Value represents GCL permeability after permeation with a 0.1 M calcium chloride solution (11.1 g CaCl2 in 1-liter water)
(8) Value represents the minimum percent strength retained from the as-manufactured value after oven aging at 60°C for 50 days
(9) Durability criteria should follow the appropriate specification for the geomembrane used; i.e., GRI GM-13 for HDPE, GRI GM-17 for LLDPE or GRI GM-18 for fPP

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Original: March 10, 2004
Editorial Changes: May 6, 2005
Editorial Changes: August 29, 2008

GRI GT13(a) – ASTM Version*

Standard Specification for

"Test Methods and Properties for Geotextiles Used as Separation Between Subgrade Soil and Aggregate"

This specification was developed by the Geosynthetic Research Institute (GRI) with the cooperation of the member organizations for general use by the public. It is completely optional in this regard and can be superseded by other existing or new specifications on the subject matter in whole or in part. Neither GRI, the Geosynthetic Institute, nor any of its related institutes, warrant or indemnifies any materials produced according to this specification either at this time or in the future.

1. Scope

1.1 This specification covers geotextile test methods properties for subsequent use as separation between subgrade soil and aggregate predominantly in pavement systems.

Note 1: While separation occurs in every geotextile application, this pavement-related specification focuses on subgrade soils being "firm" as indicated by CBR values in ASTM D1883 higher than 3.0 (soaked) or 8.0 (unsoaked).

1.2 This specification sets forth a set of physical, mechanical and endurance properties that must be met, or exceeded, by the geotextile being manufactured.

1.3 In the context of quality systems and management, this specification represents a manufacturing quality control (MQC) document. However, its general use is essentially as a recommended design document.

1.4 This specification is intended to assure both good quality and performance of fabrics used as geotextile separators but is possibly not adequate for the complete

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specification in a specific situation. Additional tests, or more restrictive values for the tests indicated, may be necessary under conditions of a particular application.

1.5 This standard specification does not address installation practice. This item is addressed in the geosynthetics literature dealing with this particular application and under unique situations might require modifications, e.g., higher values and/or additional test properties.

2. Referenced Documents

2.1 ASTM Standards

D 1883 Test Method for CBR (California Bearing Ratio) of Laboratory Compacted Soils
D 4354 Practice for Sampling of Geosynthetics for Testing
D 4355 Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus)
D 4533 Test Method for Trapezoidal Tearing Strength of Geotextiles
D 4632 Test Method for Grab Breaking Load and Elongation of Geotextiles
D 4759 Practice for Determining the Specification Conformance of Geosynthetics
D 4873 Guide for Identification, Storage and Handling of Geotextiles
D 5261 Test Method for Measuring Mass per Unit Area of Geotextiles
D 6241 Test Method for Static Puncture Strength of Geotextiles and Geotextile Related Product Using a 50-mm Probe

2.2 AASHTO Specification

M288-00 Geotextile Specification for Highway Applications

3. Definitions

3.1 Formulation - The mixture of a unique combination of ingredients identified by type, properties and quantity. For geotextiles, a formulation is defined as the exact percentages and types of resin(s), additives and/or carbon black.

3.2 Manufacturing Quality Control (MQC) - A planned system of inspections that is used to directly monitor and control the manufacture of a material which is factory originated. MQC is normally performed by the manufacturer of geosynthetic materials and is necessary to ensure minimum (or maximum) specified values in the manufactured product. MQC refers to measures taken by the manufacturer to determine compliance with the requirements for materials and workmanship as stated in certification documents and contract specifications [ref. EPA/600/R-93/182].

3.3 Minimum Average Roll Value (MARV) – For geosynthetics, a manufacturing quality control tool used to allow manufacturers to establish published values such that the user/purchaser will have a 97.7% confidence that the property in question will meet published values. For normally distributed data, “MARV” is calculated

as the typical value minus two (2) standard deviations from documented quality control test results for a defined population from one specific test method associated with one specific property.

3.4 Minimum Value – The lowest sample value from documented manufacturing quality control test results for a defined population from one test method associated with one specific property.

3.5 Maximum Value – The highest sample value from documented manufacturing quality control test results for a defined population from one test method associated with one specific property.

3.6 Separation – The placement of a flexible porous geosynthetic between dissimilar materials so the integrity and functioning of both materials can remain intact or be improved.

Note 2: For separation of stone base courses overlying soil subgrades this primary function simultaneously prevents the stone from intruding down into the soil and the soil from pumping up into the stone.

4. Material Classification and Formulation

4.1 This specification covers geotextiles used as separation materials.

4.2 The polymer types are mainly polypropylene, but also polyester or polyethylene. Other polymers are also possible in this regard.

4.3 The type of geotextile style is not designated. However a distinction can be made based on the elongation criteria of 50%.

Note 3: It is assumed that nonwoven fabrics break at elongations higher than 50%. Woven fabrics always break at elongations significantly lower than 50%.

5. Specification Requirements

5.1 The geotextiles for use as separator shall conform to Tables 1or 2. Table 1 is given in English units and Table 2 is in SI (Metric) units. The conversion from English to SI units is “soft”, i.e., rounded off to an approximate value. All test methods are based on ASTM Standards.

Note 4: The numeric relationships between this specification based on ASTM Test Methods and GRI GT13(b) based on ISO Test Methods have been developed at the Geosynthetic Institute.

5.2 The required values for most properties in Tables 1 and 2 are to be minimum average roll values (MARV). The exceptions are AOS which is a maximum average roll value (MaxARV), and UV stability which is a minimum average value.

5.3 The required class is determined by the severity of installation conditions (i.e., size of equipment, condition of subgrade, thickness of covering lift, etc.). Table 3 gives guidance in this respect.

6. Workmanship and Appearance

6.1 The finished geotextile shall have good appearance qualities. It shall be free from such defects that would affect the specific properties of the geotextile, or its proper functioning.

6.2 General manufacturing procedures shall be performed in accordance with the manufacturer's internal quality control guide and/or documents.

7. MQC Sampling, Testing, and Acceptance

7.1 Geotextiles shall be subject to sampling and testing to verify conformance with this specification. Sampling shall be in accordance with the most current modification of ASTM Standard D 4354, using the section titled, "Procedure for Sampling for Purchaser's Specification Conformance Testing." In the absence of purchaser's testing, verification may be based on manufacturer's certifications as a result of testing by the manufacturer of quality assurance samples obtained using the procedure for Sampling for Manufacturer's Quality Assurance (MQA) Testing. A lot size shall be considered to be the shipment quantity of the given product or a truckload of the given product, whichever is smaller.

7.2 Testing shall be performed in accordance with the method referenced in this specification for the indicated application. The number of specimens to test per sample is specified by each test method. Geotextile product acceptance shall be based on ASTM D4759. Product acceptance is determined by comparing the average test results of all specimens within a given sample to the specification MARV. Refer to ASTM D 4759 for more details regarding geotextile acceptance procedures.

8. MQC Retest and Rejection

8.1 If the results of any test do not conform to the requirements of this specification, retesting to determine conformance or rejection should be done in accordance with the manufacturing protocol as set forth in the manufacturer's quality manual.

9. Shipment and Storage

9.1 Geotextile labeling, shipment, and storage shall follow ASTM D 4873. Product labels shall clearly show the manufacturer or supplier name, style, and roll number. Each shipping document shall include a notation certifying that the material is in accordance with the manufacturer's certificate.

9.2 Each geotextile roll shall be wrapped with a material that will protect the geotextile, including the ends of the roll, from damage due to shipment, water, sunlight and contaminants. The protective wrapping shall be maintained during periods of shipment and storage.

Note 5: The project specification shall be very explicit as to the maximum exposure time between the geotextile being removed from the wrapper and being backfilled with soil or covered with another geosynthetic.

9.3 During storage, geotextile rolls shall be elevated off the ground and adequately covered to protect them from the following: site construction damage, precipitation, extended ultraviolet radiation including sunlight, chemicals that are strong acids or strong bases, flames including welding sparks, temperatures in excess of 160°F (71°C), and any other environmental condition that may damage the property values of the geotextile.

10. Certification

10.1 The contractor shall provide to the engineer a certificate stating the name of the manufacturer, product name, style number, chemical composition of the filaments or yarns, and other pertinent information to fully describe the geotextile.

10.2 The manufacturer is responsible for establishing and maintaining a quality control program to assure compliance with the requirements of the specification. Documentation describing the quality control program shall be made available upon request.

10.3 The manufacturer's certificate shall state that the finished geotextile meets the requirements of the specification as evaluated under the manufacturer's quality control program. A person having legal authority to bind the manufacturer shall attest to the certificate.

10.4 Either mislabeling or misrepresentation of materials shall be reason to reject those geotextile products.

English Units

Table 1(a) – Geotextile Properties Class 1 (High Survivability)

Property[1]	ASTM Test Method	Unit	Elongation < 50%	Elongation ≥ 50%
Grab Tensile Strength	D 4632	lb	315	203
Trapezoid Tear Strength	D 4533	lb	112	79
CBR Puncture Strength	D 6241	lb	630	440
Permittivity	D 4491	sec-1	0.02	0.02
Apparent Opening Size	D 4751	in.	0.024	0.024
Ultraviolet Stability[2]	D 4355	% Ret. @ 500 hrs	50	50

Table 1(b) – Geotextile Properties Class 2 (Moderate Survivability)

Property[1]	ASTM Test Method	Unit	Elongation < 50%	Elongation ≥ 50%
Grab Tensile Strength	D 4632	lb	248	158
Trapezoid Tear Strength	D 4533	lb	90	56
CBR Puncture Strength	D 6241	lb	500	320
Permittivity	D 4491	sec-1	0.02	0.02
Apparent Opening Size	D 4751	in.	0.024	0.024
Ultraviolet Stability[2]	D 4355	% Ret. @ 500 hrs	50	50

Table 1(c) – Geotextile Properties Class 3 (Low Survivability)

Property[1]	ASTM Test Method	Unit	Elongation < 50%	Elongation ≥ 50%
Grab Tensile Strength	D 4632	lb	180	113
Trapezoid Tear Strength	D 4533	lb	68	41
CBR Puncture Strength	D 6241	lb	380	230
Permittivity	D 4491	sec-1	0.02	0.02
Apparent Opening Size	D 4751	in.	0.024	0.024
Ultraviolet Stability[2]	D 4355	% Ret. @ 500 hrs	50	50

Notes:

(1) All values are minimum average roll values (MARV) except AOS which is a maximum average roll value (MaxARV) and UV stability which is a minimum average value.

(2) Evaluation to be on 50 mm strip tensile specimens after 500 h

SI Metric Units

Table 2(a) – Geotextile Properties Class 1 (High Survivability)

Property[1]	ASTM Test Method	Unit	Elongation < 50%	Elongation ≥ 50%
Grab Tensile Strength	D 4632	N	1400	900
Trapezoid Tear Strength	D 4533	N	500	350
CBR Puncture Strength	D 6241	N	2800	2000
Permittivity	D 4491	sec-1	0.02	0.02
Apparent Opening Size	D 4751	mm	0.60	0.60
Ultraviolet Stability[2]	D 4355	% Ret. @ 500 hrs	50	50

Table 2(b) – Geotextile Properties Class 2 (Moderate Survivability)

Property[1]	ASTM Test Method	Unit	Elongation < 50%	Elongation ≥ 50%
Grab Tensile Strength	D 4632	N	1100	700
Trapezoid Tear Strength	D 4533	N	400	250
CBR Puncture Strength	D 6241	N	2250	1400
Permittivity	D 4491	sec-1	0.02	0.02
Apparent Opening Size	D 4751	mm	0.60	0.60
Ultraviolet Stability[2]	D 4355	% Ret. @ 500 hrs	50	50

Table 2(c) – Geotextile Properties Class 3 (Low Survivability)

Property[1]	ASTM Test Method	Unit	Elongation < 50%	Elongation ≥ 50%
Grab Tensile Strength	D 4632	N	800	500
Trapezoid Tear Strength	D 4533	N	300	180
CBR Puncture Strength	D 6241	N	1700	1000
Permittivity	D 4491	sec-1	0.02	0.02
Apparent Opening Size	D 4751	mm	0.60	0.60
Ultraviolet Stability[2]	D 4355	% Ret. @ 500 hrs	50	50

Notes:

(1) All values are minimum average roll values (MARV) except AOS which is a maximum average roll value (MaxARV) and UV stability which is a minimum average value.

(2) Evaluation to be on 50 mm strip tensile specimens after 500 hours exposure.

Table 3 - Required Degree of Survivability as a Function of Subgrade Conditions, Construction Equipment and Lift Thickness
(Class 1, 2 and 3 Properties are Given in Table 1 and 2; Class 1 + Properties are Higher than Class 1 but Not Defined at this Time)

	Low ground-pressure equipment ≤ 25 kPa (3.6 psi)	Medium ground-pressure equipment > 25 to ≤ 50 kPa (>3.6 to ≤ 7.3 psi)	High ground-pressure equipment > 50 kPa (> 7.3 psi)
Subgrade has been cleared of all obstacles except grass, weeds, leaves, and fine wood debris. Surface is smooth and level so that any shallow depressions and humps do not exceed 450 mm (18 in.) in depth or height. All larger depressions are filled. Alternatively, a smooth working table may be placed.	Low (Class 3)	Moderate (Class 2)	High (Class 1)
Subgrade has been cleared of obstacles larger than small to moderate-sized tree limbs and rocks. Tree trunks and stumps should be removed or covered with a partial working table. Depressions and humps should not exceed 450 mm (18 in.) in depth or height. Larger depressions should be filled.	Moderate (Class 2)	High (Class 1)	Very High (Class 1+)
Minimal site preparation is required. Trees may be felled, delimbed, and left in place. Stumps should be cut to project not more than ± 150 mm (6 in.) above subgrade. Fabric may be draped directly over the tree trunks, stumps, large depressions and humps, holes, stream channels, and large boulders. Items should be removed only if placing the fabric and cover material over them will distort the finished road surface.	High (Class 1)	Very high (Class 1+)	Not recommended

*Recommendations are for 150 to 300 mm (6 to 12 in.) initial lift thickness. For other initial lift thicknesses:

300 to 450 mm (12 to 18 in.): reduce survivability requirement one level;
450 to 600 mm (18 to 24 in.): reduce survivability requirement two levels;
> 600 mm (24 in.): reduce survivability requirement three levels

Note 1: While separation occurs in every geotextile application, this pavement-related specification focuses on subgrade soils being "firm" as indicated by CBR values higher than 3.0 (soaked) or 8.0 (unsoaked).

Source: Modified after Christopher, Holtz, and DiMaggio