GCLs: alternative Subtitle D liner systems

By Gregory N. Richardson, Ph.D., P.E.

Alternative liner systems for new municipal solid waste (MSW) landfills are allowed under the U.S. Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) Subtitle D Sanitary Landfill Regulations (40 CFR §258.40). This provision was adopted by a majority of states receiving authorization from EPA.

The Subtitle D provision allows the use of an alternative liner system if it can be shown that it will limit contaminant migration so that concentrations in the uppermost aquifer at the closest downgradient monitoring well are less than the maximum contaminant levels (MCLs) specified by the Clean Water Act or more restrictive state requirements. This performance-based liner system commonly is referred to as a "point-of-compliance" liner. The concept of point-of-compliance liner equivalence differs significantly from earlier concepts comparing the "performance" of alternative liner systems to that of regulatory-required liner systems.

This paper reviews the specific design considerations related to the evaluation of geosynthetic clay liner- (GCL) based alternative liner systems from both the performance and point-of-compliance perspectives. It then presents a summary of additional considerations that support the application of a GCL alternative liner system, and closes with a summary of GCL-based alternative liners systems that have been permitted so far, including cost comparisons to conventional compacted clay liners (CCLs).

Alternative liner demonstration: performance-based

Before Subtitle D, the regulations simply required alternative liner systems to provide an equivalent environmental protection to that offered by the regulatory-specified system. Although specific levels of acceptable leakage are not codified, three factors usually are considered when evaluating the equivalence of liner systems (Koerner and Daniel, 1993).

- the flow rate through the liner system (i.e., how many gallons/acre/day)
- the "break-through time" defined as the time required for liquids to travel through the system and be released to the environment
- an equivalent chemical-absorption capacity.

A common method used to evaluate each of these factors is discussed below.

Flow rate through the liner system

To predict flow rate, an estimate of the liquid head acting on the liner system must be calculated. The actual volume of leachate flowing into the collector system can be estimated using the Hydrologic Evaluation of Landfill Performance (HELP) model. This, however, does not address leachate-collection system differences or specific regulatory requirements related to allowable head. For Subtitle D landfills, this regulatory head limit is 30 cm. Alternatively, the highest rate of leakage can be estimated by assuming that 30 cm of leachate is acting on the geomembrane.

This represents the most conservative case, i.e., the most leakage, as compared to performing a HELP model analysis of the proposed landfill. Assuming good contact between the geomembrane and the CCL or GCL, the leakage through the liner system is calculated as follows.

Geomembrane plus CCL

A geomembrane overlying a CCL forms a composite barrier that has advantages over the use of either a geomembrane or CCL individually. The flow through a penetration in the geomembrane is reduced by the clay's presence and calculated as follows (Giroud and Bonaparte, 1989):

$$Q = 0.21\ h^{0.9}\ a^{0.1}\ K^{0.74}$$

where

h = the height of water standing on the geomembrane (m)
a = the area of the hole (m^2)
K = the permeability of the underlying clay (m/sec).

Again, assuming a single 1-cm^2 hole with 30 cm of leachate acting on the liner and K of 1 x 10^{-7} cm/sec, the flow through the composite barrier is 0.14 gallon/day.

Geomembrane plus GCL

If a GCL is substituted for the CCL, the leakage through the composite is calculated as (Giroud, et al.,1992):

$$Q = 0.21\ i_{ave}\ a^{0.1}\ h^{0.9}\ K^{0.74}$$

where

i_{ave} = 1 + Eh/t_{GCL}
t_{GCL} = thickness of GCL
E = 1 / [2 ln (2R/b)]
b = diameter of hole (m)
R = 0.61 $a^{0.05}$ $h^{0.45}$ $K^{-0.13}$.

Most commercial GCLs sold in the United States use Wyoming sodium-type bentonite that develops a permeability of approximately 5 x 10^{-9} cm/sec when tested under the conditions specified in ASTM D 5887. This test uses an effective confining stress of only 5 psi and a head of 2 psi. Actual long-term confining stresses acting on the GCL will be larger, resulting in lower GCL permeabilities. The flow through a single 1-cm^2 hole with 30 cm of water standing on it is 0.066 gallon/day.

The predicted leachate-flux rates through a single puncture in the geomembrane-GCL composite are less than those through the regulatory geomembrane-CCL composite. This means that for a given level of CQA program, i.e., number of penetrations per acre, the alternative composite liner systems will have a lower rate of flux than the conventional CCL composite liner. For a double composite liner system, the liner system performance will be orders of magnitude better.

Breakthrough time

The minimum breakthrough time of a liquid moving through a liner system can be calculated by summing the travel times through the individual barriers under the influence of actual hydraulic heads predicted by the HELP model (Schroeder, et al., 1994) or, more conservatively, by using the full RCRA Subtitle D allowable 30 cm (1 ft) of leachate head. For saturated soils, the vertical movement of water results in a flow gradient of 1, meaning the maximum vertical-flow velocity is approximately equal to the permeability of the soil.

Leachate that passes through the geomembrane still must travel through the soil-liner components before it can affect the environment. The time-of-travel calculations assume saturation of the liner soils and vertical flow, so that a unit gradient exists. The latter results in the maximum velocity of seepage being equal to the permeability of the soil.

Geomembrane plus 2 ft @ 1 x 10^{-7} cm/sec CCL

One can conservatively estimate the leachate travel time through a conventional composite barrier by estimating the travel time through the CCL. The travel-time calculation is performed assuming saturation of the CCL and vertical flow, so that a unit gradient exists. The latter results in the maximum velocity of seepage being equal to the permeability of the soil divided by its porosity, n (typical n = 0.33). Leachate travel time through the current composite barrier can be conservatively estimated by calculating the travel time through the soil liner as follows:

travel time = 2 ft/(1 x 10^{-7} cm/sec) x 0.33 = 2.01 x 10^{8} seconds = 6.4 years.

This model may be overly conservative, however, since it requires a leakage of approximately (1 x 10^{-7} cm/sec) (43,560 ft^2/acre) (7.48 gallons/ft^3) = 92.3 gallons/acre/day. Since a single puncture of the HDPE liner will only allow 0.14 gallons/day, the calculated total-flow rate would require more than 600 of the 1-cm^2 holes per acre. Even with fair construction quality assurance (CQA), there should be less than eight penetrations in the HDPE liner (Giroud and Bonaparte, 1989). Additionally, this assumes that the maximum head exists across the entire area of the liner. Setting the flow rate through the CCL equal to that through the composite liner, the corrected travel time can be estimated to equal:

corrected travel time = 6.4 [92.3 /(8 x 0.14)] = 528 years.

Geomembrane plus GCL

The travel time for the GCL alternative is calculated using a typical GCL thickness of 7 mm as follows:

travel time = 7 mm/(10^{-9} cm/sec) x 0.33 = 2.3 x 10^{8} sec = 7.4 years.

Maintaining this travel rate would require approximately 9,236 gallons/acre/day of leachate. If we correct the travel time by setting the flow rate through the CCL equal to that through the composite, the corrected travel time can be estimated to equal:

corrected travel time = 7.4 [9236 /(8 x 0.066)] = 1.3 x 10^{5} years.

Generally, breakout time is not viewed as an important criteria in establishing equivalency, since the time to establish the discharge from the liner system is, over the long term, not as important as the leachate's flow rate out of the liner system. Many contaminants, organics in particular, will not survive the significant times required for breakout. The travel time for both liner systems, however, greatly exceeds the post-closure monitoring period proposed for Subtitle D landfills and the anticipated life of the more mobile organic contaminants.

Equivalent chemical-absorption capacity

Chemical-absorption capacity is dependent on the cation exchange capacity (CEC) of the liner clay and the chemical characteristics of the contaminant of concern.

Absorption of inorganic contaminants is controlled by cation-exchange reactions and geochemical processes, such as precipitation. The maximum absorption capacity of a soil liner, M, may be defined as:

$$M = C\rho_d T$$

where

C = the cation absorption capacity
ρ_d = the dry mass density of the soil
T = the thickness of the liner.

The natural CEC of clay soils ranges from 100 to 150 meq/100g for bentonite to 30± for illites, and as low as 3 for kaolinites. The CEC for the default and proposed alternative composite liner system can be calculated and compared. The ratio of the GCL alternative liner's CEC to that of the Subtitle D composite liner, R_{CEC}, can be approximated as

$$R_{CEC} = [C_{GCL}/C_{CCL}] \times [T_{GCL}/T_{CCL}].$$

For common CCLs, this ratio will range from 0.05 to 0.5. Recently, Daniel (1996) questioned the value of comparing the chemical absorption capacity of a GCL to that of the CCL, since (1) chemical attenuation also is provided by the underlying soils, (2) over the long run the absorption capacity of any engineered system will be exhausted, and (3) with a low leachate flux, absorption is not required to ensure negligible chemical migration. The latter point is the basis for the EPA's point-of-compliance demonstration. Today's liner systems are containment oriented, not attenuation oriented.

Subtitle D point-of-compliance liner equivalence

RCRA Subtitle D regulations in 40 CFR 258 provide for an alternative method of evaluating liner equivalence. As mentioned earlier, the point-of-compliance method allows the use of an alternative liner system if it can be shown that the liner will limit contaminant migration so that contamination concentrations at the closest downgradient monitoring well are less than the MCLs specified by the CWA.

The demonstration requires first estimating the rate that leachate is leaving the liner system. This can be done using the HELP model (Schroeder, 1994) or by simply assuming that 30 cm of head acts on the liner and using the equations previously presented. Next, the movement of the leachate from the liner to the monitoring well is modeled. Presently, EPA requires this evaluation to be performed using the EPA-generated computer model MULTIMED (Salhotra, et al., 1993), which uses a closed-form solution for the contaminant transport problem and incorporates default chemical transport data.

The Subtitle D point-of-compliance demonstration is performed using EPA-required limits on the data file (Allison, 1992, and Sharp-Hansen et al., 1993).

The EPA-required general-model assumptions used for the MULTIMED analysis are:

- all model runs were steady-state Subtitle D simulations (deterministic)

- only the unsaturated- and saturated-zone models were activated
- leachate infiltration rates were calculated assuming a 30-cm head acting on the composite liner system (HELP3 analysis performed to demonstrate conservative nature of assumption).

The Subtitle D simulation also requires the following model assumptions:

- the contaminant release is continuous and constant over time
- the receptor (point of compliance) is located down gradient in the center of the contaminant plume at the top of the aquifer
- no attenuation of contaminants occurs in the leachate during flow through the composite liner
- processes of chemical reaction, biodegradation, and chemical absorption are neglected
- the primary modes of attenuation for contaminants entering the subsurface is physical dispersion and dilution in the receiving aquifer.

The MULTIMED analysis is required to show that the alternative liner system will ensure that groundwater concentrations of possible chemicals that may exist in the MSW leachate will not exceed health-based thresholds in groundwater at the point of compliance. Some states may have stricter (lower concentrations) standards than the MCLs in Subtitle D based on bio-accumulation limits, or even "no net ground water impact" requirements.

MULTIMED has two options for landfill simulations: (1) generic landfill and (2) Subtitle D landfill. In this study, the Subtitle D option was used. Under the Subtitle D option, the contaminant source is never removed, thereby creating a continuous source over time. This steady-state solution will estimate the maximum contaminant concentrations under long-term equilibrium conditions. It does not allow the evaluation of the time required for this steady-state condition to develop.

There are several restrictions to the ability of MULTIMED to model site conditions. The model does not account for multiple aquifers, pumping wells, and certain site-specific boundary conditions. To the extent possible, site-specific hydrogeologic and physical data are used to define applicable input parameters. Such input data

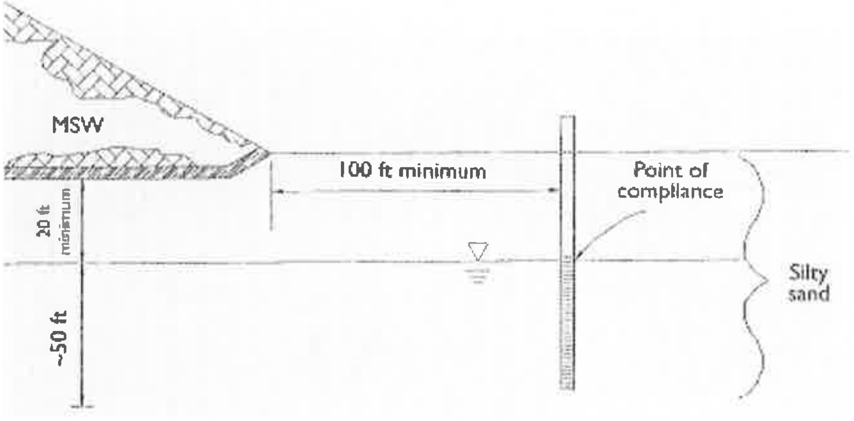

Figure 1. The geometry assumed in the MULTIMED model.

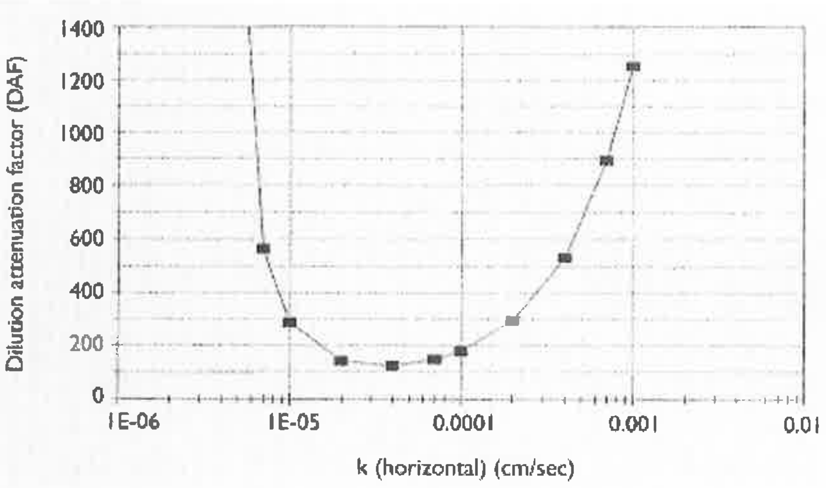

Figure 2. DAF value calculated for a typical site (saturated layer).

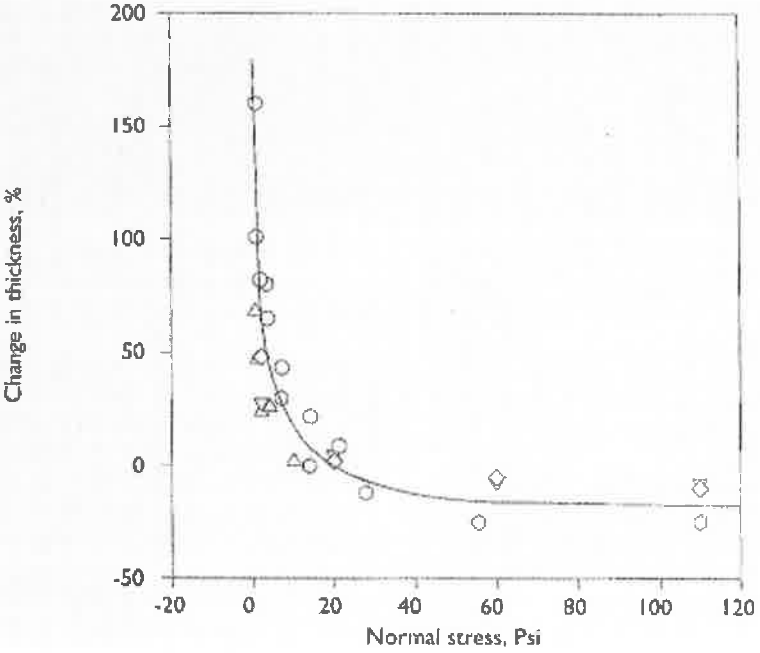

Figure 3. GCL normal load vs. thickness.

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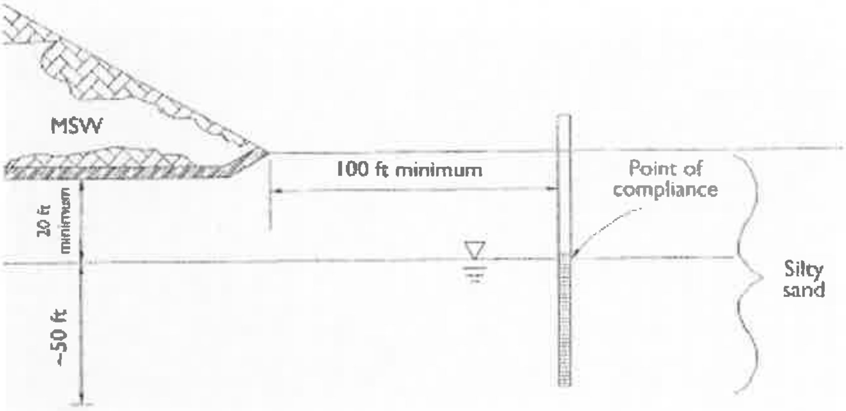

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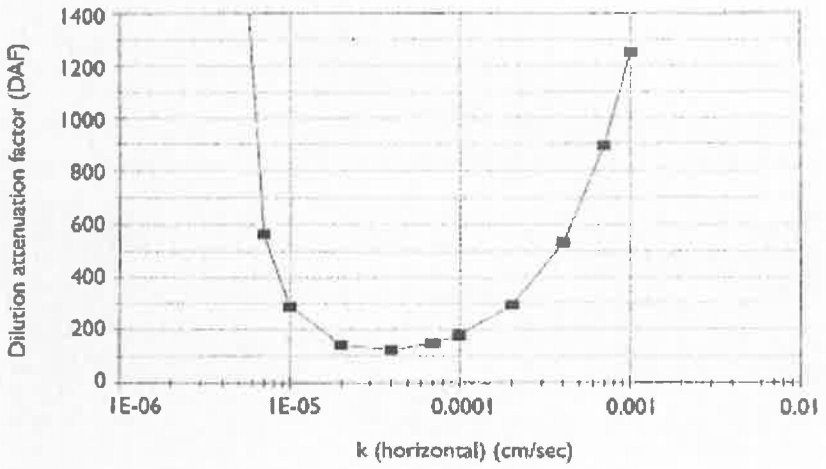

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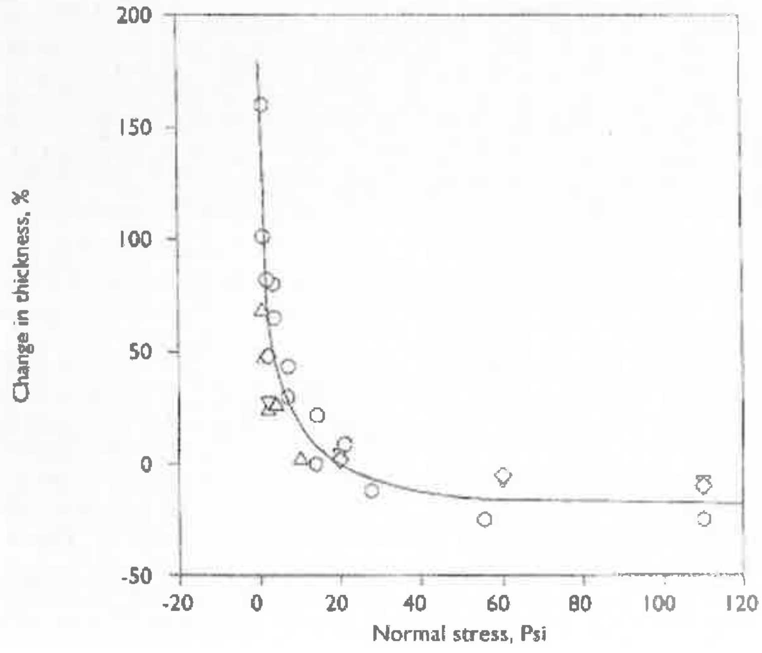

Figure 3. GCL normal load vs. thickness.

TABLE 3. POST-1993 PERMITTED SUBTITLE D LANDFILLS LINERS USING A GCL COMPOSITE LINER

State	Owner	Landfill	State	Owner	Landfill
Alabama	Dothan	City of Dothan	Michigan	United Waste	Menominee
Alaska	City of Anchorage	Eastwind: Phase 2	Michigan	BFI	Allis Park
Arizona	Unknown	Big D	Michigan	Phillip Envirn.	McGill Road
California	Los Angeles Sanitation	Lopez Canyon: Area C	Michigan	BFI	Vienna Junction
California	Kern county	ShafterWasco: Module 2	Ohio	BFI	Carbon Limestone
California	Los Angeles Sanitation	Puente Hills: Phase 1B	Oregon	Valley Landfills	Coffin Butte
California	Los Angeles Sanitation	Sunshine Canyon: Phase I	Oregon	Rogue Disposal	Dry Creek
California	BFI	Vasco Road: Unit 6	Pennsylvania	BFI	Imperial
California	Norcal	B&J: Module 2.2	Pennsylvania	USA/CH	Duapin Meadows
California	Norcal	Cummings Road	Pennsylvania	United	Kelly Run
California	City of Whittier	Calabasas	Pennsylvania	Arnoni	Arnoni
California	Santa Cruz	Buena Vista	Pennsylvania	MCSWA	Kness
California	Sacto Co.	Kiefer Road	Pennsylvania	Chrin Brothers	Chrin Brothers
California	Laidlaw	Chiquita Canyon	Pennsylvania	Clinton County	Clinton County
Colorado	Rio Grande City	Rio Grande	Pennsylvania	Greater Lebanon RA	Lebonon
Florida	USA/Chambers	Berman Road: Cells 3, 7	Pennsylvania	Vogel Disposal	Seneca
Georgia	Habersham County	Habersham County	New Mexico	City of Carlsbad	Carlesbad
Georgia	Addington	Swift Creek	New Mexico	City of Gonzales	Johnson Canyon
Georgia	Southern States	Taylor County	New Mexico	Sunland Park	JOAB
Georgia	Sanifill	Bolton Road	New York	Jamestown	Ellery
Georgia	Gordon Co.	Red Bone Ridge	South Carolina	Greenville County	Enoree
Hawaii	County of Kauai	Kekaha	Texas	City of Midland	Midland
Idaho	Kootenai County	Kootenai County	Texas	City of Odessa	Odessa
Kentucky	Addington	Epperson	Virginia	Sussex	Bramble USA
Kentucky	Kelchner Environmental	Walton	Virginia	USA/Chambers	Charles City
Kentucky	Rumpke	Butler	Virginia	USA/Chambers	Amelia
Maryland	USA/Chambers	Mountain View	Wyoming	City of Cheyenne	Cheyenne

should be consistent with the EPA recommended value ranges (Sharp-Hansen, et al., 1993). For the MULTIMED model, the point of compliance at some distance and depth below the bottom of the liner system must be assumed. **Figure 1** shows the geometry assumed in the model.

Dilution-attenuation values

The dilution-attenuation factor (DAF) is defined as the initial leachate concentration divided by the MULTIMED-predicted concentration at the point of compliance. If the calculated DAF is equal to or greater than 100, the alternative liner is acceptable (Sharp-Hansen, et al., 1993). This is based on the EPA's observation that the actual concentration of common contaminants in MSW landfill leachate is typically less than 100 times the MCL values.

A parametric study commonly is performed to determine the calculated DAF's sensitivity to changes in input variables. For the given site geometry, the only significant variation in the calculated DAF value results from changes in the horizontal permeability of the saturated layer. **Figure 2** shows that the DAF value calculated for a typical site when the horizontal permeability of the upper aquifer ranges between $1 \times 10^{[illegible]}$ cm/sec and $1 \times 10^{[illegible]}$ cm/sec.

A seasoned hydrogeologist (we cook them in cajun spices) realizes that the MULTIMED evaluation is simply a dilution analysis. In a given period of time, the landfill will leak some water at a given contaminant concentration. The actual rate that leachate reaches the groundwater also may be controlled by the permeability of the soil beneath the liner. The quantity of water flowing beneath the landfill during this period can be evaluated based on the transmissivity of the soil strata and gradient of the water table.

Thus, when the subgrade's permeability is high, the DAF is large, because a large quantity of water will flow under the landfill and dilute the leachate. Conversely, when the subgrade's permeability is very low, the rate that leachate can reach the water table is limited (unit gradient case) and the resulting DAF is high. The "saddle" curve shown on Figure 2 illustrates this relationship. Under this analysis, dilution is the solution. The current MULTIMED model presents significant challenges to inward-gradient liner systems and sites with complex groundwater hydrogeology.

Construction implications for a GCL liner system

The evaluation for the alternative GCL composite liner system is based on key assumptions about the GCL component and the quality of its field placement. These assumptions require that specific conditions be incorporated in the project specifications and CQA program to ensure the constructed system performs as predicted. The key assumptions are:

1. The geomembrane is installed with a good CQA program that limits the number of punctures in the geomembrane.
2. The geomembrane and the GCL are in good contact.
3. The GCL has a fully hydrated permeability $\leq K_{(assumed)}$
4. Under anticipated field-loading conditions, and when fully hydrated, the GCL has a thickness $\geq$ thickness$_{(assumed)}$
5. The maximum head acting on the alternative composite liner is 30 cm.
6. The permeability of the bentonite will not be affected by constituents in the subgrade soil or groundwater.

The third and fourth assumptions identify key properties of the GCL that were used to predict the rate of leachate release from the landfill.

The thickness of a GCL under a given normal load can be obtained from **Figure 3.** Such data can be conservatively developed for a generic GCL by measuring the thickness of the GCLs placed in a consolidation cell, saturated, and loaded under the desired range of normal loads. The geotextile thickness can be measured in the same manner by first removing the bentonite. A conservative estimate of the GCL thickness is then equal to the thickness of the GCL with bentonite minus the thickness of the geotextile at each normal load. It is conservative because it neglects the intrusion of bentonite into the geotextile.

It should be noted that the geosynthetics industry is trying to move away from permeability and thickness measurements for a GCL. Instead, it would prefer to measure the flux passing through the GCL and provide permittivity values for the GCL. Permittivity is defined as permeability divided by thickness and is commonly associated with geotextiles. Unfortunately, the empirical equations for flow through a geomembrane-GCL composite liner cannot currently be solved using GCL flux values. The author hopes empirical equations based on GCL flux for flow through a geomembrane-GCL composite liner under low head will be available in the next several years.

Subtitle D experience

In the three years since Subtitle D became effective, GCL alternative liner systems have become cost-effective alternatives that are accepted by many states. **Table 1** presents a listing of facilities (that the author is aware of) that have been permitted with a GCL alternative liner under Subtitle D authority. This is probably not a complete list. It does, however, demonstrate that the use of GCL alternative liner systems is not limited to a single region of the country, and that both private and municipal MSW landfill owners have adopted GCL liner systems.

The use of a GCL affects the cost and time required for construction of a lined landfill. Neglecting time of construction, the cost differences between the use of a GCL and a CCL have been as follows:

- in-place GCLs = $0.40–0.50/ft^2
- CCL (on-site clay) = $0.60–1.60/ft^2 (24-in. thick)
- CCL (bentonite amended) = $1.50–2.50/ft^2 (24-in. thick).

These costs ignore savings in time and CQA expenses. GCL composite liners clearly provide an extremely cost effective means to construct a composite barrier, while at the same time offering a comparable level of protection to the environment as CCL liners.

Summary

The use of a GCL as the soil component of a composite barrier is becoming an accepted means of economically achieving the goals of RCRA Subtitle D. The significant advantages associated with the use of a GCL to replace a CCL include the following:

- In arid and semi-arid regions, the use of a GCL eliminates the long-term concerns regarding the dessication of the clay liner system and, thus, is a preferred solution.
- In all regions, the GCL alternative liner system provides significant savings in both construction cost and time required for the liner system.
- The GCL alternative requires less-expensive and lower skilled CQA than conventional liner systems.
- Based on observed performance and the modeling presented in this article, the GCL alternative provides equal or superior containment performance than conventional liner systems.

Although it is beyond this paper's scope, the use of a GCL in a final-cover system provides the same advantages listed above, plus the ability to survive much larger differential displacements than the CCL. RCRA Subtitle D allows for alternative final-cover systems that provide equal or superior performance to the regulatory proscribed final cover (40 CFR §258.60).

This performance comparison should reflect the EPA's revised final-closure criteria, as presented in the June 26, 1992 *Federal Register.* Essentially, this means the geomembrane plus GCL composite cover barrier must be shown to be equal to or superior to a geomembrane plus 18 inches of 1×10^{-5} cm/sec CCL. This is easily done using the relationships presented in this article.

The designer or regulator faced with the use of a GCL in a composite barrier should derive comfort from the past successes of the geomembrane plus GCL composite barrier system in both liner and final cover systems. The paper presented by Tedder (1997) at the Geosynthetics '97 conference provides significant assurance that the performance calculations presented in this paper are conservative. The author believes future studies using actual MSW leachates and the low heads associated with these facilities will future demonstrate the conservativeness of our current liner design practices.

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