AECOM

J.K. SPRUCE POWER PLANT -

PLANT DRAINS POND -

Alternative Composite Liner Design Documentation

September 2023
AECOM Project 60566130

Delivering a better world

Prepared for:

CPS Energy Calaveras Power Station
12940 U.S. Highway 181 South
San Antonio, Texas 78223

Prepared by:

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Certification Statement 30 TAC §352.721 and 40 CFR § 257.72(c) – Design of the Liner for a New CCR Surface Impoundment

CCR Unit: CPS Energy; J.K. Spruce Power Plant; Plant Drains Pond

I, Alexander W. Gourlay, being a Registered Professional Engineer in good standing in the State of Texas, do hereby certify, to the best of my knowledge, information, and belief, that the information contained in this certification package has been prepared in accordance with the accepted practice of engineering. I certify, for the above-referenced CCR Unit, that the documentation of the design of the alternative composite liner of the CCR Unit is accurate and satisfies the requirements of 30 TAC §352.721 and 40 CFR § 257.72(c).

Alexander. W Gourlay, P.E.
Printed Name

September 8, 2023
Date

Attachment 1: Calculation Package -
"Alternative Composite Liner Demonstration", AECOM Project 60566130, September 8, 2023.

ATTACHMENT 1

AECOM, 2023. ***Plant Drains Pond –***

Alternative Composite Liner Demonstration Calculation

Prepared for: CPS Energy

AECOM Job No. 60566130, September 2023.

Project Spruce Plant Drains Project	**Job No.** 60566130
Client CPS Energy	**Department/Discipline** Civil
Software Name	

Calculation Rev. No.	Originator Self Check (name and signature)	Reviewer/Checker (name and signature)	Independent Peer Reviewer (if used/required) (name & signature)	Approver (name & signature)
0	Sandy Gourlay	Chris Wigginton		Todd Ringsmuth
	[signature]	[signature]		[signature]

Add rows as required

Calculation Objective:
Demonstrate that the 60-mil HDPE and GCL bottom liner of the Spruce Plant Drains Pond (PDP) satisfies the requirements of 30 TAC §352.721 “Liner Design Criteria for New and Lateral Expansions of Coal Combustion Residuals Surface Impoundments”.

30 TAC §352.721 adopts by reference 40 Code of Federal Regulations §257.72 (Liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment) as amended through the April 17, 2015, issue of the Federal Register (80 FR 21301). 40 CFR Part 257 is referenced as “the CCR Rule.”

Calculation Methodology:
Describe how the design satisfies all relevant requirements of the CCR Rule.

Use published references and site-specific laboratory test data to demonstrate compatibility of HDPE and GCL liner materials with Coal Combustion Residual (CCR) waste materials.

Use Darcy’s Law to demonstrate that discharge through the GCL is less than or equal to discharge through a prescriptive compacted clay liner.

References / Inputs/ Field Data:
See calculations

Assumptions: (Include comments on need to revise calculations after more data is collected/confirmed and/or after assumptions have been verified.)
See calculations

Conclusions including confirmations to be obtained:
See calculations

This calculation is complete and ready for Discipline Review:

Alexander W Gourlay	[signature]	09/08/2023
Originator Name	**Signature**	**Date**

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Background

CPS Energy owns and operates the Calaveras Power Station that includes Units 1 & 2 of the J.K. Spruce Power Plant (Spruce). The Spruce plant produces low volume waste (LVW) and Flue Gas Desulfurization (FGD) system wastewater which are comingled in the Spruce Sludge Recycle Holding (SRH) Pond. The solids in the FGD waste stream are classified a coal combustion residual (CCR) and as such are regulated by Title 40, Code of Federal Regulations, Part 257 (40 CFR §257) Subpart D, otherwise known as the Coal Combustion Residual (CCR) Rule.

Pursuant to the Resource Conservation and Recovery Act (RCRA), the Environmental Protection Agency (EPA) approved, to be effective July 28, 2021, the Texas Commission on Environmental Quality's partial State Coal Combustion Residuals (CCR) Permit Program, which now operates in lieu of the Federal CCR program, with the exception of certain provisions for which the State did not seek approval. EPA has determined that the Texas partial CCR permit program meets the standard for approval under RCRA. Facilities operating under the State's program requirements and resulting permit provisions are also subject to EPA's information gathering and inspection and enforcement authorities under RCRA and other applicable statutory and regulatory provisions.

Objective

Demonstrate that the 60-mil HDPE and GCL bottom liner of the Spruce Plant Drains Pond (PDP) satisfies the requirements of 30 TAC §352.721 "Liner Design Criteria for New and Lateral Expansions of Coal Combustion Residuals Surface Impoundments".

30 TAC §352.721 adopts by reference 40 Code of Federal Regulations (CFR) §257.72 (Liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment) as amended through the April 17, 2015, issue of the Federal Register (80 FR 21301).

30 Texas Administrative Code (TAC) §352.721

30 TAC §352.721 "Liner Design Criteria for New and Lateral Expansions of Coal Combustion Residuals Surface Impoundments" states the following:

> *The commission adopts by reference 40 Code of Federal Regulations §257.72 (Liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment) as amended through the April 17, 2015, issue of the Federal Register (80 FR 21301).*

Therefore, the only requirement of 30 TAC §352.721 is to satisfy 40 Code of Federal Regulations (CFR) §257.72 and any Sections of 40 CFR §257 incorporated by reference.

40 CFR §257.72

40 CFR §257.72 "Liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment" states the following:

> *§257.72(a) New CCR surface impoundments and lateral expansions of existing and new CCR surface impoundments must be designed, constructed, operated, and maintained with either a composite liner or an alternative composite liner that meets the requirements of §257.70(b) or (c).*
>
> *§257.72(b) Any liner specified in this section must be installed to cover all surrounding earth likely to be in contact with CCR. Dikes shall not be constructed on top of the composite liner.*

§257.72(c) Prior to construction of the CCR surface impoundment or any lateral expansion of a CCR surface impoundment, the owner or operator must obtain certification from a qualified professional engineer that the design of the composite liner or, if applicable, the design of an alternative composite liner complies with the requirements of this section.

§257.72(d) Upon completion, the owner or operator must obtain certification from a qualified professional engineer that the composite liner or if applicable, the alternative composite liner has been constructed in accordance with the requirements of this section.

§257.72(e) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in §257.105(f), the notification requirements specified in §257.106(f), and the Internet requirements specified in §257.107(f).

Satisfaction of §257.72(a)

§257.72(a) New CCR surface impoundments and lateral expansions of existing and new CCR surface impoundments must be designed, constructed, operated, and maintained with either a composite liner or an alternative composite liner that meets the requirements of § 257.70(b) or (c).

The Spruce PDP is constructed with an alternative composite liner that, therefore, must meet the requirements of §257.70(c). Additional related requirements are presented in §257.70(b). Due to the required detail of these demonstrations, they are presented in subsequent, stand-alone sections of this Calculation under the headings of "§257.70(b) Composite Liner Requirements" and "§257.70(c) Alternative Composite Liner Requirements".

Satisfaction of §257.72(b)

§257.72(b) Any liner specified in this section must be installed to cover all surrounding earth likely to be in contact with CCR. Dikes shall not be constructed on top of the composite liner.

The alternative composite liner covers the entire surface impoundment surface and extends beyond the top of the embankments into an anchor trench; the liner covers all surrounding earth likely to be in contact with CCR.

The height of the pond embankments allows for 2 feet of freeboard above the maximum normal operating level.

No portion of any dike is constructed on top of the composite liner.

Satisfaction of §257.72(c)

§257.72(c) Prior to construction of the CCR surface impoundment or any lateral expansion of a CCR surface impoundment, the owner or operator must obtain certification from a qualified professional engineer that the design of the composite liner or, if applicable, the design of an alternative composite liner complies with the requirements of this section.

This calculation has been prepared to provide additional detail in support of an updated certification that the design of an alternative composite liner complies with the requirements of this section (§257.72). An earlier version of this certification was certified by a qualified professional engineer on June 28, 2022.

Satisfaction of §257.72(d)

§257.72(d) Upon completion, the owner or operator must obtain certification from a qualified professional engineer that the composite liner or if applicable, the alternative composite liner has been constructed in accordance with the requirements of this section.

This document includes the required certification from a qualified professional engineer that the alternative composite liner has been constructed in accordance with the requirements of this section (§257.72).

Satisfaction of §257.72(e)

§257.72(e) The owner or operator of the CCR unit must comply with the recordkeeping requirements specified in §257.105(f), the notification requirements specified in §257.106(f), and the Internet requirements specified in §257.107(f).

CPS Energy acknowledges these requirements.

§257.70(b) Composite Liner Requirements

40 CFR §257.70(b) Composite Liner states the following:

§257.70(b) A composite liner must consist of two components; the upper component consisting of, at a minimum, a 30-mil geomembrane liner (GM), and the lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} centimeters per second (cm/sec). GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick. The GM or upper liner component must be installed in direct and uniform contact with the compacted soil or lower liner component. The composite liner must be:

(1) Constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to pressure gradients (including static head and external hydrogeologic forces), physical contact with the CCR or leachate to which they are exposed, climatic conditions, the stress of installation, and the stress of daily operation;

(2) Constructed of materials that provide appropriate shear resistance of the upper and lower component interface to prevent sliding of the upper component including on slopes;

(3) Placed upon a foundation or base capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift; and

(4) Installed to cover all surrounding earth likely to be in contact with the CCR or leachate.

Satisfaction of §257.70(b)

§257.70(b) A composite liner must consist of two components; the upper component consisting of, at a minimum, a 30-mil geomembrane liner (GM), and the lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} centimeters per second (cm/sec). GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick. The GM or upper liner component must be installed in direct and uniform contact with the compacted soil or lower liner component.

The upper component of the composite liner is a 60-mil thickness of HDPE geomembrane. The lower component of the composite liner is a needle-punched geosynthetic clay liner (GCL). The equivalency of the GCL to a two-foot thickness of compacted soil with a hydraulic conductivity of 1 $\times 10^{-7}$ cm/sec is demonstrated in a subsequent section of this Calculation under the heading "Satisfaction of §257.70(c)(2)".

Relative to the requirement for installation of the geomembrane "in direct and uniform contact with the compacted soil or lower liner component", the installation sequence was:

1. The soil subgrade was scarified, compacted, proof-rolled, and the soil density and moisture content were verified to comply with the project specifications.
2. The GCL was laid, in accordance with the project specifications, on the prepared soil subgrade. Due to self-weight, the GCL lies flat and in direct and uniform contact with the soil subgrade.
3. The 60-mil HDPE geomembrane was installed on top of the GCL. Standard installation procedures were used and documented by QA observations to minimize the occurrence of wrinkles in the welded HDPE geomembrane.
4. The HDPE geomembrane was then covered by a 12-inch-thick layer of sand that was pushed out by skid steer operating on the sand layer. The sand spreading operation was performed in a manner and at a time of day that pushed out wrinkles and allowed them to relax overnight.
5. The sand was then covered by six inches of reinforced concrete to serve as a working surface for muck out of solids from the impoundment.

The weight of the sand and reinforced concrete ensures that the geomembrane should remain in direct and uniform contact with the GCL that is the lower component of the composite liner. Similarly, the GCL should remain in direct and uniform contact with the compacted soil subgrade.

<u>Satisfaction of §257.70(b)(1)</u>

> *The composite liner must be:*
>
> > *(1) Constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to pressure gradients (including static head and external hydrogeologic forces), physical contact with the CCR or leachate to which they are exposed, climatic conditions, the stress of installation, and the stress of daily operation;*

This demonstration presents the requirement in italics and the demonstration in plain text.

> *The composite liner must be constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to:*
>
> "*pressure gradients (including static head and external hydrogeologic forces)*"

<u>Static Head</u> - The maximum normal operating hydraulic head that can act on the composite liner is 7.5 feet (calculated as "dike crest El. 515.0 ft" minus "2.0 ft freeboard" minus "Pond Low End El. 507.0 ft" plus "1.5-ft thickness of protective sand and reinforced concrete"). The compacted soil subgrade of the Spruce PDP provides a firm support and containment of the composite liner to resist seepage forces from the static head.

The maximum normal operating hydraulic head for the Spruce PDP is well within the operational range of both the HDPE and the GCL components. The two components are commonly used to contain ponded fluids in industrial surface impoundments and, if constructed in accordance with manufacturers' recommendation and industry standards, have sufficient strength and thickness to prevent failure due to static head pressure gradients.

External Hydrogeologic Forces – Representative groundwater elevations in the vicinity of the site are reported to be consistently at, or slightly above, the level of the adjacent Calaveras Lake at approximately El. 486 feet (Raba Kistner, Inc., "Geotechnical Engineering Study for J.K. Spruce –Calaveras Lake Power Plant, Proposed New Coal Combustion Residual Ponds, San Antonio, Texas," ASA17-096-00, February 5, 2019). The pond bottom, El. 507 feet, is approximately 21 feet above the static groundwater elevation.

The pond liner is constrained by the dead weight pressure (approximately 170 psf) of the overlying sand and reinforced concrete layers. There are no adjacent stormwater retention basins. There is not a credible mechanism within the planned life of the Spruce PDP for sufficient ground or other subsurface water to be sufficiently close and for a sufficient period of time to apply seepage (hydrogeological) force on the composite liner of the Spruce PDP.

"physical contact with the CCR or leachate to which they are exposed,"

HDPE – HDPE is commonly used in CCR containment applications and is recognized to be chemically compatible with CCR. See, for example, Electric Power Research Institute (EPRI), "State-of-the-Practice Liners and Caps for Coal Combustion Product Management Facilities", October, 2012), which is presented in Attachment A, HDPE Compatibility with CCR.

The CCR leachate expected for the Spruce PDP has pH = 6.09 ("slightly acidic"), as measured during testing for compatibility with candidate GCL liners (see CETCO, "CPS - FGD Brine Pond Composite Liner, Summary of Findings for Hydraulic Conductivity Testing of GCLS for Application Compatibility", August 16, 2021, which is presented in Attachment B, GCL Submittals) and HDPE is compatible with slightly acidic and alkali solutions. The HDPE has appropriate chemical properties to prevent failure due to physical contact with CCR leachate.

Geosynthetic Clay Liner – CPS commissioned compatibility testing of various GCL products by CETCO, a manufacturer and distributor of a range of GCL products. CETCO used long-term hydraulic conductivity testing to identify a polymer-amended product (Resistex 200FLW-9) that resisted degradation of hydraulic conductivity under long-term exposure to representative CCR leachate for the Spruce PDP.

The CETCO report (see CETCO, "CPS - FGD Brine Pond Composite Liner, Summary of Findings for Hydraulic Conductivity Testing of GCLS for Application Compatibility", August 16, 2021, which is presented in Attachment B, GCL Submittals) reported a permeability (hydraulic conductivity) for the Resistex® 200, using site leachate, of 7.59×10^{-10} cm/sec after 858.2 hours and 3.2 pore volumes of testing.

Since the measured value for site-specific leachate is lower than the equivalent value for deionized water published on the Technical Data Sheet value for Resistex 200FLW-9, the selected GCL can be understood to have appropriate chemical properties to prevent failure due to physical contact with CCR leachate.

climatic conditions,

San Antonio Climatic Conditions – The climate of San Antonio is considered to be sub-tropical, with mild winters and warm, humid summers. The composite liner of the Spruce PDP is protected from ultraviolet radiation and isolated from thermal extremes by the overlying 12 inches of sand and 6 inches of reinforced concrete. The components of the composite liner have the appropriate chemical and physical properties to be compatible with the climatic conditions of San Antonio, Texas.

the stress of installation, and

Stress of Installation – The preceding demonstration with heading “Satisfaction of §257.70(b)” presents a description of the installation sequence and procedures for the components of the composite liner of the Spruce PDP. The methods of construction utilized by the Contractor and documented by the Construction Quality Assurance team assure that the integrities of the composite liner components are not compromised by the stresses of installation.

the stress of daily operation

Stress of Daily Operation – The Spruce PDP is intended to be filled with CCR containing a significant percentage of solids that, after dewatering, must be removed using heavy equipment to the site CCR landfill. CPS has operated a very similar facility, the SRH Pond, at the same facility for many years and has satisfactory experience with the performance of that facility its concrete working surface under many years of daily operations.

The composite liner components of the Spruce PDP are protected by an overlying 12-inch sand layer and 6-inch reinforced concrete working surface. The subgrade and sand layer have been compacted to provide a firm and unyielding subgrade for the concrete paving. The integrities of the composite liner components should not be compromised by the stresses of daily operation.

Satisfaction of §257.70(b)(2)

The composite liner must be:

(2) Constructed of materials that provide appropriate shear resistance of the upper and lower component interface to prevent sliding of the upper component including on slopes;

Shear Resistance – The upper component of the composite liner is a textured (both sides) HDPE geomembrane. The lower component is a needle-punched geosynthetic clay liner with upper and lower surfaces composed of non-woven, needle-punched geotextiles. The inside side slopes of the Spruce PDP are 3.5(H):1(V).

A commonly used geosynthetics design engineering reference book, "Designing with Geosynthetics, Vol. 2, 6th Edition", Robert M. Koerner, Xlibris Corporation, 2012, provides typical interface friction values for various geosynthetic interfaces. Table 5.6 (b) "Geomembrane-to-Geotextile Friction Angles" lists a value of 32 degrees for textured HDPE against nonwoven, needle-punched geotextile.

The "Infinite Slope" method is a simple slope stability calculation for factor of safety against sliding on a planar surface. For a failure surface for which the strength to resist sliding is solely frictional (i.e. no cohesion term), the equations become independent of overburden load/pressure, which would increase both the sliding force and the resisting force (by increasing interface friction). The infinite slope calculation does not incorporate any restraint provided by the liner anchor trench at the top of slope, which is a relatively significant contribution in this case due to the short height (9 feet) of the internal slopes. The infinite slope calculation provides a conservative representation of the resistance to interface sliding of the liner components:

Infinite Slope Factor of Safety (c = 0)

FS = (Tan phi) / (Tan beta),

Where: Phi = interface friction angle, 32 degrees in this case
Beta = angle of planar surface, 15.95 degrees for 3.5:1 slope

For the Spruce PDP internal slide slopes,

FS = (Tan 32.0 degrees) / (Tan 15.95 degrees)
= 0.62 / 0.29
= 2.19

Though not explicitly required by the CCR Rule, a similar calculation may be performed to evaluate the stability of the GCL on the compacted soil subgrade. For an assumed interface friction of phi = 20 degrees against silty sand (note, Koerner (2012) reports interface friction angles for non-woven, needle-punched geotextile against concrete sand and mica schist sand as 30 and 26 degrees, respectively), the corresponding Factor of Safety against sliding is 1.27.

The composite liner of the Spruce PDP is constructed of materials that provide appropriate shear resistance of the upper and lower component interface to prevent sliding of the upper component on slopes.

Satisfaction of §257.70(b)(3)

The composite liner must be:

(3) Placed upon a foundation or base capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift; and

Foundation of Liner – The subsurface conditions and engineering characteristics of soils at the proposed site for the Spruce PDP were investigated by Raba Kistner, Inc. (RKI), a geotechnical engineering consultant with specific local geotechnical engineering experience in the San Antonio area and the Calaveras/Spruce Plant site. RKI published a an original and a supplemental Geotechnical Engineering Report for the Spruce PDP project:

1. "Geotechnical Engineering Study for J.K. Spruce –Calaveras Lake Power Plant, Proposed New Coal Combustion Residual Ponds, San Antonio, Texas," Project No. ASA17-096-00, February 5, 2019, Raba Kistner, Inc.
2. "Supplemental Geotechnical Engineering Letter, J.K. Spruce - Calaveras Lake Power Plant, Proposed Two New Coal Combustion Residual Containment Ponds, San Antonio, Texas," Project No. ASA17-096-01, May 27, 2022, Raba Kistner, Inc.

The second report contains geotechnical recommendations specific to the soils likely to be encountered at the revised, shallower elevation of the pond bottom. The project specifications, specifically Section 31 23 00 "Excavation and Fill", and the RKI geotechnical recommendations were used in tandem to assure that the foundation for the ponds and the perimeter dikes was prepared to provide a firm and unyielding support for construction and future operational loads.

RKI (2019) and RKI (2022) did not identify any deep-seated soil conditions that could allow instability of or settlement or compression of the proposed pond dikes or liner system.

RKI (2022) assessed the site for the potential for expansive soil-related movements and estimated possible movements on the order of one inch or less. No soils with possible expansive characteristics were identified during excavation.

Any other unsuitable soils were removed and replaced with compacted fill. The excavated subgrade was scarified, compacted, tested, and proof-rolled, and accepted by the Quality Assurance Engineer to verify and absence of conditions that might allow settlement, compression, or uplift of the liner system.

With regard to "uplift" on the liner system, the preceding Section "Satisfaction of §257.70(b)(1)" describes that "(t)here is not a credible mechanism within the planned life of the Spruce PDP for sufficient ground or other subsurface water to be sufficiently close and for a sufficient period of time to apply seepage (hydrogeological) force on the composite liner of the Spruce PDP."

The alternative composite liner of the Spruce PDP has been placed on a foundation capable of supporting the liner and resisting pressure gradients from above. The site conditions and site preparation preclude opportunities for failure of the liner due to settlement, compression, or uplift.

Satisfaction of §257.70(b)(4)

The composite liner must be:

(4) Installed to cover all surrounding earth likely to be in contact with the CCR or leachate.

The alternative composite liner covers the entire surface impoundment surface and extends beyond the top of the embankments into an anchor trench; the liner covers all surrounding earth likely to be in contact with CCR.

The height of the pond embankments allows for 2 feet of freeboard above the maximum normal operating level.

§257.70(c) Alternative Composite Liner Requirements

40 CFR §257.70(c) Alternative Composite Liner states the following:

(c) If the owner or operator elects to install an alternative composite liner, all of the following requirements must be met:

(1) An alternative composite liner must consist of two components; the upper component consisting of, at a minimum, a 30-mil GM, and a lower component, that is not a geomembrane, with a liquid flow rate no greater than the liquid flow rate of two feet of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} *cm/sec. GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick. If the lower component of the alternative liner is compacted soil, the GM must be installed in direct and uniform contact with the compacted soil.*

(2) The owner or operator must obtain certification from a qualified professional engineer that the liquid flow rate through the lower component of the alternative composite liner is no greater than the liquid flow rate through two feet of compacted soil with a hydraulic conductivity of 1×10^{-7} *cm/sec. The hydraulic conductivity for the two feet of compacted soil used in the comparison shall be no greater than* 1×10^{-7} *cm/sec. The hydraulic conductivity of any alternative to the two feet of compacted soil must be determined using recognized and generally accepted methods. The liquid flow rate comparison must be made using Equation 1 of this section, which is derived from Darcy's Law for gravity flow through porous media.*

(Eq. 1) $$\frac{Q}{A} = q = k\left(\frac{h}{t} + 1\right)$$

Where,

Q = flow rate (cubic centimeters/second);
A = surface area of the liner (squared centimeters);
q = flow rate per unit area (cubic centimeters/second/squared centimeter);
k = hydraulic conductivity of the liner (centimeters/second);
h = hydraulic head above the liner (centimeters); and
t = thickness of the liner (centimeters).

(3) The alternative composite liner must meet the requirements specified in paragraphs (b)(1) through (4) of this section.

Satisfaction of §257.70(c)(1)

(1) An alternative composite liner must consist of two components; the upper component consisting of, at a minimum, a 30-mil GM, and a lower component, that is not a geomembrane, with a liquid flow rate no greater than the liquid flow rate of two feet of compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec. GM components consisting of high density polyethylene (HDPE) must be at least 60-mil thick. If the lower component of the alternative liner is compacted soil, the GM must be installed in direct and uniform contact with the compacted soil.

Liner Components – The upper component of the composite liner is a 60-mil thickness of HDPE geomembrane. The lower component of the composite liner is a geosynthetic clay liner (GCL). The equivalency of the GCL to a two-foot thickness of compacted soil with a hydraulic conductivity of 1×10^{-7} cm/sec is demonstrated in a subsequent section of this Calculation under the heading "Satisfaction of §257.70(c)(2)".

Direct and Uniform Contact - A preceding demonstration with heading "Satisfaction of §257.70(b)" presented a description of the installation sequence and procedures for the components of the composite liner of the Spruce PDP and the conclusion that the geomembrane and GCL were installed in direct and uniform contact with the compacted soil subgrade.

Satisfaction of §257.70(c)(2)

(2) The owner or operator must obtain certification from a qualified professional engineer that the liquid flow rate through the lower component of the alternative composite liner is no greater than the liquid flow rate through two feet of compacted soil with a hydraulic conductivity of 1×10^{-7} cm/sec. The hydraulic conductivity for the two feet of compacted soil used in the comparison shall be no greater than 1×10^{-7} cm/sec. The hydraulic conductivity of any alternative to the two feet of compacted soil must be determined using recognized and generally accepted methods. The liquid flow rate comparison must be made using Equation 1 of this section, which is derived from Darcy's Law for gravity flow through porous media.

(Eq. 1) $$\frac{Q}{A} = q = k\left(\frac{h}{t} + 1\right)$$

Where,

Q = flow rate (cubic centimeters/second);
A = surface area of the liner (squared centimeters);
q = flow rate per unit area (cubic centimeters/second/squared centimeter);
k = hydraulic conductivity of the liner (centimeters/second);
h = hydraulic head above the liner (centimeters); and
t = thickness of the liner (centimeters).

Lower Component – The lower component of the alternative composite liner is a needle-punched geosynthetic clay liner (GCL), specifically the Resistex 200FLW-9 GCL manufactured by CETCO Lining Technologies, Inc. (CETCO). The Technical Data Sheet for Resistex 200FLW-9 was supplied by the geosynthetic installer, EnviroCon Systems, Inc., of Houston Texas, in the pre-construction submittals and is presented in Attachment B, GCL Submittals.

GCL Hydraulic Conductivity (“k”) - CPS commissioned compatibility testing of various GCL products by CETCO. CETCO is a manufacturer and distributor of a range of GCL products. CETCO performed long-term hydraulic conductivity testing (ASTM D6766, Scenario 2 procedure) to identify a polymer-amended product (Resistex 200) that maintained low hydraulic conductivity under long term exposure to representative site CCR leachate.

The CETCO report (see Attachment B, GCL Submittals, CETCO, “CPS - FGD Brine Pond Composite Liner, Summary of Findings for Hydraulic Conductivity Testing of GCLS for Application Compatibility”, August 16, 2021) reported a permeability (hydraulic conductivity) for the Resistex® 200, using representative site CCR leachate, of 7.59×10^{-10} cm/sec after 858.2 hours and 3.2 pore volumes of testing.

Hydraulic Head (h) – As described in preceding Section “Satisfaction of §257.70(b)(1)”, the maximum normal operating hydraulic head that can act on the composite liner is 7.5 feet, or 228.60 cm.

Soil Liner Thickness (t) – The thickness of the reference two feet of compacted soil liner is 60.96 cm.

GCL Thickness (t) - In personal email communication to AECOM dated 8/24/23, Reza Gorakhki, PhD, Technical Services Engineer with CETCO, reported initial and final thickness measurements at five standard locations on the GCL sample for the ASTM D6766 laboratory test. The average initial and final thicknesses were 6.924 mm and 6.926 mm, respectively. For this calculation, the final value of 6.926 mm, equal to 0.6926 cm, is used.

Unit Flow Rate Comparison -

Reference 2-ft Thickness of 1.0×10^{-7} cm/sec Compacted Soil –

$$
\begin{aligned}
q_{soil} &= k\,(h/t + 1) \\
&= 1.0 \times 10^{-7} \text{ cm/sec} \times (228.60 \text{ cm} / 60.96 \text{ cm} + 1) \\
&= 4.75 \times 10^{-7} \text{ cm/sec}
\end{aligned}
$$

Comparison Resistex 200FLW-9 GCL –

$$
\begin{aligned}
q_{GCL} &= k\,(h/t + 1) \\
&= 7.59 \times 10^{-10} \text{ cm/sec} \times (228.60 \text{ cm} / 0.6926 \text{ cm} + 1) \\
&= 2.51 \times 10^{-7} \text{ cm/sec}
\end{aligned}
$$

Demonstration – Therefore, by calculation, the liquid flow rate through the lower component of the alternative composite liner, q_{GCL}, is no greater than the liquid flow rate through two feet of compacted soil with a hydraulic conductivity of 1×10^{-7} cm/sec, q_{soil}.

Satisfaction of §257.70(c)(3)

(3) The alternative composite liner must meet the requirements specified in paragraphs (b)(1) through (4) of this section.

Satisfaction of the requirements specified in paragraphs (b)(1) through (4) of §257.70 is demonstrated in preceding paragraphs of this calculation titled "Satisfaction of §257.70(b)(1)" through "Satisfaction of §257.70(b)(4)".

Conclusion

This calculation package describes the proposed alternative composite liner, consisting of a 60-mil HDPE geomembrane overlying Resistex 200FLW-9 geosynthetic clay liner, and documents how it complies with the requirements of 40 CFR §257.72 "Liner design criteria for new CCR surface impoundments and any lateral expansion of a CCR surface impoundment" and the referenced detailed requirements for an alternative composite liner presented in 40 CFR §257.70(b) Composite Liner

Therefore, since the 60-mil HDPE and GCL alternative composite liner of the Spruce Plant Drains Pond (PDP) satisfy the requirements of 40 CFR §257.72 and §257.70(b), the requirement of the "directing" 30 TAC §352.721 "Liner Design Criteria for New and Lateral Expansions of Coal Combustion Residuals Surface Impoundments" is also satisfied.

Attachment A – HDPE Compatibility with CCR

A.1 - **"***State-of-the-Practice Liners and Caps for Coal Combustion Product Management Facilities*,"
October 2012,
Electric Power Research Institute (EPRI).

ELECTRIC POWER RESEARCH INSTITUTE

State-of-the-Practice Liners and Caps for Coal Combustion Product Management Facilities

2012 TECHNICAL REPORT

State-of-the-Practice Liners and Caps for Coal Combustion Product Management Facilities

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1023741

Final Report, October 2012

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NOTE

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Acknowledgments

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

State-of-the-Practice Liners and Caps for Coal Combustion Product Management Facilities. EPRI, Palo Alto, CA: 2012. 1023741.

Abstract

Approximately 40% of the coal combustion products (CCPs) generated in the United States are beneficially reused in applications such as concrete products, road construction, and wallboard, with the remaining volume managed in landfills and ponds. Most new management units since 1994 have been lined landfills; pending federal regulations are expected to accelerate that trend.

The objective of this report is to provide environmental managers with an overview of the state of the practice for landfill liner and cap systems as they apply to CCP management units.

While there are a variety of site-specific and material-specific factors to consider in a landfill design, this report broadly defines a state-of-the-practice liner as one with a barrier layer overlain by a leachate collection system to control leachate head on the liner, and it provides guidance on configurations and materials most commonly used in these systems. A state-of-the-practice cap system is broadly defined as a performance-based cap that is less permeable than the liner system and minimizes percolation to the extent practical and necessary considering site-specific climate, liner system design, and hydrogeology.

While this report focuses primarily on landfills, many of the technologies are equally applicable to CCP ponds. In particular, the capping technologies described here are applicable for ash ponds and unlined legacy landfills, as well as new landfills. In an associated project on CCP management, EPRI is currently developing guidance documents on dewatering and closure of existing CCP ponds, as well as construction of new disposal facilities over closed ponds.

Keywords
Coal combustion products
Landfill
Liner
Cap
Geomembrane
GCL

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Section 1: Introduction

Overview of Current Electric Power Industry CCP Disposal and Utilization Practices

More than 130 million tons of coal combustion products (CCPs) are generated annually in the United States from the generation of electricity. Fly ash, wet flue gas desulfurization (FGD) residues, and bottom ash account for most of these CCPs. Approximately 42% of this material was beneficially reused in 2010, leaving 75 million tons to be managed through alternative methods (American Coal Ash Association, 2011). Since the 1980's, most newly permitted CCP disposal facilities have been landfills (Figure 1-1), and pending federal regulation may cause all future disposal to be in landfills.

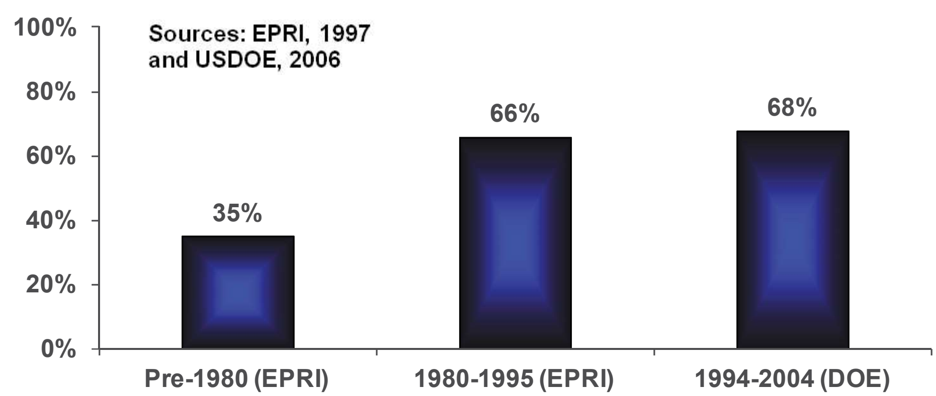

Figure 1-1
Percentage of new CCP management units built as landfills

A modern landfill system consists of multiple components, as illustrated in Figure 1-2. Components associated with preventing a release of leachate to the environment are, from bottom to top: a barrier (or liner) to prevent release of liquids from the facility; a leachate collection system to remove liquids from within the facility; and a cover system (or cap) to prevent liquids from entering the facility after it is closed.

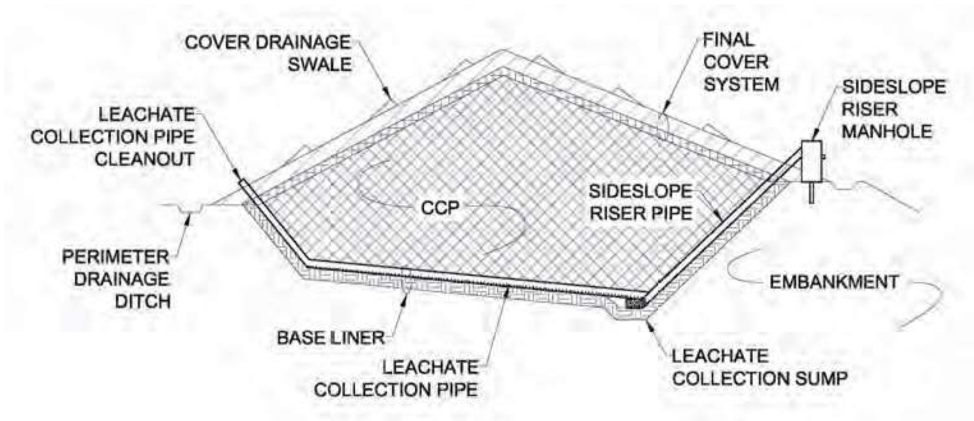

Figure 1-2
Cross-sectional view of a CCP landfill

Most CCP landfills built since the 1990's have liner systems, and most of these new liner systems include a synthetic component.

Landfills similar to the depiction in Figure 1-2 were not commonly used by the power industry for waste management units built prior to the 1980's (Figure 1-3). Since the 1990's new units commonly include liners, and the liners often have synthetic components. A joint study was performed by the United States Department of Energy (USDOE) and the United States Environmental Protection Agency (USEPA) to evaluate the management practices of CCPs at landfills and surface impoundments. The study focused on sites that were permitted, constructed, or expanded between 1994 and 2004. Out of 56 responses, the survey indicated the following breakdown of liner use: 25% compacted clay, 18% single synthetic (e.g., geomembrane or geosynthetic clay liner), 27% composites (a synthetic material over compacted clay), 4% double liners (two of the liners described above separated by a permeable layer to collect leakage through the upper liner), and 25% identified as multiple combinations of the types above (USDOE, 2006).[1]

The Association of State and Territorial Solid Waste Management Officials (ASTSWMO, 2009) issued a survey to state waste and water program managers in February 2009 to gather information regarding CCP management. Responses

[1] The percentages do not add up to 100 percent because one of the 56 facilities was designed to contain bottom ash, which was considered inert by the state, and no liner was required.

from 44 states indicated that CCPs are managed in 42 of the responding states, with 36 (86%) having permit programs for CCP landfills. Table 1-1 outlines the regulatory requirements implemented by states that regulate CCP management.

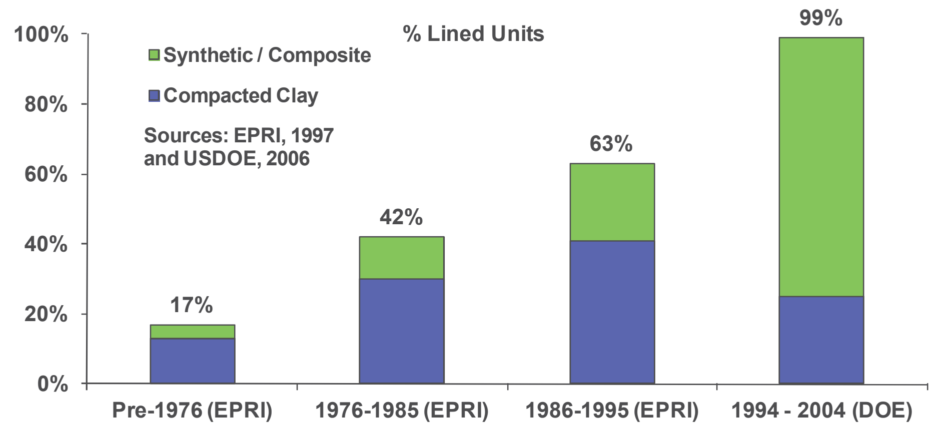

Figure 1-3
Liner use at new CCP management units

Table 1-1
Percentage of states with regulatory requirements for the management of CCP landfills and surface impoundments, based on a survey of 42 states

Regulatory Requirement	Landfills	Surface Impoundments
Bottom Liner	64%	33%
Groundwater Monitoring	81%	39%
Leachate Collection	52%	14%
Final Cover System	79%	36%
Post-Closure Care	79%	39%
Siting Controls	83%	39%
Corrective Action	86%	42%
Structural Stability	69%	36%
Financial Assurance	69%	31%

Source: ASTSWMO Letter to USEPA, April 2009.

This report is part of a series of EPRI reports related to the engineering design and costs of CCP disposal site management. While this report is generally written for landfills, many of the technologies are equally applicable to CCP ponds. Guidelines are currently being developed for dewatering and closure of existing CCP ponds, as well as construction of new disposal facilities over closed ponds. In addition, EPRI (2012) presented detailed costs for construction and closure of both CCP landfills and ponds based on the requirements in the proposed federal regulation (USEPA, 2010).

Section 2: Properties of Coal Combustion Products

Physical and Engineering Properties

Physical properties of CCPs are needed to design a structurally sound containment system and determine maximum slopes for interim filling during operations and final closure. The design of the leachate collection system is partially controlled by the permeability of the CCP for sizing collection and conveyance appurtenances, while fines in CCP will affect the gradation of the drainage blanket material or the size of perforations in the leachate collection pipe. Current design guidelines for leachate collection systems were developed for municipal solid waste (MSW), and are not necessarily applicable to CCPs. Specifically, fly ash and FGD residuals have relatively uniform, fine particle size that poses greater concerns for leachate collection system clogging than MSW.

Other physical considerations include CCP density, rate of consolidation, and filling rate, which can be used to determine the life of the landfill. Ranges of geotechnical properties for CCPs are listed in publications such as EPRI (in preparation) for fly ash, EPRI (2009) for fly ash and bottom ash, and EPRI (1995) for wet FGD products. Plant-specific values are affected by factors such as the boiler type, source coal, and flue gas additives prior to particulate collection; additional factors affecting wet FGD properties are FGD oxidation and sorbents.

Chemical Properties

CCPs are not ignitable, reactive, or corrosive (Table 2-1). They are managed in landfills and impoundments because the leachate generated when water comes in contact with the material can have concentrations of dissolved inorganic constituents higher than background concentrations. Organic constituents are not typically detected in CCPs and their leachate because the organic matter in the coal is combusted in the power plant boiler.[2]

Table 2-1
Ranges of field pH values for CCP leachate

Material[1,2]	#	Min	Med	Max
Fly Ash, Landfill, Bituminous	6	6.7	7.3	9.3
Fly Ash, Landfill, Subbituminous	8	6.4	9.9	12.2
Fly Ash, Impoundment, Bituminous	12	5.5	7.9	11.5
Fly Ash, Impoundment, Subbituminous	8	7.9	8.6	11.7
Fixated Scrubber Sludge[3] (FSS), Landfill	4	7.8	9.3	12.0
FGD Residuals[4] ($CaSO_3$), Impoundment	7	6.1	7.3	8.2

1. Source: EPRI CPInfo database
2. Results are site averages
3. All available FSS data were from landfills; two had FSS fixated using bituminous coal fly ash and three using lignite coal fly ash
4. Residual solids from inhibited and natural oxidation wet FGD systems; sample sites may contain co-disposed fly ash; all available samples for this material were from impoundments; five site averages were from plants that burned subbituminous coal and two site averages were from plants that burned lignite

The chemical properties of CCP leachate are used to evaluate chemical compatibility with liner materials, and leachate management alternatives when there is a leachate collection system. CCP leachate is generally considered compatible with geomembranes and clay materials used in landfill construction (EPRI, 1996). However, geosynthetic clay liners (GCLs) can be negatively affected by leachates with high ionic strength and/or a high ratio of divalent to monovalent cations (Kolstad et al., 2004). EPRI is performing research to evaluate the compatibility of CCP leachates with sodium bentonite clays used in GCLs.

Table 2-2 lists concentration ranges for major constituents from EPRI sampling of CCP leachate. Ranges for coal ash and FGD calcium sulfite mixtures are based on field leachate samples collected at landfills and impoundments. Ranges for FGD gypsum are based on laboratory batch leaching tests, and concentrations for some elements (such as chloride) in the FGD gypsum dataset may be lower than observed in the field due to dilution inherent in the batch leaching

[2] Power plant boilers burn coal at temperatures greater than 3,000º F. In comparison, thermal desorption units used to remediate soils containing organic contaminants typically operate at temperatures lower than 1,000º F. The lack of organic constituents in CCP leachate was noted by USEPA in volume 2 of the 1999 Report to Congress (EPA 530-R-99-010), page 3-70.

procedure and because water used to transport FGD gypsum to disposal sites is often recirculated, which increases dissolved solids concentration.

The data in Table 2-2 show that total dissolved solids (TDS) concentrations in CCP leachate are usually lower than 10,000 mg/L except for impoundments where sluice water was recirculated. Recirculation can cause accumulation of very high concentrations of dissolved solids.

Leachate from bituminous coal ash and FGD gypsum is most likely to have high concentrations of divalent cations (principally calcium) relative to monovalent cations. Leachate from subbituminous coal ash and calcium sulfite FGD products is more likely to have high concentrations of monovalent cations (principally sodium) relative to divalent cations.

Table 2-2
CCP leachate concentrations

Parameter [1, 2, 3]	Fly Ash Landfill Bituminous			Fly Ash Landfill Subbituminous			Fly Ash Impoundment Bituminous			Fly Ash Impoundment Subbituminous			Fixated Scrubber Sludge[4] (FSS) Landfill			FGD Residuals[5] ($CaSO_3$) Impoundment			FGD Gypsum $CaSO_4$ (unwashed) Lab Leachate		
	#	Med	Max	#	Med	Max	#	Med	Max	#	Med	Max	#	Med	Max	#	Med	Max	#	Med	Max
Alkalinity	1	275	275	4	BDL	909	2	124	233	1	104	104	0			2	BDL	169	0		
Bicarbonate	5	113	247	3	137	481	8	49	535	3	104	157	4	11	28	5	19	174	0		
Calcium	6	418	623	8	157	505	14	97	389	8	153	1,288	5	695	1,334	8	575	1,248	8	691	771
Carbonate	5	0.13	5.5	3	50	103	8	BDL	4.9	3	2.9	32	4	1.4	21	5	BDL	BDL	0		
Chloride	6	32	123	8	50	97	12	20	127	8	57	42,380	5	1,116	2,605	8	3,051	37,859	8	43	77
Magnesium	6	76	220	8	4.5	61	14	12	50	8	30	1,521	5	8.2	87	8	1,429	3,405	8	33	64
Potassium	6	41	219	8	86	130	14	9.3	58	8	25	493	5	350	578	8	300	928	8	1.9	7.2
Sodium	6	98	455	8	795	3,160	14	19	91	8	305	22,985	5	652	2,310	8	3,419	42,132	8	7.7	71
Sulfate	6	1,751	2,410	8	1,693	6,070	14	231	1,017	8	842	16,562	5	1,481	4,710	8	10,810	95,120	8	1,381	1,549
TDS	0			3	2,767	2,983	7	759	1,770	1	3,344	3,344	2	6,467	8,128	2	20,600	35,279	0		

1. Sources: EPRI CPInfo database for fly ash, FSS, and FGD residuals data; EPRI (2011) for FGD gypsum data
2. Concentrations in mg/L
3. Results are site averages; BDL indicates that the site average at the median or maximum value was lower than the method detection limit
4. All available samples for this material were from landfills; two sites were fixated using bituminous coal ash and three sites using lignite coal ash
5. Residuals from inhibited and natural oxidation wet FGD systems; sample sites may contain co-disposed fly ash; all available samples for this material were from impoundments; six site averages are for plants that burned subbituminous coal and two are for plants that burned lignite

Section 3: Liner Systems

Overview

A liner is a material with low hydraulic conductivity placed beneath a waste to isolate it from underlying soils and groundwater. A liner system includes the liner and other components engineered to isolate materials and leachate managed in landfills from native soils and groundwater. The state-of-the-practice design for a non-hazardous landfill liner system includes a liner to contain leachate in the landfill, and an overlying leachate collection system to remove the leachate.

National rules for regulation of CCP disposal proposed by USEPA in 2010 called for a composite liner (geomembrane underlain by compacted clay), with a leachate collection system. This liner system was proposed for both the non-hazardous and hazardous alternatives considered by USEPA.

USEPA (2010) proposed two regulatory alternatives for regulating CCPs—one alternative under RCRA Subtitle D and another under Subtitle C. The two proposals had identical liner system requirements consisting of a leachate collection system underlain by a 30-mil geomembrane and 2 feet of compacted clay (a composite liner), with the caveat that the geomembrane must be 60 mil if it is composed of HDPE due to its low puncture resistance and susceptibility to stress cracking.

This section focuses on liner configurations and materials used in the system. The leachate collection portion of liner systems is described in Section 4.

Liner Configurations

Liners are described based on the configuration of the liner portion of the system: single, composite, and double.

Single Liners

Single liners have one barrier layer between the waste material and the underlying native environment. These liners are constructed using compacted clay, a geomembrane, or a geosynthetic clay liner (GCL). Use of a single liner may sometimes be a viable alternative, for example in areas where the native substrate material has low hydraulic conductivity and can be worked to provide for good contact with an overlying geomembrane used as the primary barrier layer.

Composite Liners

A composite liner consists of two different materials, typically a fine-grained soil and a geomembrane, that perform as a single liner. This type of system provides redundancy and improved environmental protection relative to a single liner. When a geomembrane is installed over a fine-grained soil—particularly a clay—the potential for leakage is greatly reduced compared to either material individually, because the geomembrane provides very low hydraulic conductivity while perforations in the geomembrane are plugged by the underlying clay, creating a self-healing liner.

Common configurations include a geomembrane over a compacted clay, a geomembrane over a GCL, a GCL over a compacted clay, or both a geomembrane and a GCL over a compacted clay (USEPA, 2000).

Double Liners

Double liners are usually not necessary for CCP management sites, and were not included in USEPA's 2010 proposed rule for national regulation of CCP disposal.

Double liners are usually not necessary for CCP management sites. Double liners are required for hazardous waste landfills regulated under RCRA Subtitle C (or equivalent state programs), but were not included in either option in the USEPA's proposed rule for CCP management (USEPA, 2010).

A double liner is constructed with two single or composite liners that have a leak detection layer in between. The lower, secondary liner is intended as a backup in case defects develop in the primary, or upper liner. Liquid accumulation is monitored in the leak detection layer between the two liners to evaluate the effectiveness of the primary liner. Accumulation greater than 20 gallons/acre/day is a guideline, or action leakage rate (ALR), for evaluating the integrity of the primary liner (USEPA, 2000).

Liner System Materials

The components of a liner system may include some or all of the following:

- Liner materials to isolate the CCPS from the environment and contain leachate
- Geotextiles to provide soil filtration and/or separation, and enhance stability and drainage
- Geonets to enhance drainage

Each of these components is discussed in this subsection. Some of these materials are also used in leachate collection systems, which are also part of the liner system and are described in Section 4, as well as in caps as described in Section 5.

Liner Materials

Compacted Clay

Compacted clay is used to create a single liner with low hydraulic conductivity. Design criteria typically range from 2 to 5 feet in thickness, with compaction to achieve a hydraulic conductivity of 1×10^{-7} cm/s or lower. Clay liners are inherently more puncture resistant than GCLs or geomembranes, which are relatively thin (less than 10 mm for GCLs and less than 1.5 mm for geomembranes).

Landfill regulations typically specify clay as a single liner or as a component in a composite liner. However, clay is not readily available in some areas of the country, and some states have approved installation of composite liners with less clay thickness than a single clay liner, or with a GCL in place of the clay.

<u>Design Considerations</u>

Considerations when selecting and designing a compacted clay liner are typically associated with the availability of source material, achieving target hydraulic conductivity, and preserving the integrity of the liner during and after construction.

Clay liners are constructed using natural clays, silty clays, or sandy clays. Selected soils should be identified as CL or CH, using the Unified Soil Classification System (USCS). Hydraulic conductivity of the compacted material decreases with increasing plasticity index from 7 to 30 or increasing liquid limit from 20 to 40, with little appreciable change after that; however, a single index property is not adequate for predicting hydraulic conductivity (Benson and Trast, 1995). It may be difficult to break clods for soils with plasticity indices higher than 30. Benson et al. (1994) developed the following minimum recommendations for compacted clays to achieve a geometric mean hydraulic conductivity of less than 1×10^{-7} cm/s:

- Liquid limit: 20
- Plasticity index: 7
- Percentage fines (i.e., particles passing the No. 200 sieve): 30
- Percentage of clay: 15
- Activity: 0.3

Alternative soils not meeting the criteria of a clayey soil may be approved by regulatory agencies upon demonstration that the proposed material meets or exceeds the applicable regulations. Proposals for alternative liner soils may require testing of the physical properties of the material and test pad results. A test pad is constructed in accordance with design specifications and is used to show the effectiveness of the liner material prior to implementing in the landfill liner system.

Proper compaction effort and thin lifts will break down clods and remold the soils to achieve the desirable microstructure for low hydraulic conductivity. For example, 4 to 6 lifts may be sufficient to meet compaction requirements for a 2 to 3 foot thick clay liner (Benson and Daniel, 1994). Compaction requirements for typical loose and compacted lift thicknesses in the range of 8 and 6 inches, respectively, may be met using a tamping foot or sheepsfoot roller having feet as long as practical.

Performance testing is conducted during and after construction to verify that in-place density, moisture, and hydraulic conductivity of the clay liner meets the design specifications. Soils are compacted wet of the optimum moisture content to achieve desirable microstructure necessary for low hydraulic conductivity. Conventional clay liner construction specifications require a minimum in-place dry density typically greater than 90% of the maximum dry density, and a range of water content within 0 to 4% wet of the optimum moisture content based on the Modified Proctor laboratory test. This type of specification is acceptable for stability but can be insufficient for achieving a low hydraulic conductivity. A more advanced construction specification for achieving low hydraulic conductivity is to require a specified percentage (more than 70 to 80%) of the compaction field data points to fall above the line of optimums unique to the liner material. The line of optimums is obtained by connecting the peaks of three different laboratory compaction methods: Modified Proctor, Standard Proctor, and Reduced Proctor. The line of optimums specification assures that the liner material is compacted at a water content that allows sufficient structural remolding of the clay at both the macro- and micro-scale to achieve low hydraulic conductivity.

Performance testing using the line-of-optimums method reduces the potential that portions of a compacted clay liner will fail to meet hydraulic conductivity criteria, relative to performance testing based on compaction criteria.

Research by Benson, et al. (1999) evaluated the performance of 85 full-scale clay liners and test pads that were constructed with the purpose of achieving low hydraulic conductivity. Results showed that 26% of the liners failed to achieve a hydraulic conductivity less than 1×10^{-7} cm/s even though their construction met the "compaction-type" specification. However, all liners constructed with at least 90% of the compaction data on or above the line of optimums achieved hydraulic conductivities less than 1×10^{-7} cm/s. The research recommended amending compaction specifications to require at least 70% of the compaction data to be on or above the line of optimums.

The use of the line of optimums specification is displayed in Figure 3-1. The three laboratory compaction methods are plotted and connected by the line of optimums for the liner material. A construction specification based on the Modified Proctor test assumes that the field compaction will be the same throughout the facility, e.g., minimum dry density of 110 pounds per cubic foot and minimum moisture content of 11.3% moisture. The line of optimums specification is dynamic and is intended to achieve a low permeability soil barrier without regard to its load bearing capacity. Following the line of optimum in Figure 3-1, as the moisture content increases the minimum dry density requirement decreases and vice versa. This way a low permeability soil barrier can be achieved with potentially less moisture conditioning or compactive effort in the field. Keep in mind, however, a soil with high moisture content will not necessarily be capable of being compacted, no matter how much effort is applied, and may need to be sufficiently dried to meet the minimum dry density required by the line of optimums. Likewise, a dry soil may require moisture addition to adequately lubricate the soil particles in order for the soil to be molded and compacted to meet the minimum dry density requirements.

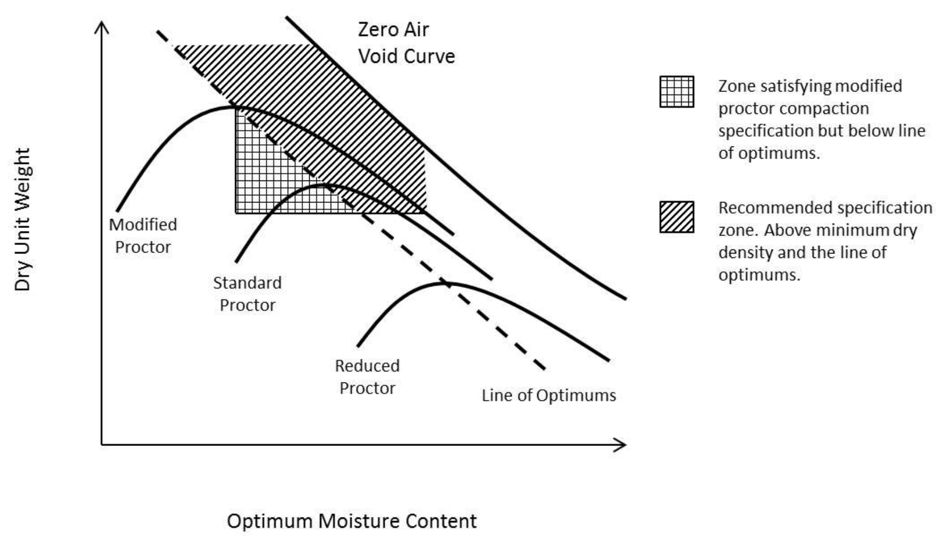

Figure 3-1
Example line of optimums diagram (modified from Daniel and Benson, 1990)

The zero-air-void curve shown in Figure 3-1 is the theoretical line of optimum dry unit weight achievable if all air voids were removed from the soil. Therefore, the compaction curves will never cross the zero-air-void curve (Das, 2002).

Construction and Cost Considerations

Clay liners are typically constructed with at least four lifts and a final thickness of at least two feet. Construction of a clay liner is achieved by placing and compacting layers or lifts of clay until the final design thickness is achieved (Figure 3-2). Each lift of clay is moisture conditioned and clay clods are broken up. Moisture conditioning can require either adding moisture or drying the clay to meet design criteria. Clay clods are broken up during placement and compaction with heavy equipment.

Figure 3-2
Grading a compacted clay liner

Construction sequencing considers the soil balance of the proposed landfill to reduce the volume of off-site materials that must be imported, and the area required to stockpile excess soils. To determine the proper balance of soils, the following factors are considered:

- Subbase excavation
- Clay liner
- Daily cover (not typically required for CCPs)
- Clay cover
- Rooting zone
- Topsoil

Likewise, balancing material needs during construction will limit the number of times the soil is handled to reduce costs. Typically, construction is sequenced in phases. This is accomplished by excavating half of a landfill sequence (i.e., cell or phase) then using clay from the other half of the sequence to construct the clay liner in the previously excavated area. Excavated soil from a new cell may also be used for capping an existing cell that has reached maximum capacity.

Cost for placement and compaction of readily available clay from an onsite stockpile generally ranges from approximately $3 to $6 per cubic yard. An important factor affecting clay liner cost is the availability of suitable material from local borrow sources. Trucking costs will escalate clay liner construction costs if a nearby borrow source is not available.

Construction Quality Assurance

Construction of landfill components is typically accompanied by observation, testing, verification, and documentation by a party not affiliated with the earthwork contractor. This is achieved through implementation of a construction quality assurance (CQA) program. CQA programs for placement of a landfill clay liner or cap typically include observation, testing, verification, and documentation of the following:

- Clay placement, conditioning, and mechanical compaction
- Field verification of moisture and density (moisture-density gauge or sand cone test)
- Laboratory sampling (e.g., Atterberg, soil classification grain size, density, permeability)
- Survey subbase and base grade to verify clay thickness and line and grade of final surface

The CQA program for a clay liner is typically conducted by a trained soils technician under the direction of a State licensed engineer. Testing requirements and frequencies vary between projects and State or Federal agency requirements.

Long-Term Performance Considerations

Leachate compatibility testing may be warranted for CCPs prior to selecting clay as the primary landfill liner component. Although CCP monofill leachate is not typically acidic and does not contain detectable concentrations of organic compounds, it can exhibit high alkalinity with a pH of 12 or higher.

The compacted clay should be covered as soon as possible to minimize exposure to the environment. Desiccation and freezing are two environmental conditions that can lead to cracking in the clay liner. If CCPs will not be placed in the landfill cell soon after construction is complete, then alternative cover materials can include native soils, bottom ash, or FGD gypsum, although the latter two materials may cause the cell to be considered active for regulatory purposes.

Geomembrane

Geomembranes are polymeric materials used in liner applications. The primary function of a geomembrane is to serve as a hydraulic barrier to contain liquids within the facility in liner applications, or to prevent liquids from percolating into the facility in cap applications. Geomembrane materials used in landfill liner systems include:

- high density polyethylene (HDPE)
- linear low density polyethylene (LLDPE)
- chlorosulfonated polyethylene (CSPE or Hypalon)
- polyvinyl chloride (PVC)
- flexible polypropylene (fPP)
- ethylene interpolymer alloy (EIA)
- ethylene propylene diene M-class rubber (EPDM)

All of these geomembranes can be evaluated for use in a CCP landfill liner. Factors to consider for selecting the most cost effective and environmentally protective geomembrane are discussed in this subsection. Table 3-1 contains a summary of the advantages and disadvantages for each of the geomembrane types.

Geomembrane Selection and Design Criteria

Geomembrane materials have differing physical and chemical properties making some better suited for certain applications than others. The variety of materials allows selection of a geomembrane that is compatible with the anticipated waste and underlying soil. The material manufacturer is an excellent source for helping specify and select an appropriate geomembrane product. In addition, preliminary material selection can be made using the annual *Geosynthetics Specifier's Guide*, which lists manufacturers, their products, and corresponding physical and mechanical properties (http://geosyntheticsmagazine.com/specifiersguide).

Key factors to consider when selecting a geomembrane are its performance during installation and welding, chemical resistance, and environmental durability (Scheirs, 2009). More specifically, performance factors to consider for installation and welding include:

- The melting point of the geomembrane provides insight to the acceptable welding temperature range. Some geomembranes, such as HDPE, have narrow melting temperature ranges, making welding more difficult at extreme ambient temperatures. On the other hand, fPP has a broad melting point and is capable of successful welds at very low temperatures (Scheirs, 2009).
- Puncture resistance is an important physical property due to the stresses caused during installation and backfilling. Punctures can be created by equipment, tools, and stones during installation. Additionally, geomembranes are subject to puncture during installation of the granular drainage blanket and overburden pressures from the waste fill. Some geomembranes are manufactured with a scrim reinforcement, significantly increasing puncture resistance.
- Use of a textured geomembrane on the base of a slope, where normal stresses are higher, and a smooth geomembrane on a slope may provide an optimal design from a slope stability perspective. However, geomembranes are hydrophobic and can be slippery when wet, potentially posing worker safety concerns. Use of a textured geomembrane on the slopes is therefore an important design consideration from a worker safety perspective.
- Some geomembranes can be manufactured into large sheets and folded for transport to the site. Large prefabricated sheets of geomembrane reduce installation time relative to smaller sheets because there are fewer seams to weld.

- Some geomembranes, such as CSPE and PVC, are subject to aging and can potentially lose the ability to be adequately welded or repaired.
- Geomembrane density varies between materials. Higher densities may affect design specifications for material delivery and installation, depending on site-specific design geometry and logistics.
- Thermal properties of geomembranes can affect how flat the material lays in warm and cold temperatures. Thermal expansion/contraction can cause the geomembrane to expand and create large wrinkles when warmed, or shrink and bridge across transitions in the subgrade when cold. Reinforced geomembranes have very little thermal expansion/contraction compared to the unreinforced materials of the same polymeric content. Selection of the most appropriate material will be based on site-specific requirements for limiting thermal expansion in consideration of such factors as the time of year for installation and geographic location. Costs may also be an important consideration as reinforced geomembranes can be more expensive.
- Low temperatures cause geomembranes to lose flexibility and become brittle, and in extreme situations, the brittleness can lead to cracking. More commonly, however, cold geomembranes are more difficult to install. If cold weather installation is anticipated, careful consideration should be given to selecting materials that provide greater flexibility at lower temperatures.

Thermal fusion welding is the easiest way to seam most geomembranes, provides the highest quality seam, and is the easiest to nondestructively test.

Seaming sheets together is a critical construction component of nearly any geomembrane liner installation. Some geomembranes can be prefabricated into large sheets and others are welded in the field as the material is installed. Typical seaming methods include thermal fusion, extrusion, chemical fusion, and chemical adhesive welded seams. Thermal fusion welding is the easiest way to seam most geomembranes, provides the highest quality seam, and is the easiest to nondestructively test. For these reasons, thermal fusion is generally used whenever possible to weld seams. However, thermal fusion welding requires equipment access to both sides of the geomembrane sheets to apply the proper temperature and pressure, which is in contrast to extrusion and chemically bonded seams that can be completed from the surface. Therefore, when it is not possible to thermally fuse a geomembrane, for example when making a repair, extrusion or chemically bonded seams are made.

Thermal fusion welding can be used on a wide array of geomembranes, including HDPE, LLDPE, PVC, fPP, CSPE, EIA, and, if specially manufactured, EPDM. Thermal fusion seams are created by applying heat to both sheets to be bonded then applying pressure to seal the seam (Figure 3-3). Thermal fusion seams can be welded to include an air channel along the center of the seam. The air channel is then used to nondestructively test the integrity of the seam (Figures 3-4 and 3-5).

Figure 3-3
Thermal fusion welding HDPE geomembrane sheets together in the field

Figure 3-4
Nondestructive pressure testing of a dual-track fusion weld

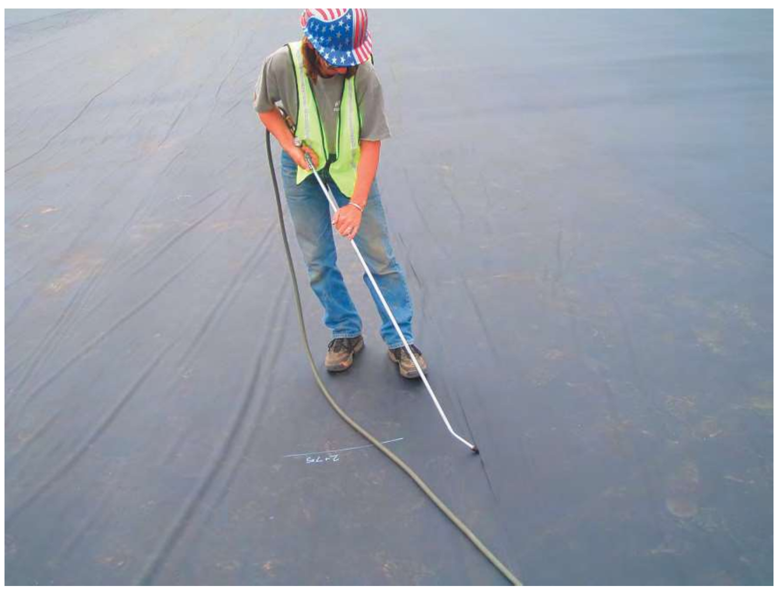

Figure 3-5
Nondestructive testing of a single-track fusion weld using an air lance

Extrusion welding is a process that bonds two separate panels of geomembrane by applying a molten bead of extrudate to the prepared seam (Figure 3-6). Extrusion welding can be performed on polyolefin geomembranes such as HDPE, LLDPE, and fPP.

Figure 3-6
Extrusion welding along the tie-in of existing geomembrane to geomembrane in a new construction phase of the landfill

Chemical seaming or solvent welding can be performed on PVC, EIA, and CSPE geomembranes. Similar to welding PVC pipe, a solvent, such as tetrahydrofuran or xylene, is applied along the seam area and pressure is applied using rollers to seal the seam (Figure 3-7). EPDM geomembrane seams are bonded using chemical adhesives. The chemical adhesives are applied to both surfaces of the geomembrane then pressure is applied using rollers to bond the sheets.

Figure 3-7
Geomembrane repairs performed by solvent welding a patch to the parent PVC geomembrane sheet

The primary chemical compatibility consideration for geomembranes in CCP monofills is the potential for elevated pH levels in leachate. The potential effects of high pH on geomembranes, however, are not well documented in the published literature.

Chemical resistance is a consideration with geomembrane liners in many municipal and industrial waste applications if the materials managed contain constituents that may cause swell, decrease flexibility, or even increase permeability of the geomembrane. CCPs are not highly acidic and do not leach organic liquids that could cause chemical incompatibility. The primary chemical compatibility consideration for CCPs is the potential for highly alkaline leachate.

For the most part, the effect of acids on geomembranes is of greater concern than the effect of alkaline leachate. However, little research has been performed to date to determine geomembrane compatibility with alkaline leachate. Limited testing on HDPE, LLDPE, and fPP returned variable results, with no degradation in some samples and slight degradation in others, and no material performed substantially better or worse than the others (Scheirs, 2009; Hornsey et al., 2010; Fourie et al., 2010).

If highly alkaline pH is anticipated, testing can be performed to evaluate potential compatibility issues with geomembranes. ASTM method D5885 is specifically designed for oxidative solutions, while EPA Method 9090 is a general test method used for chemical compatibility testing of geomembranes with leachate and other liquids that may be present in a landfill or impoundment environment. If highly alkaline leachate is anticipated and the test results indicate that geomembrane degradation is possible, then the geomembrane manufacture can incorporate additional hindered amine light stabilizers (HALS) that resist extraction and hydrolysis (Hornsey et al., 2010; Scheirs, 2009).

Another consideration when selecting a geomembrane is stability. Landfill stability is critical during construction and waste filling. Textured geomembrane increases the slope stability and is also used along the floor to increase the global stability of the waste mass. For example, a critical location for slope stability is at the phased termination of the waste mass. At the phased waste mass termination, the temporary slope extends to the landfill base and has limited toe support. Using textured geomembrane can improve global stability in these situations, potentially increasing the maximum vertical fill height before construction of subsequent phases. It should be noted, however, that some very flexible geomembranes achieve comparable interface friction values to textured geomembranes. Geomembranes such as PVC and fPP conform to the small bends and indents in the adjacent soils to make more surficial contact than can be achieved by HDPE. Laboratory analysis of the proposed soil and geomembrane can be conducted to measure the achievable interface friction between the proposed layers.

Global and veneer stability are considerations for both liners and caps. The stability of the liner is most critical during construction and filling (short-term stability). Caps are subject to short-term (during construction) and long-term (post-construction) stability concerns. Interface shear testing using the direct shear method (ASTM D5321 or ASTM D6243) is used to confirm that the materials have sufficient shear strength to ensure veneer stability of the geosynthetic/soil interfaces proposed for the liner or cap.

Table 3-1 provides a summary of selected geomembranes and their advantages and disadvantages with regard to resistance to weathering, chemicals, UV exposure, and other performance criteria.

Table 3-1
Selected geomembranes and respective advantages and disadvantages for CCP landfill applications

Geomembrane	Advantages	Disadvantages
HDPE (high density polyethylene)	Excellent resistance to chemical degradation and has been extensively used for landfills.	Potential for stress cracking, high degree of thermal expansion, poor puncture resistance, poor multiaxial strain properties, and low flexibility.
PVC (polyvinyl chloride)	High chemical resistance. Easy to seam and available in large prefabricated panels. Good puncture resistance. Mechanical properties unaffected by a large range of elongation. Not susceptible to environmental stress cracking. Excellent interface friction without being textured. Available with scrim reinforcement.	Subject to ozone and UV degradation (leaches plasticizers and becomes brittle). Low tear strength and seam strength. Low abrasion and erosion resistance. Needs to be treated with biocides to resist microbial attack. Not recommended in exposed applications. Brittle at low temperatures.
CSPE (chlorosulfonated polyethylene)	Good chemical resistance. Highly resistant to inorganic chemicals. Aging increases tensile strength, chemical resistance, and UV resistance. Maintains flexibility. Low coefficient of thermal expansion. Relatively impervious to attack from oxygen, ozone, or UV light. Suitable for exposed applications. Available with scrim reinforcement.	Cannot be thermally welded after aging. Difficult to solvent weld in low temperatures. Short shelf life – must be installed within 6 to 12 months of manufacturing.
LLDPE (linear low density polyethylene)	Good resistance to most chemicals but not as good as HDPE. Greater flexibility than HDPE. Good multiaxial strain properties and environmental stress crack resistance. Excellent large scale puncture resistance. Available with scrim reinforcement.	Moderate weathering and UV resistance qualities. Poor dimensional stability. Susceptible to oxidation.

Table 3-1 (Continued)
Selected geomembranes and respective advantages and disadvantages for CCP landfill applications

EPDM (ethylene propylene diene M-class rubber)	Good resistance to UV, oxidation, ozone, and aging. Elastic and chemically stable. No defined yield point under strain. Excellent resistance to punctures and microbial attack. Low coefficient of thermal expansion. Not susceptible to stress cracking. Can be used in exposed environments. Available with fabric reinforcement.	Low tear strength. Poor seam quality. Electrically conductive.
fPP (flexible polypropylene)	Excellent chemical and environmental stress-crack resistance. Highly flexible, and high toughness and puncture resistance. Excellent multiaxial properties and maintains flexibility at very low temperatures. Not affected by UV, ozone, and soil bacteria. Chemically inert and plasticizer and chlorine free. Easily repaired even after aging. Low coefficient of thermal expansion. Available with fabric reinforcement.	Susceptible to oxidative stress cracking along folds and creases.
EIA (ethylene interpolymer alloy)	Wide spectrum of chemical resistance. Outstanding resistance to UV, chemical, and microbiological attack. Excellent multiaxial properties. Tough and abrasion resistant. Maintains flexibility in extreme temperature environments. Can be used in exposed environments. Typically manufactured with scrim fabric reinforcement.	May exhibit poor flex cracking resistance. Heat degradation may lead to tearing.

Modified from Koerner (2005), and Scheirs (2009)

As shown, many geomembrane materials with various qualities are available. Chemical compatibility is typically not an issue for CCP applications; therefore, the main selection criteria for geomembrane are material availability, cost, whether or not it will be exposed to atmospheric conditions, and approval for use from the regulatory agency (USEPA's proposed CCP rule does not specify a particular geomembrane).

Construction and Cost Considerations

An advantage to using geomembranes relative to compacted clay includes the ease of material transport and installation. Geomembranes are transported by truck in rolls or accordion folded on pallets (Figure 3-8). The geomembrane is deployed over the prepared subgrade and seamed by qualified technicians.

Certain geomembranes (typically PVC and reinforced geomembranes less than 40 mil thick) can be factory fabricated into larger sheets to reduce the welding and repair efforts in the field. Factory fabricated seams reduce the welding time in the field and subsequent destructive and nondestructive testing, potentially saving time and money during field installation. However, larger factory fabricated panels generally require more labor (Figure 3-9) and may require larger equipment for deployment.

Figure 3-8
Geomembrane accordion folded on a pallet prior to deployment

Figure 3-9
Deployment of a large factory fabricated sheet of PVC geomembrane

Since leaks are more likely along geomembrane seams than within sheets, avoidance of seams at low points such as leachate collection trenches and sumps minimizes potential for leaks.

The subgrade should be smooth and free of objects that could puncture the membrane (Figure 3-10). An increase in hydraulic head on the liner increases the driving force for liquids to permeate the geomembrane. As discussed in Section 4, the leachate head on the liner is typically controlled to be less than 1 foot. Since leaks are more likely along seams than within sheets, avoidance of seams at low points such as leachate collection trenches and sumps minimizes potential for leakage.

Figure 3-10
Smooth rolling the subgrade prior to deployment of a 60-mil HDPE geomembrane liner

Geomembranes and other geosynthetics are typically anchored at the top of embankments or at other permanent liner terminations (Figure 3-11). The anchor trench does not support the materials on the slope; instead the material interface friction is relied upon for slope stability. The anchor trench is used mainly to hold the material in place during construction and prevent storm water seepage under the liner.

Figure 3-11
Geosynthetics placed in an anchor trench during installation; white material in the foreground is a GCL and dark material in the background is 40-mil LLDPE

A geomembrane requires a more intensive construction quality assurance (CQA) program than a clay liner.

A geomembrane requires a more intensive construction quality assurance (CQA) program than a clay liner (USEPA, 2000). Implementing the proper CQA program will greatly improve the long-term function of a landfill liner or cover system. Index tests are performed on the geomembrane to assure that the material has the specified material properties. Seams between panels are tested for strength and to assure that there are no holes. Lastly, a leak detection survey is performed after the entire liner system has been constructed, and before CCPs are placed in the landfill. A leak location survey is a nondestructive electrical resistance test capable of locating pin-hole leaks over the entire survey area. A voltage is connected to electrodes in contact with conductive soils above and below the geomembrane. Most geomembranes are electrical insulators, with the exception of EPDM due to its high percentage of carbon black. Therefore, the electrical current can only cross the nonconductive geomembrane through leaks, and any such current flows will cause areas of high current density that can be measured at the surface to identify the location of the leak.

Fine grading in preparation for geosynthetics deployment can cost approximately $1 per square yard depending on the level of effort required to achieve a suitably smooth clay surface.

Supply and installations of geomembranes typically range from $0.45 to $1.50 per square foot. Costs are affected by the size of the facility to be lined, site access, deployment options, and any applicable pay scales. Generally, the unit cost of installation decreases with increasing size of the site, although site access and deployment options also influence installation costs. Sites may have limited access due to active site operations or existing physical features. Some sites are limited in the available methods of deployment; for example, if the subgrade is too soft to accommodate heavy equipment, the geomembrane may have to be deployed by hand or using a block and tackle. Design features, such as liner penetrations, also increase the skill required and associated cost to deliver a successful installation.

Long-Term Performance Considerations

Penetrations in the geomembrane to accommodate pipe penetrations are difficult to adequately seal around due to the confined area, sudden direction change, and connection of a flexible material to a rigid pipe or structure.

Settlement of subsoils can affect liner performance by causing tensile strain. Settlement can be accounted for in the design. Differential settlement of the base liner may additionally cause restricted leachate flow and increased hydraulic head above the liner, increasing potential for leakage.

Some geomembranes will degrade if exposed to surface conditions for prolonged periods.

When considering an application that requires an exposed geomembrane, there are specific material types that will perform long-term against UV exposure and weathering (see Table 3-1). Additionally, the application must consider animal control, and restricted access for maintenance vehicles. A sacrificial geosynthetic that would be allowed to degrade may be used to provide protection, extend the life, and reduce maintenance of the geomembrane.

Geosynthetic Clay Liner

Geosynthetic clay liners (GCLs) may be considered to replace all or part of a traditional compacted clay liner. GCLs are made of granular or powdered bentonite clay that is bonded to one or more geosynthetic layers (e.g., geotextiles or geomembranes). Conventional configurations consist of clay encased between two geotextiles (i.e., fabric encased). GCLs are also available with a geotextile on one side and a geomembrane on the other as illustrated in Figure 3-12 (USEPA 2000, 2001) or with a geomembrane laminated onto a geotextile-encased GCL (i.e., a laminated GCL, also known as a GCLL). For the purposes of this discussion the focus will be on geotextile-encased GCL applications.

Figure 3-12
Typical GCL cross-sectional configurations (modified from GRI, 2000)

Design Criteria

Advantages of using GCLs over compacted clay barriers include the ease of transport and installation, self-healing properties, and thickness. Similar to geomembranes, GCLs are transported in rolls and can be unrolled over a prepared subgrade. Seaming GCL requires less technical skill than seaming geomembranes and is accomplished by overlapping panels and applying additional granular bentonite that will swell when hydrated. This provides a continuous seal between GCL panels. Heat bonding is sometime used to bond the geotextile along the panel seams to secure the panels during placement of overlying layers of materials. The internal bentonite of the GCLs has the ability to swell around small punctures, preventing the development of preferential pathways for liquid to penetrate the liner. Lastly, the thin profile of the GCL saves air space compared to the thickness of compacted clay required to achieve the same hydraulic barrier properties.

GCLs can provide equivalent or superior performance to clay liners if the bentonite can be maintained in a hydrated condition and is not allowed to desiccate.

GCLs can provide equivalent or superior performance to traditional clay liners if the bentonite can be maintained in a hydrated condition and is not allowed to desiccate. For low hydraulic conductivity, bentonite granules must be allowed to swell to form a gel-like consistency. Studies have also shown that GCLs are resilient to freeze/thaw conditions (Kraus et al., 1997).

Other design considerations for GCLs include compatibility with waste materials and stability on slopes. Leachate with high ionic strength can decrease the swelling ability of the bentonite and increase its hydraulic conductivity. However, the effect of the overburden stress from the waste material tends to compress the GCL, decreasing the hydraulic conductivity, and potentially offsetting ionic strength effects (Athanassopoulos, 2011). GCL performance may also be influenced by the presence of divalent cations such as calcium and magnesium. In the presence of calcium and magnesium, sodium bentonites will transform to calcium and magnesium bentonites, which alters the swelling process from a combination of osmotic and crystalline expansion to almost an entirely crystalline expansion. This transformation results in the development of much larger inter-granular pathways and higher permeabilities during hydration (Benson, 2012a). Benson (2012a) further indicated that if initial hydration can be maintained, the resulting change in permeability will be modest and will not significantly affect long-term performance. The development of inter-granular pathways is most pronounced through desiccation and repeated rehydration, leading Benson (2012a) to suggest that GCLs should not be used without a geomembrane. EPRI is currently performing research to evaluate the effects of ionic strength and divalent cations in CCP leachate on bentonite swelling in standard and chemically resistant GCLs.

The bentonite clay in a GCL has a low shear stress that needs to be considered when placing GCLs on the side slopes of landfills. Certain GCLs are reinforced by needle punching the encasement geotextiles together through the clay. The recommended maximum slope is 10H:1V for unreinforced GCLs and 3H:1V for GCLs reinforced with needle punching (Athanassopoulos, 2011).

Construction and Cost Considerations

GCLs are manufactured with naturally occurring bentonite soil. The thickness and weight of the bentonite cause the GCL to be the heaviest of the geosynthetic liners by a factor of approximately 4. Furthermore, the apparent opening size for a nonwoven geotextile is approximately 8 mil (0.212 mm), which is larger than the maximum 3 mil (0.074 mm) diameter clay particle. Therefore, GCLs should be installed with fine-grained soil or a geomembrane on one or both sides to prevent migration of the bentonite clay (Figures 3-13 and 3-14).

Protection from excessive moisture is important during construction to prevent premature hydration of the bentonite. Premature hydration of the GCL may cause the bentonite to be squeezed out during installation, reducing the effective bentonite thickness and its effectiveness as a hydraulic barrier. Alternately, an overly dry subgrade could inhibit proper hydration.

Supply and installation cost of typical GCLs with bentonite in-between geotextile fabrics is in the range of $0.45 to $0.60 per square foot.

Figure 3-13
Typical GCL installation, showing removal from the roll and overlapping panels

Figure 3-14
Installation of a GCL, showing the geotextile components of the GCL being heat bonded; the black material in the upper left background is 60-mil LLDPE

Supporting Materials in Liner Systems

Geotextiles

Woven and nonwoven geotextiles are fabrics typically manufactured using polypropylene polymer. Woven geotextiles are manufactured using common weaving practices, such as plain, basket, and twill weaves (Koerner, 2005), and are not commonly used in landfill applications. Nonwoven geotextiles are used in landfill applications as described below, and consist of randomly spun polymer filaments bonded into a fabric. Geotextiles are widely used because they can be implemented for separation, reinforcement, filtration, and drainage, and they often perform a combination of these functions.

Geotextile Use in CCP Landfill Design

A common use for geotextiles in CCP landfill applications is as a filter fabric.

As an alternative to granular soil filters, geotextiles can be used to isolate two materials with different grain size distributions. For example, a geotextile can be used to separate the granular drainage blanket from the stone in a leachate collection trench. Geotextile filter service life may need to be considered where very fine particles may blind or clog the geotextile, reducing the flow and causing elevated hydraulic head upgradient of the geotextile.

Geotextiles can be used for temporary geomembrane protection along the leading edge of phased landfill to protect and keep the geomembrane clean until construction of the subsequent phase. The geotextile can be kept in place using soil (for longer-term applications) or sandbags (for short-term applications) until the existing geomembrane is ready to be tied in to the next sequence of geomembrane. Removal of the geotextile should reveal a relatively clean geomembrane edge, free of large soil particles, requiring minimal preparation for welding.

Soils with small grain sizes, such as sand passing the No. 4 sieve (i.e., <4.75 mm), generally do not damage an underlying or overlying geomembrane. However, granular soils retained on the No. 4 sieve and larger may be separated from the geomembrane by a protective layer of geotextile. A typical specification for geomembrane puncture protection may require a 16 oz/yd^2 nonwoven needle-punched polypropylene or polyethylene geotextile.

Geotextiles may also be used for drainage applications such as low-flow gravity drainage, and capillary migration breaks for landfill covers.

Design Criteria

Geotextiles often have combined functions of separation, reinforcement, filtration, and drainage, which can be by design or an unintended result. The designer must consider all parameters to avoid unintended consequences and for the geotextiles to adequately perform the intended function.

Physical properties such as burst resistance, tensile strength, puncture resistance, and impact (tear) resistance are important design parameters with regard to reinforcement and separation. Alternatively, apparent opening size, permittivity, and permeability parameters are considered for filtration and drainage designs. Mechanical properties are generally proportional to the mass per unit area of the geotextile; strength parameters increase with increasing mass per unit area. However, as the geotextile mass per unit area increases, the water transmission rate generally decreases.

Seaming of geotextiles is important for stability and settlement considerations. Seams can simply consist of overlapping adjacent panels but typically are continuously sewn or heat bonded. Determination of the maximum anticipated settlement can be used to specify the minimum overlap between geotextile panels to prevent separation of the seams. Where sufficient tensile strength is required, such as for slope stability, sewing and thermal bonding can be specified. Several sewn seam types can be accomplished in the field, depending on the required seam strength. The most common type of sewn seam is the prayer seam.

Thermal bonding of nonwoven geotextiles can be accomplished using two methods. The easiest is by using a hot air device or a torch to melt the overlapped material and then pressing the materials together by hand. This type of seaming can be accomplished fairly quickly but generally has low bonding strength. Additionally, care must be exercised to prevent overheating of the geotextile, which may cause melt through, leaving holes in the bonded areas (Figure 3-15).

Figure 3-15
Holes burned through geotextile during heat bonding

Another thermal bonding technique is thermal fusion wedge welding (Figure 3-16). Thermal fusion wedge welding is capable of producing a bond of equal or greater strength as the parent geotextile. However, wedge welding becomes increasingly difficult with lighter weight materials and is generally reserved for geotextiles weighing 16 oz/yd^2 or heavier. As with other polymeric materials, welding in the presence of excessive moisture reduces the bonding capability of the sheets.

Figure 3-16
Geotextile sheets fusion wedge welded together in the field; the geotextile is being placed over a 40-mil PVC geomembrane, which is visible in the background

Installation and Cost Considerations

Nonwoven geotextiles are supplied in rolls, usually 15 feet wide and in various lengths. Hand placement may be required to protect underlying geomembranes from equipment damage. Overlapping of adjacent geotextile panels may be sufficient where stability issues do not exist. Alternatively, seaming by means of sewing or thermal bonding is required when greater bond strength is required. Supply and installation of typical nonwoven geotextiles materials for landfill liner applications are expected to range from \$0.15 to \$0.30 per square foot.

Long-Term Performance Considerations

Nonwoven geotextiles do not weather well and should be protected from UV exposure and weathering. Geotextiles should be covered within 30 days of installation to prevent degradation. Long-term performance should also consider physical and biological clogging of the geotextile where filtration or drainage is required.

Geonets

Geonets are drainage materials made of strips of HDPE bonded in a crisscross pattern that provide a flow path for subsurface water. A typical configuration of geonet is shown in Figure 3-17.

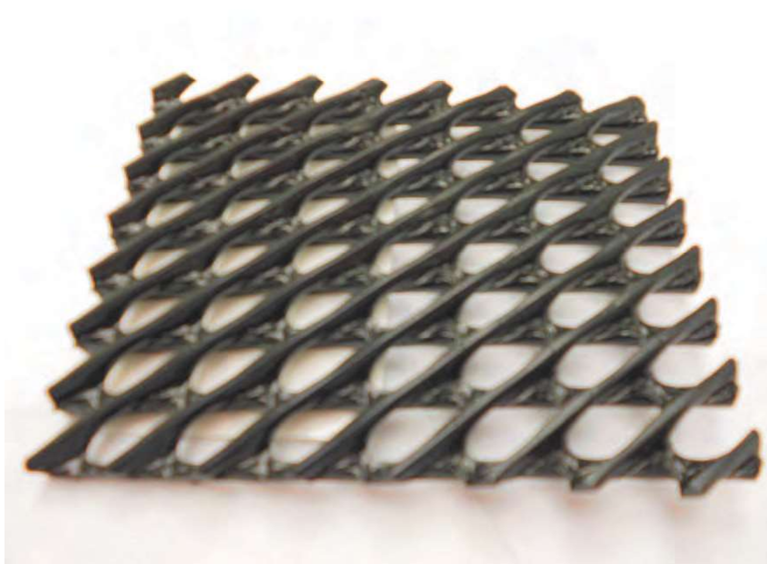

Figure 3-17
Geonet, constructed from strips of HDPE polymer fused together in a crisscross pattern that allows for liquid or gas flow through the void space

If a granular material is placed above or below the geonet, a filter geotextile is required to prevent clogging. Geocomposites (described below) are manufactured with nonwoven geotextiles bonded to one or both sides of the geonet. A geonet without a filter geotextile can be used against a geomembrane; however, the interface friction between a geonet and a geomembrane is very low and may need to be analyzed for stability.

Two or more strands or ribs of HDPE can be incorporated into a geonet depending on the desired flow capacity. Commonly manufactured geonets are termed biplanar and triplanar with respect to the number of intersecting rib layers. Biplanar is most commonly used and triplanar is considered where higher compressive strength and flow capacity is required. Geonets are generally available in thicknesses ranging from 200 to 300 mils (5.0 to 7.6 mm).

Geonet Use in CCP Landfill Design

Geonets typically function as a component of a drainage system, but could potentially be used in separation or protection applications. Drainage applications using geonets include porewater pressure relief under a landfill liner, landfill leachate collection, and landfill cover drainage. Geonets can also perform multiple functions, such as geomembrane protection when implemented as part of the leachate collection system with a geotextile and granular soil overlying the geonet.

Geonets can be used for leachate collection systems, as described in Section 4. In CCP applications, a geotextile filter is needed between the geonet and the overlying CCPs to avoid clogging of the geonet with CCP. Geonets provide minimal geomembrane protection against construction equipment traffic and, for this reason, are not used as the sole drainage component above the liner if heavy equipment will be used to fill and manage the facility.

Zone-of-saturation landfills may utilize geonets in a porewater underdrain system to prevent hydrostatic pressure from causing uplift that can damage the liner. The porewater underdrain system is operated until the waste mass reaches an elevation that will counteract the hydrostatic pressure. Once installed, the porewater underdrain system may be incorporated in the long-term monitoring program.

A geonet can be implemented as a leak detection layer in a double liner system consisting of the following example composite liner, described from the upper layer down:

- Geomembrane
- Recompacted clay
- Geotextile
- Geonet

- Geomembrane
- Recompacted clay

If a fine-grained soil is adjacent to the geonet, a filter geotextile will be required to separate the geonet from the soil. This could be in the form of a geotextile placed above the geonet to separate the soil and geonet.

<u>Design Criteria</u>

A key design consideration for a geonet is its drainage and conveyance capacity, which is based on material thickness and flow direction with respect to orientation of HDPE strands. This is especially relevant for applications in leachate collection systems.

Compression of a geonet and adjacent geosynthetics causes creep of the surrounding materials into the drainage paths of the geonet. Additionally, the HDPE strands used to fabricate the geonet can fold or lay down, reducing the drainage profile and conveyance capacity. This reduction in flow capacity is referred to as long-term creep and is accounted for in the design method suggested by GRI, GC8 "Determination of the Allowable Flow Rate of a Drainage Geocomposite" (Geosynthetic Research Institute, 2001). Compressibility testing can be performed on geonets to determine long-term drainage performance and creep reduction factor.

Slope stability is another consideration for geonets adjacent to other geosynthetics on slopes. Geocomposites (described next) incorporating geotextiles bound to one or both sides of the geonet provide higher internal friction as opposed to unbounded geotextile layers.

<u>Installation and Cost Considerations</u>

Geonets are manufactured in rolls and can be deployed, or unrolled, by hand or using machines. The geonet panels are overlapped 4 to 6 inches longitudinally and the netting is tied together using cable ties spaced every 5 to 6 feet. End seams have larger overlaps between panels and the cable ties are installed every 6 inches. End seams are avoided on slopes because they create a potential line of failure along the slope. Supply and installation of typical biplanar geonet materials for landfill liner applications range from $0.50 to $0.60 per square foot; this cost increases by about $0.30 per square foot if a triplanar geonet is used.

Long-Term Performance Considerations

Long-term flow capacity in geonets may be reduced due to creep and decreased thickness resulting from overburden pressures. Creep causes collapse of geonet structure, and surrounding materials may also impede the void space otherwise created by the geonet.

Like other geosynthetics, slope stability can be an issue due to the planar surface created by separating soil types.

Geocomposites

A geocomposite is the combination of a geonet with one or two geotextiles, heat bonded on one or both sides of the geonet, to form a single-sided or double-sided geocomposite as pictured in Figure 3-18. The geotextile can be woven or nonwoven.

Figure 3-18
Double-sided geocomposite, showing the geonet sandwiched between layers of geotextile

Geocomposite Use in CCP Landfill Design

Geocomposites are often used at CCP landfills to drain water either in a leachate collection system or as part of a cap system.

Single or double-sided geocomposites can be used as, or to supplement, a landfill leachate collection system (Figure 3-19). In addition, double-sided geocomposites are often used as a drainage layer in final cover construction.

Figure 3-19
Geocomposite installation, showing the geonet overlap being tied together using plastic cable ties

Design Criteria

Conveyance capacity may not be sufficient for long flow paths and may require supplemental drainage features such as piping. Periodic drain pipe along a slope can facilitate drainage.

Manufacturers typically report transmissivity of the geocomposite in the maximum flow direction, parallel to the panel length (or machine direction). The direction of deployment should consider the design parameters with respect to the multi-directional flow capacity, which can be less than half in the cross-machine direction. Designs, therefore, need to account for the reduced cross-flow capacity where geocomposite panels are installed perpendicular to the direction of flow. An example of an installed geocomposite experiencing cross-directional flow is along the base of a landfill leachate drainage blanket.

Slope stability is an important consideration when geocomposites are implemented on long slopes. A textured geomembrane will provide greater interface friction than a non-textured geomembrane installed against a geocomposite. Material properties, such as bonding strength of the geotextile to the geonet, can also affect slope stability and can be verified by conformance testing (ASTM D7005).

Installation and Cost Considerations

Each layer of the geocomposite must be considered during installation. The lower geotextile layer is not typically mechanically seamed; however, overlapping the lower geotextile is recommended to prevent migration of the subsoil into the geonet. The geonet panels are overlapped 4 to 6 inches longitudinally and the netting is tied together using cable ties spaced every 5 to 6 feet (Figures 3-19 and 3-20). End seams have larger overlaps between panels and the cable ties are installed every 6 inches. The upper geotextile layer is seamed by sewing or thermal bonding.

Commonly used double-sided biplanar geocomposites will range in cost from $0.55 to $0.70 per square foot, including material and installation.

Figure 3-20
Seaming geocomposite panels together using cable ties to secure the geonet and sewing the upper layer of geotextile

Long-Term Performance Considerations

Long-term flow capacity in the geonet layer may be reduced due to creep and decreased thickness resulting from overburden pressures. Creep causes collapse of geonet structure, and surrounding materials may also impede the void space otherwise created by the geonet.

Like other geosynthetics, slope stability can be an issue due to the planar surface created by separating soil types.

Section 4: Leachate Collection Systems

Overview

National rules for regulation of CCP landfills proposed by USEPA in 2010 called for a leachate collection system that would limit leachate head on the liner to 30 cm (~1 foot) or less.

Leachate collection systems are used in lined landfill designs to remove leachate that collects above the landfill liner and reduce the driving force (hydraulic head) of water on the liner. A typical leachate collection system uses a permeable drainage layer above the liner to facilitate flow to perforated collection pipes that direct leachate to a sump or manhole for removal and treatment (Figure 4-1). Leachate collection systems are typically designed to maintain less than 1 foot of leachate head above the liner (USEPA, 2000).

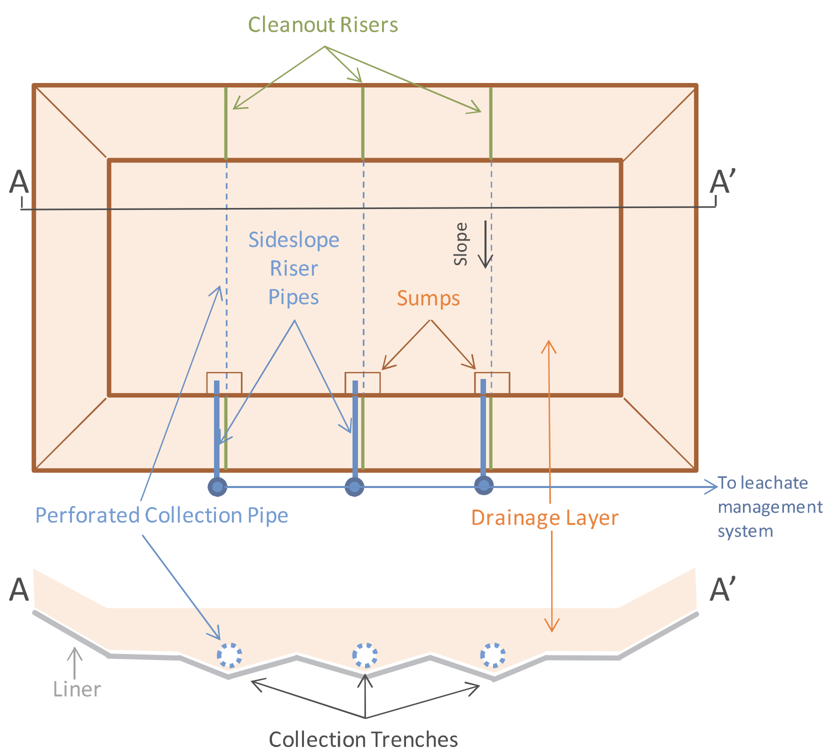

Figure 4-1
Schematic drawing showing components of a leachate collection system in plan view (top) and cross-section (bottom)—not to scale

Design Criteria and Configurations

Considerations Specific to CCPs

A leachate collection system for a CCP landfill has different design criteria than in a municipal solid waste landfill because the fine-grained texture of the CCPs can cause clogging of drainage media, and low hydraulic conductivity may hinder effective leachate collection.

Leachate collection design criteria for a CCP landfill differ from those of municipal solid waste landfills.

- CCPs are composed of fine particles that can clog filter and drainage layers if the layers are not designed to account for the material.
- Compacted CCPs may have low hydraulic conductivity, preventing adequate flow of leachate to the drainage layer. Leachate collection systems in CCP landfills may require vertical drains to facilitate flow to the base drainage layer.

Coarse-Grained vs. Geocomposite Drainage Layers

In a conventional leachate collection system, a granular drainage blanket lies above the liner system to collect and gravity drain leachate to perforated conveyance pipes (Figures 4-2 and 4-3). A minimum thickness of 12 inches is placed with a gradation that has a minimum hydraulic conductivity of 1×10^{-2} cm/s (USEPA, 2000). The granular drainage blanket also provides protection for the underlying landfill liner.

Figure 4-2
Granular drainage blanket placement over a 60-mil HDPE Geomembrane

Figure 4-3
Placement of the granular drainage blanket over a 12 oz/yd² nonwoven geotextile, which is protecting an underlying 60-mil HDPE Geomembrane

An alternative to using a granular drainage layer is to place a geocomposite drainage layer above the liner. Advantages of geocomposite drainage materials include lower cost and faster installation time compared to conventional sand drainage layers. Geocomposites are thin sheets that save airspace compared to the thickness of sand required to obtain the same drainage rates. However, depending on the length of the drainage path and the anticipated volume of leachate generation, a geocomposite alone may not be able to convey leachate fast enough to prevent heads in excess of 12 inches over the landfill liner, and may need to be used in conjunction with conveyance pipes. Furthermore, if used over a geomembrane, geocomposites do not provide the level of protection that would be afforded by a granular drainage layer.

Collection Pipes and Sumps

Leachate collected in the drainage layer is directed to a network of perforated collection pipes to transport the leachate to a sump. From the sump, leachate is removed from the landfill and managed. Collection pipes are typically made of HDPE or PVC (Figures 4-4 and 4-5) and the design should address the anticipated leachate flow, drainage slope, pipe spacing, and structural strength of the pipe to determine pipe diameter and allowable bend radius (Pichtel, 2005).

Pipes should be designed for the maximum anticipated leachate flow and the maximum overburden weight that will cause pipe deflection. Collection pipes are typically 4 inches or more in diameter. Cleanout pipes are usually connected to the collection pipes and extend to the ground surface at the landfill perimeter to provide access for pipe jetting to clean out the lines.

Figure 4-4
Assembly of HDPE leachate collection pipe by means of fusion welding

Figure 4-5
Installation of leachate collection pipe in the leachate collection trench

Sumps are located at the low point of the landfill or in each phase of landfill construction. Sumps are constructed over the liner and consist of low points in the liner, rather than concrete structures, that may be filled with a coarser material than the drainage layer to facilitate rapid flow to the sideslope riser pipe and pump. The sump is designed to maximize the life of the pump by balancing the influent flow with the required pump runtime. Drainage capacity of the leachate collection system may limit the distance between sumps in order to minimize leachate head on the liner.

Sideslope riser pipes (SSRs) provide a conduit large enough for a submersible pump to access the sump beneath the waste material (Figure 4-6). SSRs are typically 12 inches or larger in diameter. The SSR pipe is perforated at the low-point to convey leachate through the pipe walls to the pump. Deep landfills may have SSRs installed in sections due to the weight of the pipe and maximum equipment capacity. When installed in sections, pipe lengths are not typically connected using metal flanges because they may have protrusions that can damage the underlying geomembrane.

Figure 4-6
Sideslope riser pipe being installed in a leachate collection sump

Pumps are used to extract leachate from collection sumps, holding tanks, and other low points in the system (Figure 4-7). Wheeled pumps are available for installation into pipes placed on slopes. Pump specifications can account for the pH of the leachate, which can be neutral to highly alkaline in CCP landfills. Spark resistors are commonly required for landfills, although this is not a concern for CCP monofills because they do not generate gas and the leachate is not ignitable.

Figure 4-7
Installation of a leachate extraction pump in the sideslope riser pipe through the open riser vault

Installing a sidewall liner penetration that gravity drains leachate to a holding tank or outside sump reduces operating costs by eliminating the sideslope riser pipe and pump. Sidewall penetrations may limit the landfill depth or otherwise require deep, confined space manholes. Sidewall liner penetrations are difficult to install, especially with a geomembrane, due to the difficulty of welding the geomembrane around the pipe exiting the landfill. Additionally, the pipe potentially creates a preferential flow path along the outside pipe wall. For this reason, permitting a landfill cell design with sidewall liner penetrations may be more difficult than permitting a design that utilizes sumps and sideslope riser pipes.

Leachate head wells may be installed as part of the leachate collection system to monitor the leachate head on the liner outside of the sump area. The wells are constructed with a perforated section of pipe that follows an elevation contour along the cell floor to the toe of slope. From the toe, a solid pipe is extended up the slope to the perimeter of the landfill for access. Vertical leachate head wells can also be installed after the CCPs are placed.

Leachate conveyance pipes outside the limits of the landfill may be designed to provide secondary containment and the ability to detect leaks in the conductor pipe. Dual containment uses two pipes, one inside the other, or a pipe and a compacted barrier soil surrounding the pipe. The conveyance system can be a force main or gravity pipe, depending on site topography.

Operation and Maintenance

Leachate collection and conveyance systems are usually automated, and gravity flow is implemented where possible. Pumps are controlled by floats or pressure level sensors. Over time, mechanical components will require regular maintenance or replacement. Pump maintenance and replacement is a common cost realized with active pumping systems.

Collection and conveyance piping should be designed to prevent the buildup of solids and be accessible for cleaning when needed. Properly sloped gravity pipe will convey the majority of solids without clogging. Cleanout access can be accomplished through manholes and cleanout risers. Routine maintenance typically includes the use of jetting equipment that can be used to free entrapped particles from the system. Modern jetting equipment is capable of cleaning pipes that are 1,000 feet or longer.

Collected leachate is commonly held onsite in a storage tank and periodically trucked offsite to a wastewater treatment plant (WWTP). Facilities close to sanitary sewer service may be able to draft an agreement with the municipality to directly discharge leachate to the sewer. Depending on leachate characteristics, WWTP operators may require pretreatment prior to discharging to the municipal sewer. CCP landfills at power plants with onsite WWTPs can evaluate whether or not it is feasible to include leachate treatment in the plant's wastewater discharge permit.

Using leachate for moisture conditioning and landfill dust control can reduce leachate management and disposal costs.

To reduce the cost of leachate transport and disposal, landfill facilities can implement leachate recirculation during active landfill operation. CCP landfills often recirculate leachate for dust control. In addition, leachate can be used for moisture conditioning of dry fly ash prior to or during placement in the landfill. Some of the leachate utilized for dust control evaporates, which decreases the leachate disposal volume, and leachate used for moisture conditioning of extremely dry fly ash is held by the ash until the moisture deficit is met, further reducing initial leachate disposal volume.

Long-Term Performance

Considerations for long-term performance include pipe crushing, leachate containment, drainage efficiency (pipe and drainage blanket), and reducing leachate generating sources. Corresponding pipe maintenance issues could include buildup of precipitates such as calcite and/or iron minerals. Cover systems significantly reduce percolation into the landfill, thereby reducing the generation of leachate over time.

Materials such as metal are strong but are susceptible to corroding. Therefore, special leachate compatible coatings may be considered when utilizing metal pipes, tanks, and pumps. Outside of the landfill footprint, dual contained conveyance and holding structures may be implemented to reduce potential for leaks that can be misinterpreted as a release through the landfill liner. Primary conveyance and holding structures can be monitored for leaks when dual containment is employed.

Section 5: Cap Technologies

Overview

A state-of-the-practice cap is broadly defined in this document as a performance-based cap that is less permeable than the liner system and minimizes percolation to the extent practical and necessary considering site-specific climate, liner system design, and hydrogeology.

The primary objective of the cap system is to minimize percolation of water into the CCP and the subsequent generation of leachate. Secondary functions are to prevent blowing of CCPs and prevent direct contact with the material. There are different types of cap systems capable of meeting these objectives depending on site-specific conditions. Cap systems that have been approved at CCP management sites range from very simple approaches using a single layer of soil to more complex multiple layer systems using a combination of earthen and geosynthetic materials. Primary considerations affecting cap design are climatic conditions, whether or not the facility has a liner, whether or not CCP in an unlined facility is below the water table, and the design of the liner and leachate collection system of a lined facility. Given these variables, a state-of-the-practice cap design is broadly defined in this document as a performance-based cap that is less permeable than the liner system and minimizes percolation to the extent practical and necessary for local conditions.

Cap Design Considerations

Typical minimum design specifications for landfill caps include (from top down):

- An surface or topsoil layer constructed of earthen materials with a minimum thickness of 6 inches capable of supporting native vegetative growth
- A cover layer constructed of earthen materials at least 18 inches in thickness
- An earthen barrier layer (e.g., compacted clay) with hydraulic conductivity no greater than 1 x 10^{-5} cm/s

Much of the cap design guidance provided in the literature today is directed toward capping municipal solid waste (MSW) landfills, which may not fully reflect design considerations unique to the long-term management of CCPs, specifically:

- Virtually all water in the coal evaporates during combustion in the power plant boiler, and fly ash that is collected and managed dry (i.e., without use of sluice water) has a moisture deficit; therefore, it will retain water that it comes in contact with until the moisture deficit is eliminated. This is different than MSW, which may contain free liquids when placed in a landfill. Therefore, a tight cap that allows very little water to infiltrate into the fly ash can effectively stop leachate generation and mitigate risk of a release to the environment, especially for an unlined CCP management facility, assuming that the facility is vertically isolated from the water table.
- CCPs tend to be narrowly graded with relatively uniform particulate diameters that potentially make the CCPs moisture sensitive. This means that CCPs that are not self-cementitious[3] and are placed near optimum moisture may exhibit a hard durable surface that may lose integrity when saturated.
- Because of their potential moisture sensitivity, CCPs that are not self-cementitious may be subject to slope instability under high moisture or saturated conditions. CCPs with rounded and uniform particle size, such as fly ash, can exhibit lower shear strength in comparison to other materials, such as poorly sorted sand or clay, and may result in low interface friction angles with different types of capping materials.
- Long-term settlement or consolidation of CCPs is generally less of a concern than at MSW landfills, with the exception of impoundments where the CCPs are typically placed as slurry that requires dewatering prior to capping. If the CCPs can be maintained relatively dry, they will exhibit a high degree of durability and hardness, which can provide a suitable subgrade for cap construction.

[3] Some class C fly ash is self-cementitious; other CCPs are not self-cementitious.

- Leachate management can be one of the most significant cost factors for post-closure management because the material may leach inorganic constituents beyond the typical 30-year post-closure care period.

Accounting for these characteristics, design factors to consider during the cap selection process include:

- Type of Liner System: Regulatory criteria typically specify that the cap should be less transmissive than the liner system. Use of capping materials that have higher permeability than the liner system may allow infiltrating water to accumulate in the bottom of the landfill, which can lead to performance issues. Leachate collection systems are designed to prevent excessive head buildup on the liner, but if the cap is more transmissive than the liner then the leachate collection system will need to be operated for the long term. Long term performance and requirements for leachate collection will be controlled by the integrity of the cap which is true for any waste containment facility.
- Allowable Grades for Surface Water Drainage: Subgrade preparation and cap construction can be designed to produce grades that facilitate effective surface water drainage away from the landfill and minimize surface water percolation. However, there may be circumstances where less than optimum grades can be maintained for suitable surface water drainage and/or steeper grades are required that may pose concerns for erosion and/or slope instability.
- Options and Costs for Post-Closure Leachate Management: Projected long-term estimates for the quantities and the costs for managing leachate need to be assessed in comparison with the type of cap, capital costs for construction, and long-term cap operation and maintenance costs.
- Geographic Location: Different climate zones will pose different challenges for managing surface water and long-term performance, depending on the types of construction materials and capping approach selected. These challenges include freeze/thaw durability, desiccation, water and wind erosion, and long-term cap maintenance.

- Availability of Suitable Materials for Cap Construction: Access to locally available materials for construction, such as a borrow source for clay, will factor directly into the capital costs for construction and is usually included as part of the selection process.
- Regulatory Requirements: State and local regulatory requirements vary and may limit flexibility on the number of available capping options considered.

Capping Technologies

Capping technologies can be divided into three general categories based in their approach to minimizing percolation into the underlying CCP:

- Single Component Caps: Single component caps have one barrier layer consisting of compacted clay or other earthen materials, a geomembrane, or a GCL.
- Composite Caps: Composite caps incorporate a two-part barrier analogous to the composite liners described in Section 3. The barrier commonly is a geomembrane over compacted clay or a geomembrane over a GCL.
- Evapotranspiration (ET) Caps: ET caps are fundamentally different than single component or composite caps. They are typically constructed with fine-textured soils and rely on the unsaturated properties of soils to store water within the cover profile during wet periods and evapotranspiration to remove stored water during drier periods. In some ET cap designs, a coarse-grained soil is placed beneath the fine-grained soil to create a capillary break to enhance moisture retention in the fine-grained layer; although, use of capillary breaks is not common (Benson, 2012b).

Single and composite caps may include one or more of the following additional components:

- Drainage Layer: This layer is placed directly above the barrier layer and consists of either a granular free-draining soil (sand or gravel) or a geocomposite consisting of a geonet bonded with a geotextile on one or both sides. Construction using a granular free-draining soil layer may include a non-woven geotextile filter fabric between the barrier layer and drainage layer and between the drainage layer and upper materials to prevent potential piping and/or migration of fines into the drainage layer that could lead to clogging. The thickness of the drainage layer depends on the design slope and the anticipated percolation flows; a typical thickness for granular soil is 12 inches with a minimum 3% slope (USEPA, 2000). A thickness less than 12 inches tends to pose constructability issues (e.g., achieving uniform design thickness across the cap and maintaining design grades) and/or concerns for potential damage to the barrier layer during placement. The selected drainage material typically has a hydraulic conductivity of 10^{-2} cm/s or higher. When a geocomposite is used instead of granular soils, then intermediate slope drains may be incorporated into the design to assure that the material is capable of draining water and relieving porewater pressure that can cause unstable slopes under the heaviest anticipated storm event. Presently, use of gecomposites are the more common design approach (Bensen , 2012b).

- Cover Layer: This layer is located directly over the drainage layer, or directly over the barrier layer if a drainage layer is not used (Figures 5-1 and 5-2). The cover layer is designed to meet several objectives depending on the site-specific conditions, including protection from vegetative root penetration and animal intrusion into the drainage or barrier layers, and minimizing potential damage due to freeze/thaw, desiccation, and erosion. In some applications, it may be designated as an erosion layer or rooting zone. The design thickness for this layer depends on site-specific requirements—for example, greater than the frost penetration depth in northern climates. A variety of soil materials are suitable for this layer.
- Surface or Topsoil Layer: The primary objective for this layer is to establish and sustain adequate vegetative growth to minimize erosion, protect the cover, and enhance overall visual appearance. Topsoil is the most commonly used material, but in some locations where it may be difficult to support growth, such as arid or desert-like regions, other materials such as sand, gravel, or cobbles may be more suitable. Different types of geosynthetic applications are also available that include the use of synthetic turf layers that eliminate the need for maintaining vegetation, reduce long-term concerns for cap stability, and provide the appearance of a manicured landscape.

Figure 5-1
Placement of a cover layer

Gas collection is not useful or necessary at CCP monofills because CCPs have negligible amounts of the organic materials that generate gas.

A gas collection layer is typically included in MSW and some industrial waste landfill cap systems, but is not necessary or useful for CCP monofills because CCPs have negligible amounts of the organic materials that generate gas. Figure 5-2 shows an example composite cap system incorporating the components described above.

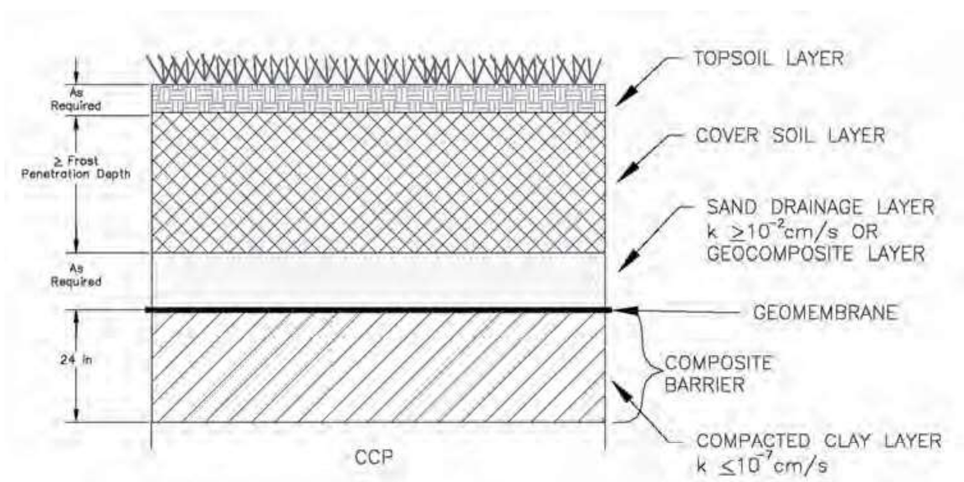

Figure 5-2
Profile view of a composite cap system with topsoil, cover soil, drainage, and barrier layers

Synthetic materials used in cap construction are similar to and typically require the same level of construction QA/QC as those used for liner construction, and are described in Section 3.

Single Component Caps

Earthen Materials

An earthen cap may be suitable for an unlined CCP management facility situated below the water table and where most leachate is generated due to groundwater contact.

Earthen materials, in the context of this discussion, are sands, silts, and loams, which are often locally available. The hydraulic conductivity of such earthen materials will be higher than a compacted clay, geomembrane, or GCL, and a cap constructed from earthen materials therefore has the potential to allow more percolation than caps incorporating hydraulic barriers such as geomembranes or GCLs. However, earthen caps may perform as effectively as single component caps using compacted clay in situations where the cap is subject to freeze/thaw or desiccation conditions, which can increase the bulk hydraulic conductivity of both earthen materials and compacted clay.

An example application where an earthen cap may be appropriate is an unlined CCP management facility where the CCP is below the water table and the cap therefore has negligible effect on generation of leachate. In cases such as this, the primary function of the cap is to provide protection from blowing, erosion, and direct contact. Minimum thickness is approximately 2 feet to allow placement of the cover in controlled lifts and provide sufficient thickness for a rooting zone. Construction may or may not include a drainage layer and/or placement of a surface or topsoil layer, depending on the types of materials that are being used for the cap.

General design considerations include:

- Compactive effort should be evaluated with respect to other performance criteria such as estimates of allowable percolation and suitability for long-term sustainable vegetation growth.
- Capacity to effectively store surface water percolation in conjunction with the cap's ability to promote surface water drainage may be given consideration, similar to designs for ET caps, depending on the types of materials available

for construction and site location. In this respect, a lower level of compactive effort may provide better performance.

- The design thickness of the cap is evaluated with respect to storage capacity, long-term stability, and potential for erosion.

Compacted Clay

Compacted clay caps are most useful in climates where they can be protected from freeze/thaw and desiccation, either of which can substantially degrade cap performance. Acceptable materials for compacted clay in cap applications are identical to compacted clay in liner applications, and are described in Section 3.

Other considerations for selection of an appropriate material include:

- Greater thicknesses may be required if there is a concern for repeated exposures to freeze/thaw conditions. In northern portions of the United States, frost depth penetration can exceed six feet below ground surface. Clay barrier layers are ideally located below the frost depth.
- More rigorous specifications for low permeability may be required to address concerns for repeated wet/dry cycles and/or if the site-specific conditions will not allow for development of sufficient grades to promote effective drainage.
- Differential settlement beneath the clay cap can cause the formation of stress cracks that can become preferential pathways for water percolation (USEPA, 2000).

Figure 5-3 shows a compacted clay barrier layer during early stages of construction, and Figure 5-4 shows an advantage of a compacted clay over geomembranes in that it is more amenable to construction around existing structures.

Figure 5-3
Placement and compaction of a clay barrier in a cap application using a sheepsfoot roller

Figure 5-4
Placement and compaction of compacted clay around existing structures

Geomembrane

Geomembranes provide a relatively impermeable barrier layer that can be constructed using a variety of commercially available materials. Typical materials for cap applications include linear low density polyethylene (LLDPE), HDPE, and PVC, although there are many options as discussed in Section 3. Use of LLDPE has become more common in cap applications than HDPE because it has greater flexibility for design considerations such as differential settlement. Geomembranes are delivered in rolls or large sheets that are unrolled or unfolded and seamed together. The material is more flexible than compacted clay and can better accommodate differential settlement without compromising cap integrity. In contrast to clay barriers, geomembranes can be installed within the frost zone with less concern for degradation due to freeze/thaw effects.

A design consideration for using geomembranes in cap applications is the stability of the final cover slopes. Smooth geomembranes exhibit low interface friction that can cause overlying soil layers to slide. Different geomembranes (e.g., PVC vs. HDPE) exhibit different interface friction angles that can be a consideration for material selection. For example, PVC has higher elasticity and will provide higher interface friction than HDPE. Project-specific direct shear interface friction testing is typically performed using materials planned for the cap construction. Textured geomembranes can be used to increase the interface friction but are also typically more expensive than non-textured geomembranes.

Global and veneer stability are considerations for both liner and caps. Generally, the stability of the liner is most critical during construction and filling (short-term stability). Caps are subject to short-term (during construction) and long-term (post-construction) stability concerns. Interface shear testing using the direct shear method (ASTM D5321 or ASTM D6243) is used to confirm veneer stability of the geosynthetic/soil interfaces proposed for the liner or cap.

Subgrade preparation is an important consideration for proper geomembrane installation. Water can percolate through a geomembrane via punctures created during installation of the geomembrane and placement of overlying layers. A common design specification when using compacted coal ash, or any other material, as the subgrade is that particle sizes no larger than 3/8 inch be present at the subgrade surface in order to minimize potential puncturing of the geomembrane. Fly ash usually makes an acceptable subgrade material because of its uniform, fine-grained particle distribution. If subgrade conditions are not acceptable, a layer of engineered fill can be placed over the CCP. Alternatively a thick (e.g., 12-ounce per square yard) non-woven geotextile can be used in lieu of the engineered fill. Figure 5-5 shows an example of a prepared fly ash subgrade and placement of a single component cap using a PVC geomembrane as the barrier layer. In this example, no additional subgrade materials were required to provide a suitable surface. Note the smooth, uniform appearance of the compacted CCP.

Figure 5-5
Placement of a PVC geomembrane (background) directly over a compacted fly ash subgrade (foreground)

Figure 5-6 shows construction of single component cap system featuring a PVC barrier layer with an overlying geocomposite drainage layer. A cover layer is visible in the background that also served as the surface layer for this facility because the locally available borrow material had sufficient organic matter to support vegetation.

Figure 5-6
Placement of a geocomposite drainage layer (foreground) over a PVC barrier (mid-ground) followed by a soil cover/surface layer (brown material in background)

Geosynthetic Clay Liner

GCLs provide an alternative to compacted clays. Performance of GCLs compares favorably to compacted clay with the advantage that a GCL requires less space for installation, which allows greater landfill volume for CCP placement. A typical profile for a single component cap using a GCL is illustrated in Figure 5-7.

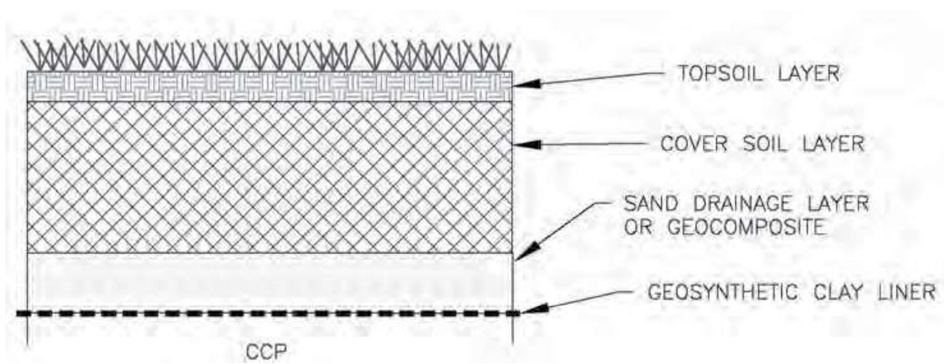

Figure 5-7
Typical profile for single component cap system using a GCL

GCLs can be procured in unreinforced or reinforced configurations. As discussed in Section 3, the typical fabrication for a GCL consists of a layer of sodium bentonite that is fixed or bonded to a layer of geotextile on either side. GCLs can also be procured with a geomembrane laminated on one side, but this is less common in field applications. For geotextile applications, bonding of the material to the bentonite can involve the use of adhesives, stitch bonding, needle punching, or a combination of the three, depending on the field application requirements. For geomembrane applications, the membrane is bonded to the bentonite using adhesives.

A key design consideration is the low internal shear strength of the bentonite, which can lead to stability problems on landfill cover slopes. Consideration is warranted for use of GCLs with respect to cap geometry, anticipated slopes, and interface friction angles between the material the GCL is capping and materials used for layers over the GCL. Stability is evaluated with respect to an acceptable veneer factor of safety for sliding of the cover material over the barrier material. A typical acceptable factor of safety for veneer stability is 1.5 (USEPA, 2001). GCLs using either needle punching or stitch bonding can be used to increase the safety factor against sliding. Needle-punched geotextile will typically yield the highest shear strength, followed by stitch bonding. Unreinforced GCLs are not recommended for slopes greater than 10:1 (horizontal to vertical). In contrast, reinforced GCLs using needle punching have been successfully installed in applications with slopes greater than 3:1.

Long-term performance of a GCL will be directly related to the amount of bentonite swelling that is achieved and exposure to desiccation. To achieve a low hydraulic conductivity (e.g., less than 1×10^{-9} cm/sec), sodium bentonite granules need to swell and form a gel or paste and the swelled material must be maintained to sustain a low permeability. Performance of a GCL is therefore highly sensitive to changes in moisture conditions. Use of a GCL in combination with a geomembrane can reduce concerns for desiccation and may perform as well as barrier systems using a combination of compacted clay with a geomembrane. The potential chemical compatibility issues with CCPs described in Section 3 are less of a concern for GCLs in cap applications than in liner applications, although they are not entirely eliminated because of potential water movement along the CCP-GCL interface and seeps on side slopes.

Composite Caps

Clay with Geomembrane

When a geomembrane is used together with compacted clay, the clay provides a smooth base for the geomembrane, minimizing the potential for punctures from below during installation, while the geomembrane protects the clay against desiccation and cracking (Figure 5-8). A significant design consideration for this configuration is the interface between the smooth clay and the geomembrane, which can have low friction and may be susceptible to veneer sliding failures. A textured geomembrane can be used to increase the interface friction between the two layers (USEPA, 2000).

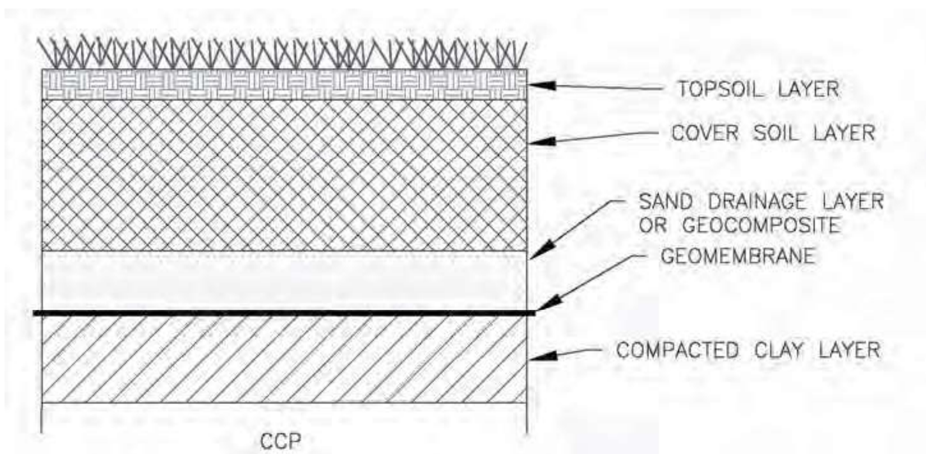

Figure 5-8
Typical profile for composite cap system with a geomembrane and clay barrier layer

Geosynthetic Clay Liner (GCL) with Geomembrane

Geomembranes and GCLs used together can provide a hydraulic barrier that is more flexible and more accommodating to differential settlement of the underlying CCPs than compacted clay. This profile also offers the GCL more protection from desiccation than a single component GCL cap (Figure 5-9).

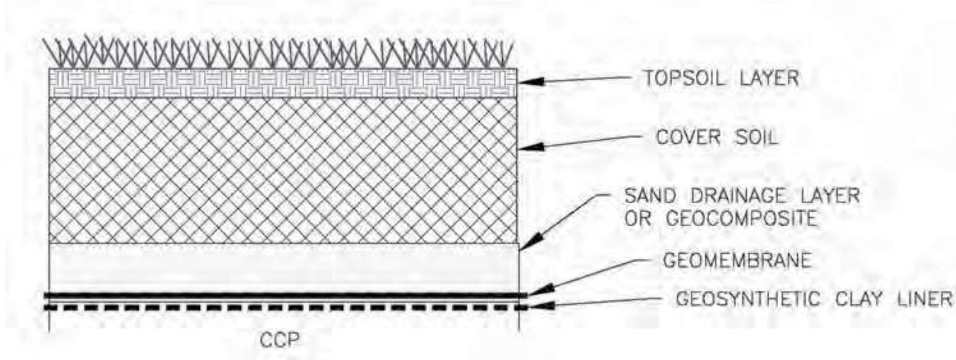

Figure 5-9
Typical profile for composite cap system with geomembrane and GCL barrier layer

As previously discussed, stability is a consideration with respect to an acceptable veneer factor of safety for sliding of the cover material over the barrier material. Needle-punched or stitch-bonded GCLs can be used to increase the safety factor against sliding between the GCL and geomembrane. Textured geomembranes can also be considered. Alternatively, a GCL with the geomembrane glued to one side can be obtained.

Evapotranspiration (ET) Caps

ET caps rely on soil moisture retention and evapotranspiration to prevent percolation, rather than on a barrier layer.

ET caps use water balance properties and rely on a soil's storage capacity rather than barrier layers to minimize percolation of water into the underlying CCP. ET caps use soil layers to store water until the water is removed through evapotranspiration. Proper function relies on a balance between surface runoff, percolation, soil storage, and evapotranspiration. ET caps are most suitable in arid and semi-arid regions (i.e., the western United States), although ET caps have been installed at demonstration sites in Maryland, Pennsylvania, Georgia, Illinois, Michigan, and Wisconsin (USEPA, 2003). ET caps have greater self-healing capability than compacted clays and are therefore less susceptible to settlement than compacted clay caps, and are also less susceptible to freeze-thaw and desiccation.

Monolithic ET caps rely on the storage properties of a single soil layer (Figure 5-10). The soil layer is constructed to a thickness capable of storing water at the peak time of the year based on rainfall data and other sources (e.g., spring snowmelt). The soil layer needs to have a storage capacity greater than the peak percolation volume to minimize percolation into the underlying material.

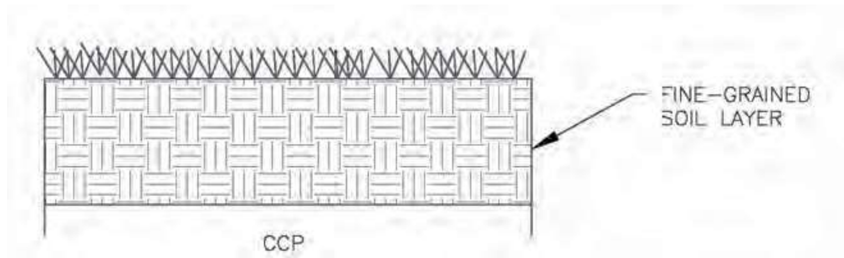

Figure 5-10
Monolithic ET cap configuration

Capillary break ET caps rely on unsaturated soil hydraulic properties to create a capillary break by placing a fine-grained soil layer directly over a coarse-grained soil layer (Figure 5-11). The fine-grained layer serves as a moisture retention layer while the coarse layer provides a capillary break, which serves to increase the moisture retention capacity for the fine-grained layer. This system will function as designed as long as the moisture content of the fine-grained layer is lower than its field capacity. Therefore, it is important to characterize the water balance of the area to ensure that sufficient layer thicknesses are constructed for capillary break ET caps. The fine-grained layer can range from 1.5 to 5 ft in thickness, and the coarse-grained layer can range from 0.5 to 2 ft thick (USEPA, 2003). If the moisture retention capability of the fine-grained layer is exceeded, then moisture will infiltrate to the coarse-grained layer. Depending on the cap design, some of this moisture will infiltrate into the underlying CCPs and generate leachate, while some may drain laterally in the coarse-grained layer if it is also designed as a drainage layer. Such drainage may require management as leachate since there is potential surface contact with the CCP.

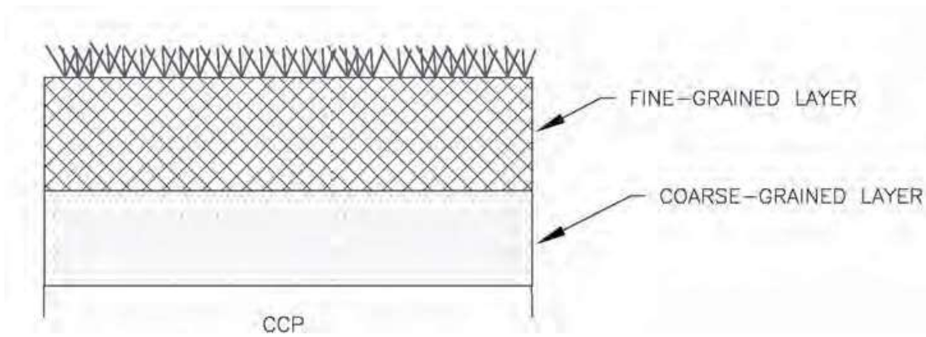

Figure 5-11
Capillary break ET cap configuration

Innovative Capping Technologies

The previous discussions focused on capping technologies that are currently used and accepted. However, there are ongoing innovations in the development of new geosynthetic products and applications involving beneficial reuse of CCPs that are providing new opportunities for capping applications. These innovations can be divided into three general categories:

- New Types of Geosynthetic Products: New developments include the use of synthetic "turf" material to replace conventional surface layers and integration of solar energy using photovoltaic solar panels as a part of the cap for renewable energy generation.
- Use of Other Types of CCP: Innovative applications include the use of filter cake recovered from wet scrubbers as a protective subbase between the CCPs and barrier layers or as part of the barrier layer.
- Use of Fly Ash as a Barrier Layer: This approach features stabilization/solidification technologies to construct a cap using fly ash.

Landfill owners have driven new product developments to reduce final closure and long-term O&M costs associated with vegetated surface layers, which require regular maintenance and upkeep. In response to this demand, synthetic turf materials have been developed that may provide the following benefits in comparison with vegetated surface layers (Geosynthetics, 2012):

- Lower the capital costs for construction of the cap by reducing the amount of imported fill required to construct the vegetated surface layer

- Minimize long-term O&M costs due to reduced concerns for erosion from severe weather events and the need for mowing and vegetation maintenance
- Improve long-term veneer stability in areas that are more steeply graded
- Improve long-term barrier layer protection and performance

One available application is a multi-layer system consisting of a geomembrane overlain by two layers of a geotextile filter fabric for drainage followed by a turf layer (UV resistant artificial grass) interlocked with sand ballast for stability. Installation is accomplished using spikes integral to the geomembrane to anchor the geosynthetic system to the subgrade. Applicability of this type of approach needs to be evaluated on a case-by-case basis depending on site-specific parameters such as availability of local materials and site geometry.

Renewable solar energy was integrated as part of the cap design for the Hickory Ridge Landfill outside of Atlanta, Georgia (Scientific American, 2012). Construction of the final cap included more than 7,000 thin-film photovoltaic solar panels. Objectives for the installation included:

- Creating revenue as an alternative energy source
- Making use of available undeveloped land with limited options for future redevelopment
- Reducing typical O&M requirements for mowing, vegetation replacement, and erosion control

Applications using CCPs such as filter cake have successfully received regulatory approval as a component for capping applications. Filter cake consists of fines collected during screening of gypsum from a forced-oxidation wet scrubber; it is not suitable for use above the barrier layer because any contact with surface water would require management as leachate. It is, however, a highly suitable subgrade for placement between the waste material and a geomembrane. The compacted filter cake provides a protective subgrade to prevent puncturing of the geomembrane from below.

Applications using fly ash stabilization/solidification technologies to create a barrier layer for a cap have been tested through bench scale studies and a limited full scale application (VFL Technology Corporation, 2002). Construction of the barrier layer would be performed by mixing the fly ash with an engineered blend of Portland cement or other pozzolanic materials in a batch plant at an onsite staging area, and placing it in lifts to a minimum specified thickness. The cap would then be completed with a rooting zone and vegetative layer. Illustrations of a typical batch plant operation and compaction of a stabilization/solidification cover are presented in Figures 5-12 and 5-13.

Figure 5-12
Typical batch plant for a cap incorporating stabilized/solidified fly ash

Figure 5-13
Compaction operations for a cap incorporating stabilized/solidified fly ash

The resulting material would be tested for several parameters including chemical leachability, unconfined compressive strength, and hydraulic conductivity to demonstrate conformance with long-term performance objectives. Bench scale tests performed for the authors have yielded hydraulic conductivity values in the range from 1 x 10^{-6} to 1 x 10^{-7} cm/sec and unconfined compressive strengths greater than 150 psi. The results of the previous studies indicate that this may be a viable capping approach, although it requires further testing, particularly for long-term leachability, before implementation.

Comparison of Capping Technologies

Table 5-1 compares the traditional capping technologies reviewed above with respect to several criteria:

- Constructability: Under most applications, compacted fly ash will provide a suitable subgrade for construction of a variety of different types of capping configurations. Ease or difficulty of construction will be influenced by the types of materials selected and type of cap (i.e., single vs. composite component or ET cap).
- Hydraulic Conductivity: Low hydraulic conductivities may be achieved under a variety of capping scenarios, depending on material availability and

site-specific drainage conditions, but the material choice needs to be weighed against potential concerns for long-term durability.

- Freeze/Thaw Durability: Durability refers primarily to the degradation of the capping materials due to repeated cycles of freezing and thawing. The relative durability resistance will be influenced by geographic location and type of materials and thickness of cap construction.
- Desiccation: Desiccation refers to the degradation of the capping materials due to the loss of minimum required moisture content necessary to maintain hydraulic conductivity. Repeated cycles of desiccation and rehydration can fundamentally alter material performance properties, particularly for clay or GCL applications. Design considerations include the type of capping material relative to geographic location (e.g., arid environments) and engineering controls to prevent moisture loss.

Summarizing points from Table 5-1 and other discussion in this chapter:

- Clay may be cost prohibitive if a local borrow source with acceptable material is not available due to the added cost to import.
- With the exception of earthen caps, low permeabilities can be achieved, but long-term performance will be influenced by other design parameters such as geographic location and drainage conditions.
- In general, composite capping approaches provide a higher level of durability and resistance to desiccation compared to single component caps, with the exception of a single component cap using a geomembrane. As previously discussed, long-term performance of a GCL will be directly related to the amount of bentonite swelling that is achieved and exposure to desiccation. GCL performance is therefore highly sensitive to changes in moisture conditions, and use of a GCL in combination with a geomembrane can greatly reduce concerns for desiccation. Durability and resistance to desiccation are generally less of a concern for ET caps since management of surface water relies primarily on storage and evapotranspiration.

Capping Strategies Based on Slope and Drainage Conditions

Selection of the most appropriate capping strategy to meet anticipated slope and drainage conditions will be dependent on a number of site-specific factors and the intended function for the cap that include:

- Design limits for surface water percolation
- Availability and type of local materials for cap construction
- Limitations for allowable grades to promote effective drainage
- Logistical constraints based on surrounding topography and existing land use

Potentially applicable capping strategies based on site-specific grading and surface water drainage conditions are summarized in Table 5-2.

A comparative evaluation of the applicability for these various capping technologies and conditions indicates:

- Gently graded slopes and drainage conditions will require significant reliance on barrier layers or evapotranspiration to prevent surface water percolation through the cap. Cap slopes of less than 3 percent are generally avoided whenever practical because, depending on the geographic location, inadequate drainage may lead to extended periods of saturated conditions that could pose long-term O&M challenges for maintaining acceptable cap vegetation and landscaping.
- Moderately graded slopes provide optimum conditions for a range of capping technologies able to meet long-term cap performance objectives.
- In contrast to gently graded conditions, steeply graded slopes pose concerns for veneer stability and/or erosion of cover materials that could preclude the use of materials such as GCLs with low interface friction angles.
- Construction using earthen materials may be applicable for steeply graded slopes if the material can be adequately compacted to minimize concerns for erosion, which could be a concern for ET covers where less compaction is applied due to the desire to enhance surface water storage capacity.

- Steeply graded slopes may also pose challenges for placement of barrier layers using clay with respect to maintaining minimum required lift thickness and achieving required specified moisture content ranges and densities during placement. Difficulties may be encountered for operation and control of compaction and grading equipment, potentially resulting in unacceptable variations in CQA/QC.

Design Considerations for Future Site Development over the Cap

The design and construction of a cap sometimes needs to accommodate future development including roads, building foundations, and other structures. Design considerations include:

- Improvement of subgrade conditions beneath the cap such as excavation and re-compaction of CCPs and/or over-excavation and replacement with engineered fill (e.g., stone or other granular material) to improve subgrade stability.
- Use of alternative cap materials with higher percentages of sand and/or gravel to provide suitable subgrade conditions for future development. Placement of materials with the high degree of plasticity exhibited by low permeability clay layers may not provide suitable bearing strength for foundations and beneath roadways.
- Use of geosynthetics such as geotextiles or geogrids to improve subgrade stability and maintain cap integrity.
- Integrating the cap with new foundation structures to minimize surface water percolation.

Table 5-1
Comparison of cap systems

Type of Cap	Constructability	Hydraulic Conductivity	Freeze/Thaw Durability	Desiccation
Single Component Caps				
Earthen	Placement and compaction in lifts to meet designed compaction requirements	Varies but may achieve less than 1×10^{-5} cm/sec	Variable depending on material	Variable depending on material
Compacted Clay (CL, CH, SC)	Higher level of placement and compaction control required than for earthen caps	Varies—typically from 1×10^{-5} to less than 1×10^{-7} cm/sec	Low durability if not provided sufficient cover for frost penetration	Low to moderate resistance if not provided sufficient cover for moisture loss
Geomembrane	LLDPE, HDPE, or PVC can be placed directly over prepared CCP subgrade	Less than 1×10^{-7} cm/sec	High durability	High resistance
GCL	GCLs can be placed directly over prepared CCP subgrade	Less than 1×10^{-7} cm/sec	High durability	Low resistance if not provided sufficient cover for moisture loss
Composite Caps				
Clay with Geomembrane	Clay layer would be placed directly over CCP subgrade followed by geomembrane	Less than 1×10^{-7} cm/sec	Reduced durability if not provided sufficient cover for frost penetration	High resistance
GCL with Geomembrane	Use GCL bonded to geomembrane and place directly over CCP subgrade	Less than 1×10^{-7} cm/sec	High durability	High resistance

Table 5-1 (Continued)
Comparison of cap systems

Type of Cap	Constructability	Hydraulic Conductivity	Freeze/Thaw Durability	Desiccation
Evapotranspiration (ET) Caps				
Monolithic	Place in lifts with limited compaction (e.g., rubber tired or tracked equipment)	Not applicable because performance relies on storage of surface water percolation rather than a barrier layer		
Capillary Break	Place fine-grained layer in lifts with limited compaction (e.g., rubber tired or tracked equipment)	Not applicable because performance relies on storage of surface water percolation rather than a barrier layer		

Table 5-2
Applicable cap technologies based on slope and drainage conditions

Type of Cap	Applicable Cap Technologies Based on Slope and Drainage Conditions		
	Condition 1 – Gently Graded Slopes (less than 5%) with Poor or Restricted Drainage	**Condition 2 – Moderately Graded Slopes (5 to 10%) with Positive Drainage**	**Condition 3 – Steeply Graded Slopes with Rapid Drainage**
Single Component Caps			
Earthen	Less Applicable	Applicable	Potentially Applicable
Compacted Clay (CL, CH, SC)	Applicable	Applicable	Less Applicable
Geomembrane	Applicable	Applicable	Applicable
Geosynthetic Clay Liner (GCL)	Applicable	Applicable	Potentially Applicable
Composite Caps			
Clay with Geomembrane	Applicable	Applicable	Less Applicable
Geosynthetic Clay Liner with Geomembrane	Applicable	Applicable	Potentially Applicable
Evapotranspiration (ET) Caps			
Monolithic	Potentially Applicable	Applicable	Less Applicable
Capillary Break	Potentially Applicable	Applicable	Less Applicable

Applicable indicates that the technology can be applied effectively using standard engineering and construction practices

Potentially Applicable indicates that advanced engineering or construction practices may be needed to effectively implement the technology

Less Applicable indicates that there are significant engineering, construction, or maintenance issues that must be resolved for effective long-term implementation of the technology

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Attachment B – GCL Submittals

B.1 – "*CPS - FGD Brine Pond Composite Liner, Summary of Findings for Hydraulic Conductivity Testing of GCLs for Application Compatibility*,"

August 16, 2021,

CETCO Lining Technologies, Inc.

B.2 – Technical Data (Sheet)

Resistex® 200FLW-9

Polymer Enhanced Geosynthetic Clay Liner

CETCO Lining Technologies, Inc.

B.3 - Personal Email Communication,

Reza Gorakhki, PhD, Technical Services Engineer,

CETCO Lining Technologies, Inc.,

August 24, 2023.

Attachment B – GCL Submittals

B.1 – "*CPS - FGD Brine Pond Composite Liner, Summary of Findings for Hydraulic Conductivity Testing of GCLs for Application Compatibility*,"

August 16, 2021,

CETCO Lining Technologies, Inc.

August 24, 2023.

CETCO 2870 Forbs Avenue Hoffman Estates, IL 60192
847.851.1800 800.527.9948 Fax 847.851.1339 www.cetco.com

August 16, 2021

Kimberly Deschenes
AECOM
9400 Amberglen Blvd, Suite E
Austin, TX 78729

RE: CPS - FGD Brine Pond Composite Liner
Summary of Findings for Hydraulic Conductivity Testing of GCLS for Application Compatibility.

Dear Kimberly Deschenes,

The purpose of this letter is to present the status of the ongoing compatibility testing of the CETCO® Resistex® geosynthetic clay liners for the above-mentioned project. Initial findings were previously conveyed for the Tier I & II testing (and are attached) for this project. This report is made to convey final results, and report on continued permeability testing. All testing has been performed at the CETCO in-house GAI-LAP accredited laboratory located in Hoffman Estates, Illinois.

CETCO initiated a geosynthetic clay liner (GCL) chemical compatibility evaluation as outlined in our Technical Reference (TR-345, attached) after receiving representative sample of site leachate. Completion of Tier I & II evaluations indicated that a standard GCL (such as Bentomat®) in the presence of the leachate would not likely provide suitable performance as defined by permeability. CETCO initiated Tier III testing of Resistex® U40 and Resistex® 200 after finishing Tier I & II.

- After 858.2 hours, permeability testing on Resistex® 200 was terminated. The final permeability for Resistex 200 with the site leachate is 7.59×10^{-10} cm/sec after 3.2 pore volumes.
- After 744.3 hours, permeability testing on Resistex® U40 was terminated. The final permeability for Resistex U40 with the site leachate is 4.70×10^{-9} cm/sec after 13.7 pore volumes.
- Due to the result on the Resistex U40, a sample of Resistex U41 has been set up with the site leachate. Results of this testing will be reported at a later date.

Permeability testing was completed in general accordance with ASTM D6766, Scenario II with the leachate. For this testing, a cell pressure of 80 pounds per square inch (psi), 77 psi headwater pressure and 75 psi tailwater pressure were utilized and represent test conditions that CETCO utilizes in evaluating our GCL products. It should be noted that testing utilizing field condition pressures could yield different results.

Please feel free to contact me for further information.

Sincerely,

M. Reza. Gorakhki, Ph.D.

M. Reza Gorakhki

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GEOSYNTHETIC CLAY LINER COMPATIBILITY ANALYSIS

ASTM D6141 - 20

Project:	CPS Energy Plant Drains Pond	Date:	5/18/2021
Location:	San Antonio, Texas	Project Type and Citation:	Liner Compatibility BMG/LT-11-7
Requested By:	Kimberly Deschenes, AECOM	Sample ID:	LT21-4
Sample Type(s)[1]:	Leachate		

Test Results:

Leachate Used for Testing	Site Leachate	
Bentonite/Product	Resistex 200	Resistex U40
Fluid Loss (mL), ASTM D5891 modified[1]	55.10	50.3
Free Swell (mL/2g), ASTM D5890 modified[1]	13.5	13.5
Conductivity (μS/cm)	39500	
pH	6.08	
Chloride (ppm)	11263[2]	

Note:
1) Test method modified for use with site specific hydration fluid in place of deionized water.
2) Measured at George Mason University.

ICP Elemental Analysis

Element	ppm
Silver	0
Aluminum	7.245
Arsenic*	0
Boron	29.976
Barium	0.659
Calcium	841.457
Cadmium	0.882
Chromium	0.144
Copper	10.045
Iron*	7.136
Mercury*	4.603
Potassium	736.256
Magnesium	1565.34
Manganese	24.504
Molybdenum	0.917
Sodium	6434.78
Nickel	1.457
Phosphorus	18.999
Lead*	0.356
Sulfur	2877.09
Antimony	0.592
Selenium*	0.424
Titanium	0.093
Zinc	1.298
Zircon	0.212

1) Accuracy is ±0.005 ppm except for arsenic, iron, mercury, lead and selenium which have accuracy limits of 0.02 ppm.
2) The sample was diluted 1:99 prior to testing and the results were scaled up by 100x.

Analyst: DW

CETCO EP Project Information **ASTM D6766 Perm Test Results** **Accreditation: GRI-LAP-22-97**		
Project	CPS Energy Plant Drains Pond	CPS Energy Plant Drains Pond
Product Tested for Hydraulic Conductivity	Resistex U40	Resistex 200
Product Lot #	20GCL007-2 Roll 1	19GCL002-3 Roll 61
Leachate Description	CPS Energy	CPS Energy
Leachate Code#	LT 21-4	LT 21-4
Leachate pH	6.08	6.08
Leachate EC (uS/cm)	39500	39500
Ionic Strength Estimated by ICP (mol/L)	0.6645	0.6645
RMD Estimated by ICP (M^0.5)	1.0157	1.0157
Sulfate /Chloride Ratio	0.28	0.28
Hydration Liquid	CPS Energy	CPS Energy
Permeation Liquid	CPS Energy	CPS Energy
Pressure Difference (PSI) =	2	2
Max. Effective Stress (PSI) =	5	5
Actual Hydraulic Conductivity k (cm/sec)	4.70E-09	7.59E-10
PVF	13.67	3.19

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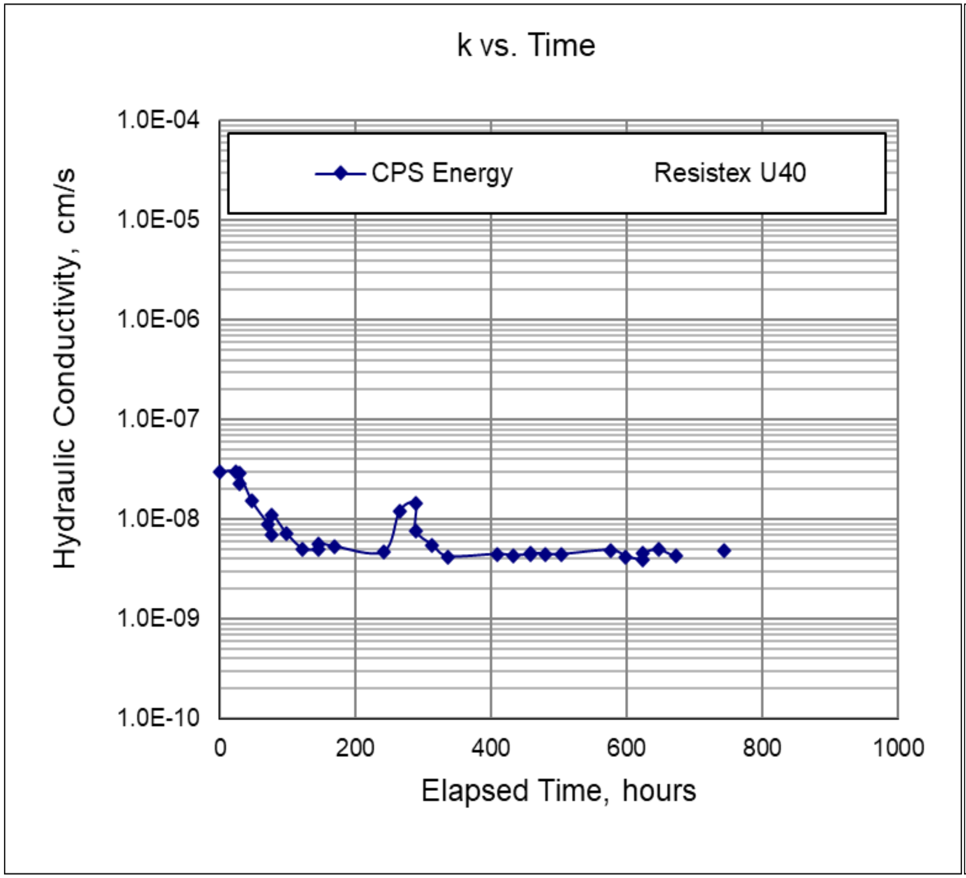

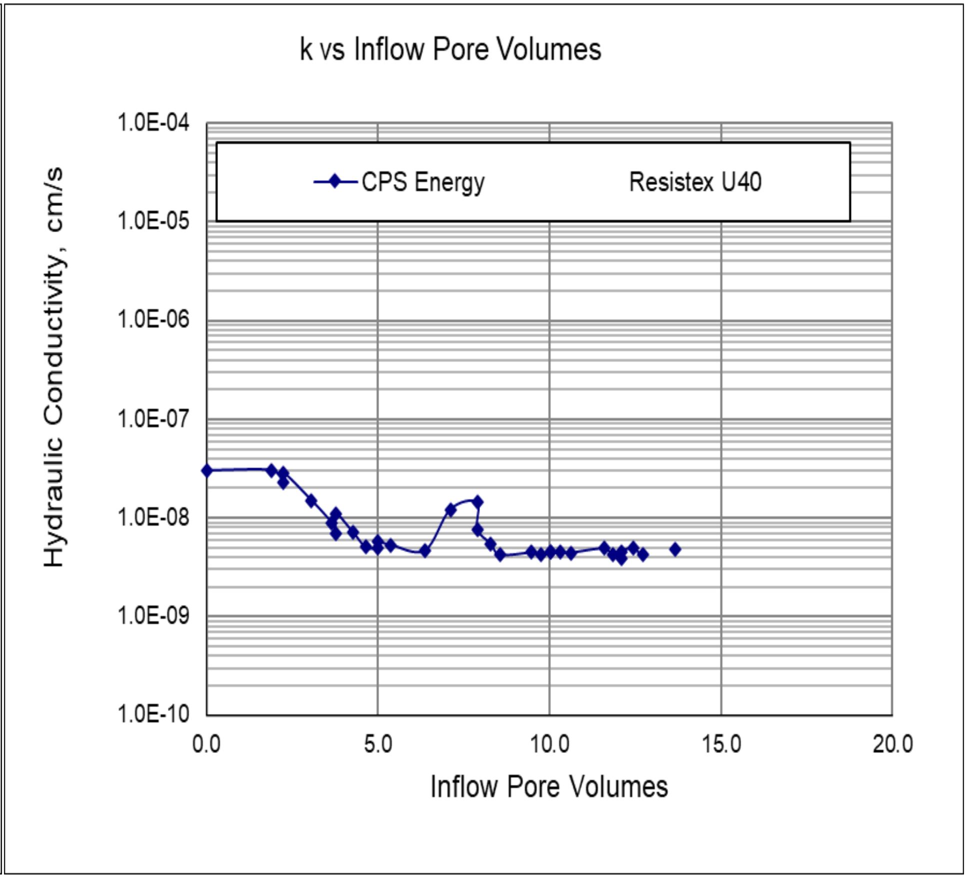

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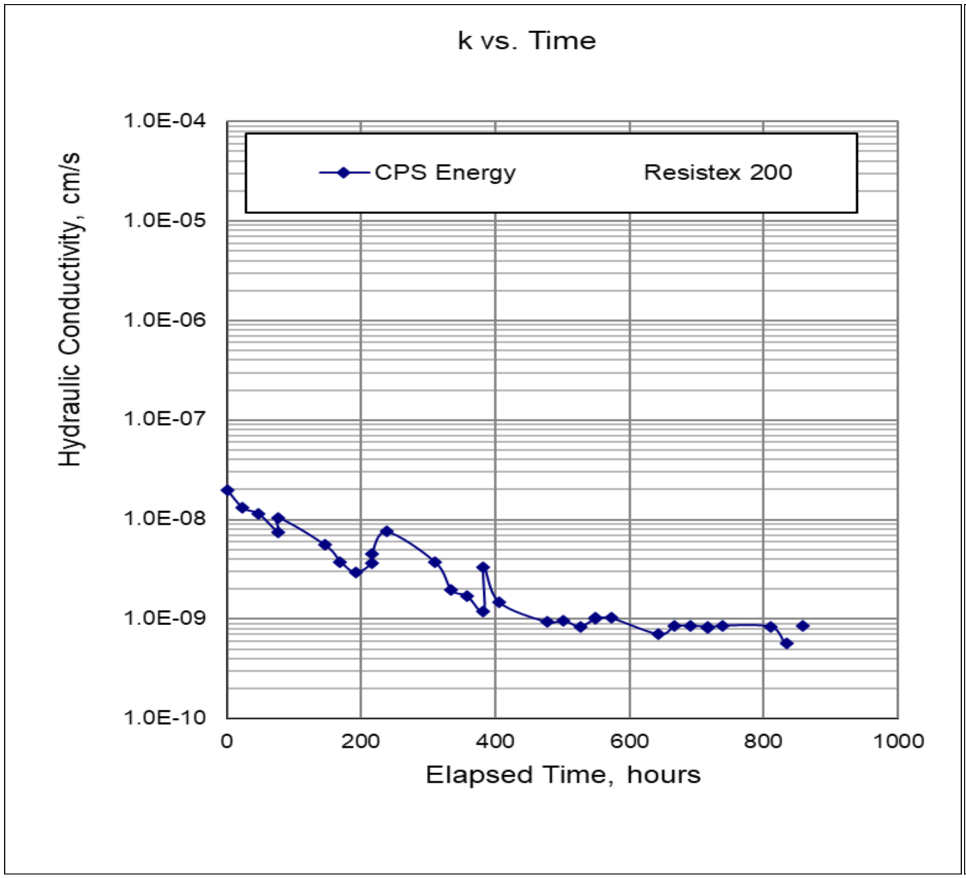

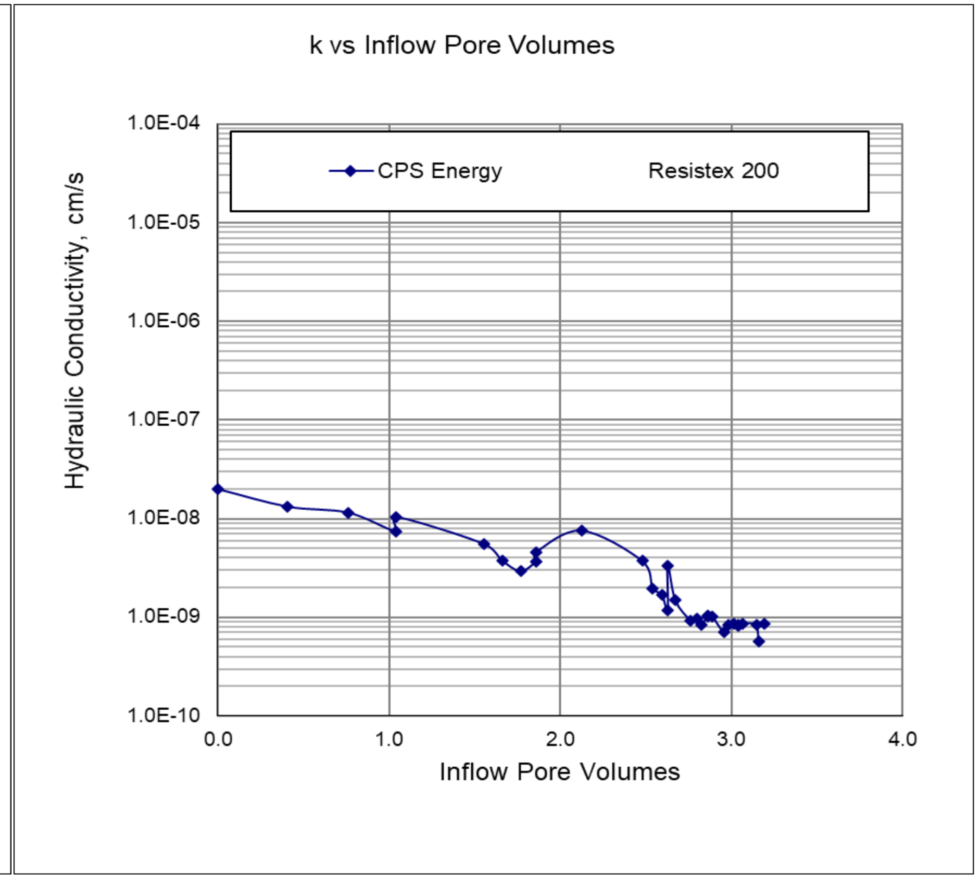

EVALUATING GCL CHEMICAL COMPATIBILITY

Sodium bentonite is an effective barrier primarily because it can absorb water (i.e., hydrate and swell), producing a dense, uniform layer with extremely low hydraulic conductivity, on the order of 10^{-9} cm/sec. Water absorption occurs because of the unique physical structure of bentonite and the complementary presence of sodium ions in the interlayer region between the bentonite platelets. Sodium bentonite's exceptional hydraulic properties allow GCLs to be used in place of much thicker soil layers in composite liner systems.

Sodium bentonite which is hydrated and permeated with relatively "clean" water will perform as an effective barrier indefinitely. In addition, past testing and experience have shown that sodium bentonite is chemically compatible with many common waste streams, including Subtitle D municipal solid waste landfill leachate (TR-101 and TR-254), some petroleum hydrocarbons (TR-103), deicing fluids (TR-109), livestock waste (TR-107), and dilute sodium cyanide mine wastes (TR-105).

In certain chemical environments, the interlayer sodium ions in bentonite can be replaced with cations dissolved in the water that comes in contact with the GCL, a process referred to as ion exchange. This type of exchange reaction can reduce the amount of water that can be held in the interlayer, resulting in decreased swell. The loss of swell usually causes increased porosity and increased GCL hydraulic conductivity. Experience and research have shown that calcium and magnesium are the most common source of compatibility problems for GCLs (Jo et al, 2001, Shackelford et al, 2000, Meer and Benson, 2004, Kolstad et al, 2004/2006). Examples of liquids with potentially high calcium and magnesium concentrations include: leachates from lime-stabilized sludge, soil, or fly ash; extremely hard water; unusually harsh landfill leachates; and acidic drainage from calcareous soil or stone. Other cations (ammonium, potassium, and sodium) may contribute to compatibility problems, but they are generally not as prevalent or as concentrated as calcium (Alther et al, 1985), with the exception of brines and seawater. Even though these highly concentrated solutions do not necessarily contain high levels of calcium, their high ionic strength can reduce the amount of bentonite swelling, resulting in increased GCL hydraulic conductivity.

This reference discusses the tools that can be used by a design engineer to evaluate GCL chemical compatibility with a site-specific leachate or other liquid.

HOW IS GCL CHEMICAL COMPATIBILITY EVALUATED?

Ideally, concentration-based guidelines would be available for determining GCL compatibility with a site-specific waste. Unfortunately, considering the variety and chemical complexity of the liquids that may be evaluated, as well as the many variables that influence chemical compatibility (e.g., prehydration with subgrade moisture [TR-222], confining stress [TR-321], and repeated wet-dry cycling [TR-341]), it is not possible to establish such guidelines. Instead, a three-tiered approach to evaluating GCL chemical compatibility is recommended, as outlined below.

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Tier I

The first tier is a simple review of existing analytical data. The topic of GCL chemical compatibility has been the subject of much study in recent years, with several important references available in the literature. One of these references, Kolstad et al (2004/2006), reported the results of several long-term hydraulic conductivity tests involving GCLs in contact with various multivalent (i.e., containing both sodium and calcium) salt solutions. Based on the results of these tests, the researchers found that a GCL's long-term hydraulic conductivity (as determined by ASTM D6766) can be estimated if the ionic strength (I) and the ratio of monovalent to divalent ions (RMD) in the permeant solution are both known, using the following empirical expression:

$$\frac{\log K_c}{\log K_{DI}} = 0.965 - 0.976 \times I + 0.0797 \times RMD + 0.251 \times I^2 \times RMD$$

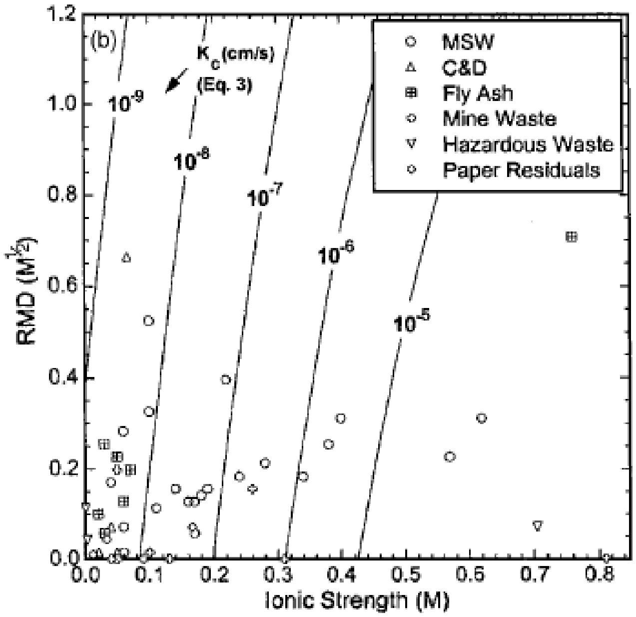
where:

I = ionic strength (M) of the site-specific leachate.

RMD = ratio of monovalent cation concentration to the square root of the divalent cation concentration ($M^{1/2}$) in the site-specific leachate.

K_c = GCL hydraulic conductivity when hydrated and permeated with site-specific leachate (cm/sec).

K_{DI} = GCL hydraulic conductivity with deionized water (cm/sec).



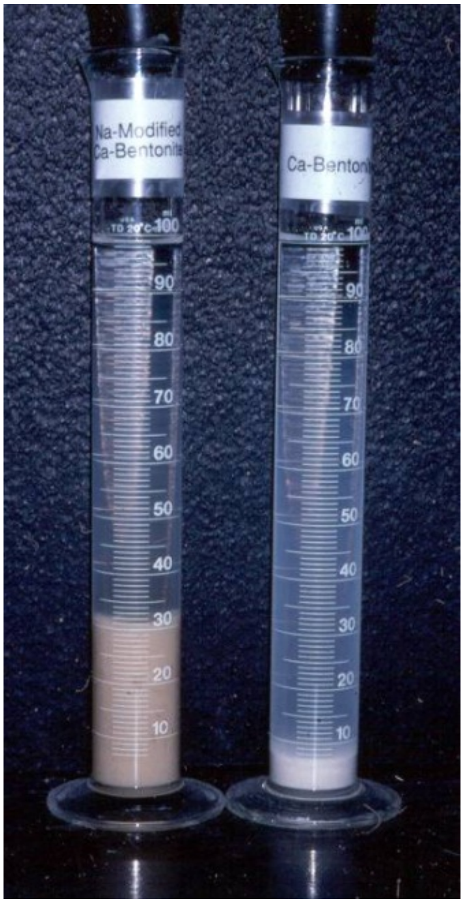
Using this tool, a Tier I compatibility evaluation can be performed if the major ion concentrations (typically, calcium, magnesium, sodium, and potassium) and ionic strength (estimated from either the total dissolved solids [TDS], or electrical conductivity [EC]) of the site leachate are known. For example, using the relationship above and MSW leachate data available in the literature, Kolstad et al. were able to conclude that high hydraulic conductivities (i.e., >10^{-7} cm/sec) are unlikely for GCLs in base liners in many solid waste containment facilities.

In many cases, the Tier I evaluation is sufficient to show that a site-specific leachate should not pose compatibility problems. However, if the analytical data indicate a potential impact to GCL hydraulic performance, or if there is no analytical data available, then it is necessary to proceed to the second tier, involving bentonite "screening" tests, which are described below.

Tier II

The next tier of compatibility testing involves bentonite screening tests, performed in accordance with ASTM Method D6141. These tests are fairly straightforward, and can be performed at one of CETCO's R&D laboratories or at most commercial geosynthetics testing laboratories.

Liquid samples should be obtained very early in the project, such as during the site hydrogeological investigation. It is important that the sample collected is representative of actual site conditions. Synthetic leachate samples may also be considered for use in the compatibility tests. The objective is to create a liquid representative of that which will come in contact with the GCL. At least 1-gallon (4-Liter) of each sample should be submitted for testing. Samples should be accompanied by a chain-of-custody or information form. When a sample is received at the CETCO laboratory, the following screening tests are performed to assess compatibility:



- Fluid Loss (ASTM D5890) – A mixture of sodium bentonite and the site water/leachate is tested for fluid loss, an indicator of the bentonite's sealing ability.
- Swell Index (ASTM D5891) – Two grams of sodium bentonite are added to the site water/leachate and tested for swell index, the volumetric swelling of the bentonite.
- Water quality – The pH and EC of the site water/leachate are measured using bench-top water quality probes. pH will indicate if any strong acids (pH < 2) or bases (pH > 12) are present which might damage the bentonite clay. EC indicates the strength of dissolved salts in the water, which can hamper the swelling and sealing properties of bentonite if present at high concentrations.
- Chemistry – The site water/leachate is analyzed for major dissolved cations using ICP. The analytical results can then be used to perform a Tier I assessment, if one has not already been done.

As part of this testing, fluid loss and free swell tests are also performed on clean, deionized, or "DI" water for comparison to the results obtained with the site water/leachate sample. Sodium bentonite tested with DI water is expected to have a free swell of at least 24 mL/2g and a fluid loss less than 18 mL. Changes in bentonite swell and fluid loss indicate that the constituents dissolved in the site water may have an impact on GCL hydraulic conductivity. However, since it is only a screening tool, there are no specific values for the fluid loss and swell index tests that the clay must meet in order to be considered chemically compatible with the test liquid in question. Differences between the results of the baseline tests and those conducted with the site leachate may warrant further hydraulic testing.

A major drawback of the D6141 tests is the potential for a false "negative" result, meaning that the bentonite swell index or fluid loss might predict no impact to hydraulic performance, where in reality, there may be a long-term adverse effect. This is primarily a concern with dilute calcium or magnesium solutions, which may slowly affect GCL hydraulic performance over months or years. Short-term (2-day) bentonite screening tests would not be able to capture this type of long-term effect. This is not expected to be a concern with strong calcium or magnesium or high ionic strength solutions, which have been shown to impact GCL hydraulic conductivity almost immediately, and whose effects would therefore be captured by the short-term bentonite screening tests. Another limitation of the bentonite screening tests is their inability to simulate site conditions, such as clean water prehydration, increased confining pressure, and wet/dry cycling. These limitations can be in part addressed by moving to the third tier, a long-term GCL hydraulic conductivity test, discussed below.

Tier III

The third-tier compatibility evaluation consists of an extended GCL hydraulic conductivity test performed in accordance with ASTM D6766. This test method is essentially a hydraulic conductivity test, but instead of permeating the GCL sample with DI water, the site-specific leachate is used. Since leachates can often be hazardous, corrosive, or volatile, the testing laboratory must have permeant interface devices, such as bladder accumulators, to contain the test liquid in a closed chamber, and prevent contamination of the flow measurement and pressure systems, or release of chemicals to the ambient air.

Method D6766 provides some flexibility in specifying the testing conditions so that certain site conditions can be simulated. For example, in situations where the GCL will be deployed on a subgrade soil that is compacted wet of optimum, the GCL will very likely hydrate from the relatively clean moisture in the subgrade (TR-222), long before it comes in contact with the potentially aggressive site leachate. Lee and Shackelford (2005) showed that a GCL which is pre-hydrated with clean water before being exposed to a harsh solution is expected to exhibit a lower hydraulic conductivity than one hydrated directly with the solution. Depending on the expected site conditions, the D6766 test can be specified to pre-hydrate the GCL with either water (Scenario 1) or the site liquid (Scenario 2).

Another site-specific consideration is confining pressure. Certain applications, such as landfill bottom liners and mine heap leach pads, involve up to several hundred feet of waste, resulting in high compressive loads on the liner systems. Although the standard confining pressure for the ASTM D6766 test is 5 psi (representing less than 10 feet of waste), the test method is flexible enough to allow greater confining pressures, thus mimicking conditions in a landfill bottom liner or heap leach pad. Petrov et al (1997) showed that higher confining pressures will decrease bentonite porosity, and tend to decrease GCL permeability. TR-321 shows that higher confining pressures will improve hydraulic conductivity even when the GCL is permeated with aggressive calcium solutions.

ASTM D6766 has two sets of termination criteria: hydraulic and chemical. To meet the hydraulic termination criterion, the ratio of inflow rate to outflow rate from the last three readings must be between 0.75 and 1.25. It normally takes between one week and one month to reach the hydraulic termination criterion. To meet the chemical termination criterion, the test must continue until at least two pore volumes of flow have passed through the sample and chemical equilibrium is established between the effluent and influent. The test method defines chemical equilibrium as effluent electrical conductivity within ±10% of the influent electrical conductivity. This requirement was put in place to ensure that a large enough volume of site liquid passes through the sample to allow slow ion exchange reactions to occur. Two pore volumes can take approximately a month to permeate through the GCL sample. However, reaching chemical equilibrium (effluent EC within 10% of influent EC), may take more than a year of testing, depending on the leachate characteristics.

ASTM D6766 is a very useful tool which provides a fairly conclusive assessment of GCL chemical compatibility with a site-specific leachate. However, the major drawback of the D6766 test is the potentially long period of time required to reach chemical equilibrium. This limitation reinforces the need for upfront compatibility testing early in the project. Clearly, requiring the contractor to perform this testing during the construction phase is not recommended.

WHAT DO THE ASTM D6766 COMPATIBILITY TEST RESULTS MEAN?

ASTM D6766 is currently the state-of-the-practice in the geosynthetics industry for evaluating long-term chemical compatibility of a GCL with a particular site waste stream. An ASTM D6766 test that is properly run until both the hydraulic (inflow and outflow within ±25% over three consecutive readings) and chemical (effluent EC within ±10% of influent EC) termination criteria are achieved, provides a good approximation of the GCL's long-term hydraulic conductivity when exposed to the site leachate. Jo et al (2005) conducted several GCL compatibility tests with weak calcium and magnesium solutions, with some tests running longer than 2.5 years, representing several hundred pore volumes of flow. The intent of this study was to run the tests until complete ion exchange had occurred, which required even stricter chemical equilibrium termination criteria than the D6766 test. The study found that the final GCL hydraulic conductivity values measured after complete ion exchange were fairly close to (within 2 to 13 times) the hydraulic conductivity values determined by ASTM D6766 tests, which took much less time to complete.

The laboratory that performs the chemical compatibility test, whether it is the CETCO R&D laboratory or an independent third-party laboratory, is only reporting the test results under the specified testing conditions, and is not making any guarantees about actual field performance or the suitability of a GCL for a particular project. It is the design engineer's responsibility to incorporate the D6766 results into their design to determine whether the GCL will meet the overall project objectives. Neither the testing laboratory nor the GCL manufacturer can make this determination.

Also, it is important to note that the results of D6766 testing for a particular project are only applicable for that site, for the specific waste stream that is tested, and only for the specific conditions replicated by the test. For instance, D6766 testing performed at high normal loads representative of a landfill bottom liner should not be applied to a situation where the GCL will only be placed under a modest normal load, such as a landfill cover or pond. Similarly, the results of a D6766 test where the GCL was pre-hydrated with clean water should not be applied to sites located in extremely arid climates where little subgrade moisture is expected, unless water will be applied manually to the subgrade prior to deployment. And finally, since D6766 tests are normally performed on continuously hydrated GCL samples, the test results should not be applied to situations where repeated cycles of wetting and drying of the GCL are likely to occur, such as in some GCL-only landfill covers, as desiccation can worsen compatibility effects.

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7. CETCO TR-107, "GCL Compatibility with Livestock Waste".
8. CETCO TR-109, "GCL Compatibility with Airport De-Icing Fluid".
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10. CETCO TR-254, "Hydraulic Conductivity and Swell of Nonprehydrated GCLs Permeated with Multispecies Inorganic Solutions".
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Attachment B – GCL Submittals

B.2 – Technical Data (Sheet)

Resistex® 200FLW-9

Polymer Enhanced Geosynthetic Clay Liner

CETCO Lining Technologies, Inc.

RESISTEX® 200FLW-9

POLYMER ENHANCED GEOSYNTHETIC CLAY LINER

DESCRIPTION

RESISTEX® 200FLW-9 Geosynthetic Clay Liner (GCL) is polymer enhanced to provide the highest level of chemical compatibility in aggressive leachate environments. Such environments may include coal combustion product storage facilities, mining operations, and industrial waste storage facilities. Site-specific compatibility testing is strongly recommended.[1]

CERTIFIED PROPERTIES

PHYSICAL PROPERTIES

MATERIAL PROPERTY	TEST METHOD	TEST FREQUENCY	CERTIFIED VALUES
Nonwoven Cap Geotextile Mass/Area[2]	ASTM D5261	200,000 ft^2 (20,000 m^2)	9.0 oz/yd^2 (305 g/m^2) min.
Nonwoven Base Geotextile Mass/Area[2]	ASTM D5261	200,000 ft^2 (20,000 m^2)	6.0 oz/yd^2 (203 g/m^2) min.
Woven Base Geotextile Mass/Area[2]	ASTM D5261	200,000 ft^2 (20,000 m^2)	3.2 oz/yd^2 (108 g/m^2) min.
Bentonite Moisture Content[3]	ASTM D2216	1 per 50 tonnes	12% max.
Bentonite Swell Index[3]	ASTM D5890	1 per 50 tonnes	24 mL/2g min.
Bentonite Fluid Loss[3]	ASTM D5891	1 per 50 tonnes	18 mL max.
Bentonite Mass/Area[4]	ASTM D5993	40,000 ft^2 (4,000 m^2)	0.75 lb/ft^2 (3.7 kg/m^2) min.
Total Mass/Area[4]	ASTM D5993	40,000 ft^2 (4,000 m^2)	0.88 lb/ft^2 (4.0 kg/m^2) min.
GCL Moisture Content	ASTM D5993	40,000 ft^2 (4,000 m^2)	35% max.
GCL Grab Strength[5]	ASTM D6768	200,000 ft^2 (20,000 m^2)	50 lbs/in (8.8 kN/m) min.
GCL Peel Strength	ASTM D6496	40,000 ft^2 (4,000 m^2)	8 lbs/in (1.4 kN/m) min.
GCL Hydraulic Conductivity[6] in DI Water	ASTM D5887	250,000 ft^2 (25,000 m^2)	3 x 10^{-11} m/s max.
GCL Hydrated Internal Shear Strength[7]	ASTM D6243	1,000,000 ft^2 (100,000 m^2)	500 psf (24 kPa) typ. @ 200 psf (9.6 kPa)

[1] Compatibility testing via ASTM D6766 recommended using site-specific leachate as the permeate fluid. Pre-hydration requirements for the GCL sample and other testing parameters such as confining stress to be prescribed by the design professional.
[2] Geotextile property tests performed on the geotextile components before they are incorporated into the finished GCL product.
[3] Bentonite property tests performed before the bentonite is incorporated into the finished GCL product.
[4] Reported at 0% moisture content.
[5] All tensile strength testing is performed in the machine direction using ASTM D6768.
[6] Index flux and hydraulic conductivity testing with deaired distilled/deionized water at 80 psi (550 kPa) cell pressure, 77 psi (530 kPa) headwater pressure and 75 psi (515 kPa) tailwater pressure.
[7] Peak values measured at 200 psf (9.6 kPa) normal stress for a specimen hydrated in the shearbox for 48 hours. Hydrating outside of the shearbox is not recommended. Site-specific materials, GCL products, and test conditions must be used to verify internal and interface strength of the proposed design.

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FORM: TDS_BENTOMAT_U20ST_AM_EN_202103_V1

Attachment B – GCL Submittals

B.3 - Personal Email Communication,
Reza Gorakhki, PhD, Technical Services Engineer,
CETCO Lining Technologies, Inc.,
August 24, 2023.

Gourlay, Sandy

From: Reza Gorakhki <reza.gorakhki@mineralstech.com>
Sent: Thursday, August 24, 2023 6:44 PM
To: Gourlay, Sandy
Cc: Marat Goldenberg
Subject: RE: RE: CPS - FGD Brine Pond Composite Liner - Recommendation for "thickness" of Resistex (R) 200
Attachments: CPS Spruce - darcy's law.xls

Sandy,

Thank you for your email.

We continued the test after sending the report to you and the final reported permeability was $8.68*10^{-10}$ cm/s. We measure the thickness of GCL in five different locations of specimen before and after the test. The relevant measurement for your case is the average “final” wet fraction. Please see below Table.

Thickness, mm	Thickness, mm
Initial dry w/text	Final wet w/text
7.260	6.610
7.330	7.210
6.980	6.960
6.700	7.350
6.350	6.500
6.924	6.926

Please find the attached file that suggests under 8 ft of head, the GCL system had lower leakage rate relative to 2 ft of compacted clay. Please be aware that we do not consider presence of any geomembrane in CCL or GCL cases.

Please let me know if you have any additional questions.

Thanks, Reza

Reza Gorakhki, PhD
Senior Technical Services Manager

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