Part IV
Protecting Ground Water

Chapter 7: Section B
Designing and Installing Liners

Technical Considerations for New Surface Impoundments, Landfills, and Waste Piles

Contents

Designing and Installing Liners—Technical Considerations for New Surface Impoundments, Landfills, and Waste Piles

This chapter will help you:

- *Employ liner systems where needed to protect ground water from contamination.*
- *Select from clay liners, synthetic liners, composite liners, leachate collection systems, and leak detection systems as appropriate.*
- *Consider technical issues carefully to ensure that the liner system will function as designed.*

Once risk has been characterized and the most appropriate design system is chosen, the next step is unit design. The Industrial Waste Management Evaluation Model (IWEM), discussed in Chapter 7, Section A—Assessing Risk can be used to determine appropriate design system recommendations. A critical part of this design for new landfills, waste piles, and surface impoundments is the liner system. The liner system recommendations in the Guide do not apply to land application units, since such operations generally do not include a liner system as part of their design. (For design of land application units, refer to Chapter 7, Section C—Designing a Land Application Program.) You should work with your state agency to ensure consideration of any applicable design system requirements, recommendations, or standard practices the state might have. In this chapter, sections I though IV discuss four design options—no liner/in-situ soils, single liner, composite liner, and double liner. Section V covers leachate collection and leak detection systems, and section VI discusses construction quality assurance and quality control.

I. In-Situ Soil Liners

For the purpose of the Guide, in-situ soil refers to simple, excavated areas or impoundments, without any additional engineering controls. The ability of natural soils to hinder transport and reduce the concentration of constituent levels through dilution and attenuation can provide sufficient protection when the initial constituent levels in the waste stream are very low, when the wastes are inert, or when the hydrogeologic setting affords sufficient protection.

What are the recommendations for in-situ soils?

The soil below and adjacent to a waste management unit should be suitable for construction. It should provide a firm foundation for the waste. Due to the low risk associated with wastes being managed in these units, a liner might not be necessary; however, it is still helpful to review the recommended location considerations and operating practices for the unit.

What technical issues should be considered with the use of in-situ soils?

In units using in-situ natural soils, construction and design of an engineered liner will not be necessary; however, there are still technical concerns to consider. These include the following:

- The stability of foundation soils.
- The compatibility of the waste with native soils.
- The location where the unit will be sited.
- The potential to recompact existing soils.

Potential instability can occur in the foundation soil, if its load-bearing capacity and resistance to movement or consolidation are insufficient to support the waste. The groundwater table or a weak soil layer also can influence the stability of the unit. You should take measures, such as designing maximum slopes, to avoid slope failure during construction and operation of the waste management unit. Most soil slopes are stable at a 3:1 horizontal to vertical inclination. There are common sense operating practices to ensure that any wastes to be managed on in-situ soils will not inappropriately interact with the soils. When using in-situ soils, refer to Chapter 4—Considering the Site. Selecting an appropriate location will be of increased importance, since the added barrier of an engineered liner will not be present. Because in-situ soil can have non-homogeneous material, root holes, and cracks, its performance can be improved by scarifying and compacting the top portion of the in-situ natural soils.

II. Single Liners

If the risk evaluation recommended the use of a single liner, the next step is to determine the type of single liner system most appropriate for the site. The discussion below addresses three types of single liner systems: compacted clay liners, geomembrane liners, and geosynthetic clay liners. Determining which material, or combination of materials, is important for protecting human health and the environment.[1]

A. Compacted Clay Liners

A compacted clay liner can serve as a single liner or as part of a composite or double liner system. Compacted clay liners are composed of natural mineral materials (natural soils), bentonite-soil blends, and other materials placed and compacted in layers called lifts. If natural soils at the site contain a significant quantity of clay, then liner materials can be excavated from onsite locations known as borrow pits. Alternatively, if onsite soils do not contain sufficient clay, clay materials can be hauled from offsite sources, often referred to as commercial pits.

Compacted clay liners can be designed to work effectively as hydraulic barriers. To ensure that compacted clay liners are well constructed and perform as they are designed, it is important to implement effective quality control methods emphasizing soil investigations and construction practices. Three objectives of quality assurance and quality control for compacted soil liners are to ensure that 1) selected liner materials are suitable, 2) liner materials are properly placed and compacted, and 3) the completed liner is properly protected before, during, and after construction. Quality assurance and quality control are discussed in greater detail in section VI.

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[1] Many industry and trade periodicals, such as Waste Age, MSW Management, Solid Waste Technologies, and World Wastes, have articles on liner types and their corresponding costs, as well as advertisements and lists of vendors.

What are the thickness and hydraulic conductivity recommendations for compacted clay liners?

Compacted clay liners should be at least 2 feet thick and have a maximum hydraulic conductivity of 1 x 10^{-7} cm/sec (4 x 10^{-8} in/sec). Hydraulic conductivity refers to the degree of ease with which a fluid can flow through a material. A low hydraulic conductivity will help minimize leachate migration out of a unit. Designing a compacted clay liner with a thickness ranging from 2 to 5 feet will help ensure that the liner meets desired hydraulic conductivity standards and will also minimize leachate migration as a result of any cracks or imperfections present in the liner. Thicker compacted clay liners provide additional time to minimize leachate migration prior to the clay becoming saturated.

What issues should be considered in the design of a compacted clay liner?

The first step in designing a compacted clay liner is selecting the clay material. The quality and properties of the material will influence the performance of the liner. The most common type of compacted soil is one that is constructed from naturally occurring soils that contain a significant quantity of clay. Such soils are usually classified as CL, CH, or SC in the Unified Soil Classification System (USCS). Some of the factors to consider in choosing a soil include soil properties, interaction with wastes, and test results for potentially available materials.

Soil Properties

Minimizing hydraulic conductivity is the primary goal in constructing a soil liner. Factors to consider are water content, plasticity characteristics, percent fines, and percent gravel, as these properties affect the soil's ability to achieve a specified hydraulic conductivity.

Hydraulic conductivity. It is important to select compacted clay liner materials so that remolding and compacting of the materials will produce a low hydraulic conductivity. Factors influencing the hydraulic conductivity at a particular site include: the degree of compaction, compaction method, type of clay material used, soil moisture content, and density of the soil during liner construction. The hydraulic conductivity of a soil also depends on the viscosity and density of the fluid flowing through it. Consider measuring hydraulic conductivity using methods such as American Society of Testing and Materials (ASTM) D-5084.[2]

Water content. Water content refers to the amount of liquid, or free water, contained in a given amount of material. Measuring water content can help determine whether a clay material needs preprocessing, such as moisture adjustment or soil amendments, to yield a specified density or hydraulic conductivity. Compaction curves can be used to depict moisture and density relationships, using either ASTM D-698 or ASTM D-1557, the standard or modified Proctor test methods, depending on the compaction equipment used and the degree of firmness in the foundation materials.[3] The critical relationship between clay soil moisture content and density is explained thoroughly in Chapter 2 of EPA's 1993 technical guidance document *Quality*

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[2] ASTM D-5084, Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.

[3] ASTM D-698, Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)).
ASTM D-1557, Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)).

Assurance and Quality Control for Waste Containment Facilities (U.S. EPA, 1993c).

Plasticity characteristics. Plasticity characteristics describe a material's ability to behave as a plastic or moldable material. Soils containing clay are generally categorized as plastic. Soils that do not contain clay are non-plastic and typically considered unsuitable materials for compacted clay liners, unless soil amendments such as bentonite clay are introduced.

Plasticity characteristics are quantified by three parameters: liquid limit, plastic limit, and plasticity index. The liquid limit is defined as the minimum moisture content (in percent of oven-dried weight) at which a soil-water mixture can flow. The plastic limit is the minimum moisture content at which a soil can be molded. The plasticity index is defined as the liquid limit minus the plastic limit and defines the range of moisture content over which a soil exhibits plastic behavior. When soils with high plastic limits are too dry during placement, they tend to form clods, or hardened clumps, that are difficult to break down during compaction. As a result, preferential pathways can form around these clumps allowing leachate to flow through the material at a higher rate. Soil plasticity indices typically range from 10 percent to 30 percent. Soils with a plasticity index greater than 30 percent are cohesive, sticky, and difficult to work with in the field. Common testing methods for plasticity characteristics include the methods specified in ASTM D-4318, also known as Atterberg limits tests.[4]

Percent fines and percent gravel. Typical soil liner materials contain at least 30 percent fines and can contain up to 50 percent gravel, by weight. Common testing methods for percent fines and percent gravel are specified in ASTM D-422, also referred to as grain size distribution tests.[5] Fines refer to silt and clay-sized particles. Soils with less than 30 percent fines can be worked to obtain hydraulic conductivities below 1 x 10^{-7} cm/sec (4 x 10^{-8} in./sec), but use of these soils requires more careful construction practices.

Gravel is defined as particles unable to pass through the openings of a Number 4 sieve, which has an opening size equal to 4.76 mm (0.2 in.). Although gravel itself has a high hydraulic conductivity, relatively large amounts of gravel, up to 50 percent by weight, can be uniformly mixed with clay materials without significantly increasing the hydraulic conductivity of the material. Clay materials fill voids created between gravel particles, thereby creating a gravel-clay mixture with a low hydraulic conductivity. As long as the percent gravel in a compacted clay mixture remains below 50 percent, creating a uniform mixture of clay and gravel, where clay can fill in gaps, is more critical than the actual gravel content of the mixture.

You should pay close attention to the percent gravel in cases where a compacted clay liner functions as a bottom layer to a geosynthetic, as gravel can cause puncturing in geosynthetic materials. Controlling the maximum particle size and angularity of the gravel should help prevent puncturing, as well as prevent gravel from creating preferential flow paths. Similar to gravel, soil particles or rock fragments also can create preferential flow paths. To help prevent the development of preferential pathways and an increased hydraulic conductivity, it is best to use soil liner materials where the soil particles and rock fragments are typically small (e.g., 3/4 inch in diameter).

Interactions With Waste

Waste placed in a unit can interact with compacted clay liner materials, thereby influencing soil properties such as hydraulic con-

[4] ASTM D-4318, Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.

[5] ASTM D-422, Standard Test Method for Particle-Size Analysis of Soils.

ductivity and permeability. Two ways that waste materials can influence the hydraulic conductivity of the liner materials are through dissolution of soil minerals and changes in clay structure. Soil minerals can be dissolved, or reduced to liquid form, as a result of interaction with acids and bases. For example, aluminum and iron in the soil can be dissolved by acids, and silica can be dissolved by bases. While some plugging of soil pores by dissolved minerals can lower hydraulic conductivity in the short term, the creation of piping and channels over time can lead to an increased hydraulic conductivity in the long term. The interaction of waste and clay materials can also cause the creation of positive ions, or cations. The presence of cations such as sodium, potassium, calcium, and magnesium can change the clay structure, thereby influencing the hydraulic conductivity of the liner. Depending on the cation type and the clay mineral, an increased presence of such cations can cause the clay minerals to form clusters and increase the permeability of the clay. Therefore, before selecting a compacted clay liner material, it is important to develop a good understanding of the composition of the waste that will be placed in the waste management unit. EPA's Method 9100, in publication SW-846, measures the hydraulic conductivity of soil samples before and after exposure to permeants.[6]

Locating and Testing Material

Although the selection process for compacted clay liner construction materials can vary from project to project, some common material selection steps include locating and testing materials at a potential borrow or commercial pit before construction, and observing and testing material performance throughout construction. First, investigate a potential borrow or commercial pit to determine the volume of materials available. The next step is to test a representative sample of soil to determine material properties such as plasticity characteristics, percent gravel, and percent fines. To confirm the suitability of the materials once construction begins, you should consider requesting that representative samples from the materials in the borrow or commercial pit be tested periodically after work has started.

Material selection steps will vary, depending on the origin of the materials for the project. For example, if a commercial pit provides the materials, locating an appropriate onsite borrow pit is not necessary. In addition to the tests performed on the material, it is recommended that a qualified inspector make visual observations throughout the construction process to ensure that harmful materials, such as stones or other large matter, are not present in the liner material.

What issues should be considered in the construction of a liner and the operation of a unit?

You should develop test pads to demonstrate construction techniques and material performance on a small scale. During unit construction and operation, some additional factors influencing the performance of the liner include: preprocessing, subgrade preparation, method of compaction, and protection against desiccation and cracking. Each of these steps, from preprocessing through protection against desiccation and cracking, should be repeated for each lift or layer of soil.

Test Pads

Preparing a test pad for the compacted clay liner helps verify that the materials and methods proposed will yield a liner that meets the desired hydraulic conductivity. A test pad also provides an opportunity to

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[6] SW-846, *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods.*

demonstrate the performance of alternative materials or methods of construction. A test pad should be constructed with the soil liner materials proposed for a particular project, using the same preprocessing procedures, compaction equipment, and construction practices proposed for the actual liner. A complete discussion of test pads (covering dimensions, materials, and construction) can be found in Chapter 2 of EPA's 1993 technical guidance document *Quality Assurance and Quality Control for Waste Containment Facilities* (U.S. EPA, 1993c). A discussion of commonly used methods to measure in-situ hydraulic conductivity is also contained in that chapter.

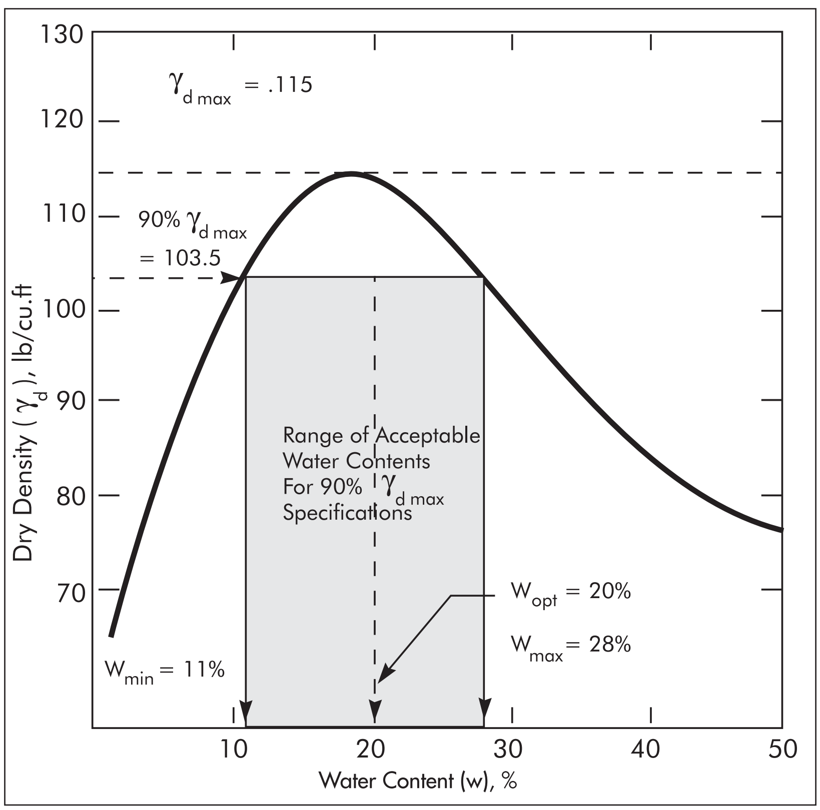
Preprocessing

Although some liner materials can be ready for use in construction immediately after they are excavated, many materials will require some degree of preprocessing. Preprocessing methods include: water content adjustment, removal of oversized particles, pulverization of any clumps, homogenization of the soils, and introduction of additives, such as bentonite.

Water content adjustment. For natural soils, the degree of saturation of the soil liner at the time of compaction, known as molding water content, influences the engineering properties of the compacted material. Soils compacted at water contents less than optimum tend to have a relatively high hydraulic conductivity. Soils compacted at water contents greater than optimum tend to have low hydraulic conductivity and low strength.

Proper soil water content revolves around achieving a minimum dry density, which is expressed as a percentage of the soil's maximum dry density. The minimum dry density typically falls in the range of 90 to 95 percent of the soil's maximum dry density value. From the minimum dry density range, the required water content range can be calculated, as shown in Figure 1. In this example the soil has a maximum dry density of 115 lb/cu ft. Based upon a required minimum dry density value of 90 percent of maximum dry density,

Figure 1.
Water Content for Achieving a Specific Density



Source: U.S. EPA, 1988.

which is equal to 103.5 lb/cu ft, the required water content ranges from 10 to 28 percent.

It is less problematic to compact clay soil at the lower end of the required water content range because it is easier to add water to the clay soil than to remove it. Thus, if precipitation occurs during construction of a site which is being placed at the lower end of the required water content range, the additional water might not result in a soil water content greater than the required range. Conversely, if the site is being placed at the upper end of the range, for example at 25 percent, any additional moisture will be excessive, resulting in water content over 28 percent and making the 90 percent maximum dry density unattainable. Under such conditions construction should halt while the soil is aerated and excess moisture is allowed to evaporate.

Removal of oversized particles. Preprocessing clay materials, to remove cobbles or large stones that exceed the maximum allowable particle size, can improve the soil's compactibility and protect any adjacent geomembrane from puncture. Particle size should be small (e.g., 3/4 inch in diameter) for compaction purposes. If a geomembrane will be placed over the compacted clay, only the upper lift of clay needs to address concerns regarding puncture resistance. Observation by quality assurance and quality control personnel is the most effective method to identify areas where oversized particles need to be removed. Cobbles and stones are not the only materials that can interfere with compactive efforts. Chunks of dry, hard clay, also known as clods, often need to be broken into smaller pieces to be properly hydrated, remolded, and compacted. In wet clay, clods are less of a concern since wet clods can often be remolded with a reasonable compactive effort.

Soil amendments. If the soils at a unit do not have a sufficient percentage of clay, a common practice is to blend bentonite with them to reduce the hydraulic conductivity. Bentonite is a clay mineral that expands when it comes into contact with water. Relatively small amounts of bentonite, on the order of 5 to 10 percent, can be added to sand or other noncohesive soils to increase the cohesion of the material and reduce hydraulic conductivity.

Sodium bentonite is a common additive used to amend soils. However, this additive is vulnerable to degradation as a result of contact with certain chemicals and waste leachates. Calcium bentonite, a more permeable material than sodium bentonite, is another common additive used to amend soils. Approximately twice as much calcium bentonite is needed to achieve a hydraulic conductivity comparable to that of sodium bentonite. Amended soil mixtures generally require mixing in a pug mill, cement mixer, or other mixing equipment that allows water to be added during the mixing process. Throughout the mixing and placement processes, water content, bentonite content, and particle distribution should be controlled. Other materials that can be used as soil additives include lime cement and other clay minerals, such as atapulgite. It can be difficult to mix additives thoroughly with cohesive soils, or clays; the resultant mixture might not achieve the desired level of hydraulic conductivity throughout the entire liner.

Subgrade Preparation

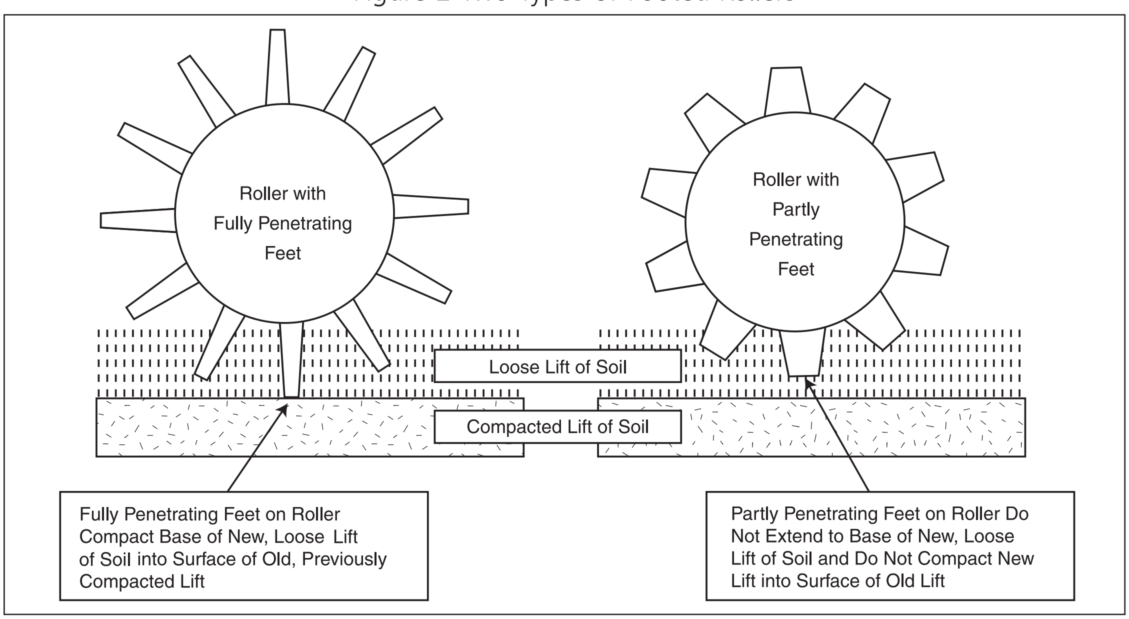
It is important to ensure that the subgrade on which a compacted clay liner will be constructed is properly prepared. When a compacted clay liner is the lowest component of a liner system, the subgrade consists of native soil or rock. Subgrade preparation for these systems involves compacting the native soil to remove any soft spots and adding water to or removing water from the native soil to obtain a specified firmness. Alternatively, in some cases, the compacted clay liner can be placed on top of a geosynthetic material, such as a geotextile. In such cases, subgrade preparation involves ensuring the smoothness of the geosynthetic on which the clay liner will be placed and the conformity of the geosynthetic material to the underlying material.

Compaction

The main purpose of compaction is to densify the clay materials by breaking and remolding clods of material into a uniform mass. Since amended soils usually do not develop clumps, the primary objective of compaction for such materials is to increase the material's density. Proper compaction of liner materials is essential to ensure that a compacted clay liner meets specified hydraulic conductivity standards. Factors influencing the effectiveness of compaction efforts include: the type of equipment selected, the number of passes made over the materials by such equipment, the lift thickness, and the bonding between the lifts. Molding water content, described earlier under preprocessing, is another factor influencing the effectiveness of compaction.

Type of equipment. Factors to consider when selecting compaction equipment include: the type and weight of the compactor, the characteristics of any feet on the drum, and the weight of the roller per unit length of drummed surface. Heavy compactors, weighing more than 50,000 pounds, with feet long enough to penetrate a loose lift of soil, are often the best types of compactor for clay liners. For bentonite-soil mixtures, a footed roller might not be appropriate. For these mixtures, where densification of the material is more important than kneading or remolding it to meet low hydraulic conductivity specifications, a smooth-drum roller or a rubber- tired roller might produce better results. Figure 2 depicts two types of footed rollers, a fully penetrating footed roller and a partially-penetrating footed roller.

Figure 2 Two Types of Footed Rollers



Source: U.S. EPA, 1993c.

For placement of liners on side slopes, consider the angle and length of the slope. Placing continuous lifts on a gradually inclined slope will provide better continuity between the bottom and sidewalls of the liner. Since continuous lifts might be impossible to construct on steeper slopes due to the difficulties of operating heavy compaction equipment on these slopes, materials might need to be placed and compacted in horizontal lifts. When sidewalls are compacted horizontally, it is important to avoid creating seepage planes, by securely connecting the edges of the horizontal lift with the bottom of the liner. Because the lift needs to be wide enough to accommodate compaction equipment, the thickness of the horizontal lift is often greater than the thickness specified in the design. In such cases, you should consider trimming soil material from the constructed side slopes and sealing the trimmed surface using a sealed drum roller.

It is common for contractors to use several different types of compaction equipment during liner construction. Initial lifts might need the use of a footed roller to fully penetrate a loose lift. Final lifts also might need the use of a footed roller for compaction, however, they might be formed better by using a smooth roller after the lift has been compacted to smooth the surface of the lift in preparation for placement of an overlying geomembrane.

Number of passes. The number of passes made by a compactor over clay materials can influence the overall hydraulic conductivity of the liner. The minimum number of passes that is reasonable depends on a variety of site-specific factors and cannot be generalized. In some cases, where a minimum coverage is specified, it might be possible to calculate the minimum number of passes to meet such a specification. At least 5 to 15 passes with a compactor over a given point are usually necessary to remold and compact clay liner materials thoroughly.

An equipment pass can be defined as one pass of the compaction equipment or as one pass of a drum over a given area of soil. It is important to clearly define what is meant by a pass in any quality assurance or quality control plans. It does not matter which definition is agreed upon, as long as the definition is used consistently throughout the project.

Lift thickness. You should determine the appropriate thickness (as measured before compaction) of each of the several lifts that will make up the clay liner. The initial thickness of a loose lift will affect the compactive effort needed to reach the lower portions of the lift. Thinner lifts allow compactive efforts to reach the bottom of a lift and provide greater assurance that compaction will be sufficient to allow homogenous bonding between subsequent lifts. Loose lift thicknesses typically range between 13 and 25 cm (5 and 10 in.). Factors influencing lift thickness are: soil characteristics, compaction equipment, firmness of the foundation materials, and the anticipated compaction necessary to meet hydraulic conductivity requirements.

Bonding between lifts. Since it is inevitable that some zones of higher and lower hydraulic conductivity, also known as preferential pathways, will be present within each lift, lifts should be joined or bonded in a way that minimizes extending these zones or pathways between lifts. If good bonding is achieved, the preferential pathways will be truncated by the bonded zone between the lifts. At least two recommended methods exist for preparing proper bonds. The first method involves kneading, or blending the new lift with the previously compacted lift using a footed roller. Using a roller with feet long enough to fully penetrate through the top lift and knead the previous lift improves the quality of the bond. A second method involves using a disc harrow or similar equipment to scarify, or roughen, and wet the top inch of the recently placed lift, prior to placing the next lift.

Protection Against Desiccation and Cracking

You should consider how to protect compacted clay liners against desiccation and freezing during and after construction. Protection against desiccation is important, because clay soil shrinks as it dries. Depending on the extent of shrinkage, it can crack. Deep cracks, extending through more than one lift, can cause problems. You should measure water content to determine whether desiccation is occurring.

There are several ways to protect compacted clay liners from desiccation. One preventive measure is to smooth roll the surface with a steel drummed roller to produce a thin, dense skin of soil; this layer can help minimize the movement of water into or out of the compacted material. Another option is to wet the clay periodically in a uniform manner; however, it is important to make sure to avoid creating areas of excessive wetness. A third measure involves covering compacted clay liner materials with a sheet of white or clear plastic or tarp to help prevent against desiccation and cracking. The cover should be weighted down with sandbags or other material to minimize exposure of the underlying materials to air. Using a light-colored plastic will help prevent overheating, which can dry out the clay materials. If the clay liner is not being covered with a geosynthetic, another method to prevent desiccation involves covering the clay with a layer of protective cover soil or intentionally overbuilding the clay liner and shaving it down to liner grade.

Protection against freezing is another important consideration, because freezing can increase the hydraulic conductivity of a liner. It is important to avoid construction during freezing weather. If freezing does occur and the damage affects only a shallow depth, the liner can be repaired by rerolling the surface. If deeper freezing occurs, the repairs might be more complicated. For a general guide to frost depths, see Figure 1 of Chapter 11—Performing Closure and Post-Closure Care.

B. Geomembranes or Flexible Membrane Liners

Geomembranes or flexible membrane liners are used to contain or prevent waste constituents and leachate from escaping a waste management unit. Geomembranes are made by combining one or more plastic polymers with ingredients such as carbon black, pigments, fillers, plasticizers, processing aids, crosslinking chemicals, anti-degradants, and biocides. A wide range of plastic resins are used for geomembranes, including high density polyethylene (HDPE), linear low density polyethylene (LLDPE), low density linear polyethlene (LDLPE), very low density polyethlene (VLDPE), polyvinyl chloride (PVC), flexible polypropylene (fPP), chlorosulfonated polyethylene (CSPE or Hypalon), and ethylene propylene diene termonomer (EPDM). Most manufacturers produce geomembranes through extrusion or calendering. In the extrusion process, a molten polymer is stretched into a nonreinforced sheet; extruded geomembranes are usually made of HDPE and LLDPE. During the calendering process, a heated polymeric compound is passed through a series of rollers. In this process, a geomembrane can be reinforced with a woven fabric or fibers. Calendered geomembranes are usually made of PVC and CSPE.

What are the thickness recommendations for geomembrane liners?

Geomembranes range in thicknesses from 20 to 120 mil (1 mil = 0.001 in.). A good design should include a minimum thickness of 30 mil, except for HDPE liners, which should have a minimum thickness of 60 mil. These recommended minimum thicknesses ensure that the liner material will withstand the stress of construction and the weight load of the waste, and allow adequate seaming to bind separate geomembrane panels. Reducing the potential for tearing or puncture, through proper construction and quality control, is essential for a geomembrane to perform effectively.

What issues should be considered in the design of a geomembrane liner?

Several factors to address in the design include: determining appropriate material properties and testing to ensure these properties are met, understanding how the liner will interact with the intended waste stream, accounting for all stresses imposed by the design, and ensuring adequate friction.

Material Properties and Selection

When designing a geomembrane liner, you should examine several properties of the geomembrane material in addition to thickness, including: tensile behavior, tear resistance, puncture resistance, susceptibility to environmental stress cracks, ultraviolet resistance, and carbon black content.

Tensile behavior. Tensile behavior refers to the tensile strength of a material and its ability to elongate under strain. Tensile strength is the ability of a material to resist pulling stresses without tearing. The tensile properties of a geomembrane must be sufficient to satisfy the stresses anticipated during its service life. These stresses include the self-weight of the geomembrane and any down drag caused by waste settlement on side slope liners.

Puncture and tear resistance. Geomembrane liners can be subject to tearing during installation due to high winds or handling. Puncture resistance is also important to consider since geomembranes are often placed above or below materials that might have jagged or angular edges. For example, geomembranes might be installed above a granular drainage system that includes gravel.

Susceptibility to environmental stress cracks. Environmental factors can cause cracks or failures before a liner is stressed to its manufactured strength. These imperfections, referred to as environmental stress cracks, often occur in areas where a liner has been scratched or stressed by fatigue. These cracks can also result in areas where excess surface wetting agents have been applied. In surface impoundments, where the geomembrane liner has greater exposure to the atmosphere and temperature changes, such exposure can increase the potential for environmental stress cracking.

Ultraviolet resistance. Ultraviolet resistance is another factor to consider in the design of geomembrane liners, especially in cases where the liner might be exposed to ultraviolet radiation for prolonged periods of time. In such cases, which often occur in surface impoundments, ultraviolet radiation can cause degradation and cracking in the geomembrane. Adding carbon black or other additives during the manufacturing process can increase a geomembrane's ultraviolet resistance. Backfilling over the exposed geomembrane also works to prevent degradation due to ultraviolet radiation.

Interactions With Waste

Since the main purpose of a geomembrane is to provide a barrier and prevent contaminants from penetrating through the geomembrane, chemical resistance is a critical consideration. Testing for chemical resistance might be warranted depending on the type, volumes, and characteristics of waste managed at a particular unit and the type of geomembrane to be used. An established method for testing the chemical resistance of geomembranes, EPA Method 9090, can be found in SW-846. ASTM has also adopted standards for testing the chemical compatibility of various geosynthetics, including geomembranes, with leachates from waste management units. ASTM D-5747 provides a standard for testing the chemical compatibility of geomembranes.[7]

Stresses Imposed by Liner Design

A liner design should take into account the stresses imposed on the liner by the design configuration. These stresses include: the differential settlement in foundation soil, strain requirements at the anchor trench, strain requirements over long, steep side slopes, stresses resulting from compaction, and seismic stresses. Often an anchor trench designed to secure the geomembrane during construction is prepared along the perimeter of a unit cell. This action can help prevent the geomembrane from slipping down the interior side slopes. Trench designs should include a depth of burial sufficient to hold the specified length of liner. If forces larger than the tensile strength of the liner are inadvertently developed, then the liner could tear. For this reason, the geomembrane liner should be allowed to slip or give in the trench after construction to prevent such tearing. To help reduce unnecessary stresses in the liner design, it is advisable to avoid using horizontal seams. For more information on design stresses, consult *Geosynthetic Guidance for Hazardous Waste Landfill Cells and Surface Impoundments* (U.S. EPA, 1987).

Designing for Adequate Friction

Adequate friction between the geomembrane liner and the soil subgrade, as well as between any geosynthetic components, is necessary to prevent extensive slippage or sloughing on the slopes of a unit. Design equations for such components should evaluate: 1) the ability of a liner to support its own weight on side slopes, 2) the ability of a liner to withstand down-dragging during and after waste placement, 3) the best anchorage configuration for the liner, 4) the stability of soil cover on top of a liner, and 5) the stability of other geosynthetic components, such as geotextiles or geonets, on top of a liner. An evaluation of these issues can affect the choice of geomembrane material, polymer type, fabric reinforcement, thickness, and texture necessary to achieve the design requirements. Interface strengths can be significantly improved by using textured geomembranes.

What issues should be considered in the construction of a geomembrane liner?

When preparing to construct a geomembrane liner, you should plan appropriate shipment and handling procedures, perform testing prior to construction, prepare the subgrade, consider temperature effects, and account for wind effects. In addition, you should select a seaming process, determine a material for and method of backfilling, and plan for testing during construction.

Shipment, Handling, and Site Storage

You should follow quality assurance and quality control procedures to ensure proper handling of geomembranes. Different types of geomembrane liners require different types of packaging for shipment and storage. Typically a geomembrane manufacturer will provide specific instructions outlining the

[7] ASTM D-5747, Practice for Tests to Evaluate the Chemical Resistance of Geomembranes to Liquids.

handling, storage, and construction specifications for a product. In general, HDPE and LLDPE geomembrane liners are packaged in a roll form, while PVC and CSPE-R liners (CSPE-R refers to a CSPE geomembrane liner reinforced with a fabric layer) are packaged in panels, accordion-folded in two directions, and placed onto pallets. Whether the liner is shipped in rolls or panels, you should provide for proper storage. The rolls and panels should be packaged so that fork lifts or other equipment can safely transport them. For rolls, this involves preparing the roll to have a sufficient inside diameter so that a fork lift with a long rod, known as a stinger, can be used for lifting and moving. For accordion panels, proper packaging involves using a structurally-sound pallet, wrapping panels in treated cardboard or plastic wrapping to protect against ultraviolet exposure, and using banding straps with appropriate cushioning. Once the liners have been transported to the site, the rolls or panels can be stored until the subgrade or subbase (either natural soils or another geosynthetic) is prepared.

Subgrade Preparation

Before a geomembrane liner is installed, you should prepare the subgrade or subbase. The subgrade material should meet specified grading, moisture content, and density requirements. In the case of a soil subgrade, it is important to prevent construction equipment used to place the liner from deforming the underlying materials. If the underlying materials are geosynthetics, such as geonets or geotextiles, you should remove all folds and wrinkles before the liner is placed. For further information on geomembrane placement, see Chapter 3 of EPA's *Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities* (U.S. EPA, 1993c).

Testing Prior to Construction

Before any construction begins, is it recommended that you test both the geomembrane materials from the manufacturer and the installation procedures. Acceptance and conformance testing is used to evaluate the performance of the manufactured geomembranes. Constructing test strips can help evaluate how well the intended construction process and quality control procedures will work.

Acceptance and conformance testing. You should perform acceptance and conformance testing on the geomembrane liner received from the manufacturer to determine whether the materials meet the specifications requested. While the specific ASTM test methods vary depending on geomembrane type, recommended acceptance and conformance testing for geomembranes includes evaluations of thickness, tensile strength and elongation, and puncture and tear resistance testing, as appropriate. For most geomembrane liner types, the recommended ASTM method for testing thickness is ASTM D-5199.[8] For measuring the thickness of textured geomembranes, you should use ASTM D-5994.[9] For tensile strength and elongation, ASTM D-638 is recommended for the HDPE and LLDPE sheets, while ASTM D-882 and ASTM D-751 are recommended for PVC and CSPE geomembranes, respectively.[10] Puncture resistance testing is typically recommended for HDPE and LLDPE geomembranes using ASTM D-4833.[11] To evaluate tear resistance for HDPE, LLDPE, and PVC geomembrane

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[8] ASTM D-5199, Standard Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes.

[9] ASTM D-5994, Measuring Core Thickness of Textured Geomembranes.

[10] ASTM D-638, Standard Test Method for Tensile Properties of Plastics.
ASTM D-882, Standard Test Methods for Tensile Properties of Thin Plastic Sheeting.
ASTM D-751, Standard Test Methods for Coated Fabrics.

[11] ASTM D-4833, Standard Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products.

liners, the recommended testing method is ASTM D-1004, Die C.[12] For CSPE-R geomembranes, ply adhesion is more of a concern than tear or puncture resistance and can be evaluated using ASTM D-413, Machine Method, Type A.[13]

Test strips. In preparation for liner placement and field seaming, you should develop test strips and trial seams as part of the construction process. Construction of such samples should be performed in a manner that reproduces all aspects of field production. Providing an opportunity to test seaming methods and workmanship helps ensure that the quality of the seams remains constant and meets specifications throughout the entire seaming process.

Temperature Effects

Liner material properties can be altered by extreme temperatures. High temperatures can cause geomembrane liner surfaces to stick together, a process commonly referred to as blocking. On the other hand, low temperature can cause the liner to crack when unrolled or unfolded. Recommended maximum and minimum allowable sheet temperatures for unrolling or unfolding geomembrane liners are 50°C (122°F) and 0°C (32°F), respectively. In addition to sticking and cracking, extreme temperatures can cause geomembranes to contract or expand. Polyethylene geomembranes expand when heated and contract when cooled. Other geomembranes can contract slightly when heated. Those responsible for placing the liner should take temperature effects into account as they place, seam, and backfill in the field.

Wind Effects

It is recommended that you take measures to protect geomembrane liners from wind damage. Windy conditions can increase the potential for tearing as a result of uplift. If wind uplift is a potential problem, panels can be weighted down with sand bags.

Seaming Processes

Once panels or rolls have been placed, another critical step involves field-seaming the separate panels or rolls together. The selected seaming process, such as thermal or chemical seaming, will depend on the chemical composition of the liner. To ensure the integrity of the seam, you should use the seaming method recommended by the manufacturer. Thermal seaming uses heat to bond together the geomembrane panels. Examples of thermal seaming processes include extrusion welding and thermal fusion (or melt bonding). Chemical seaming involves the use of solvents, cement, or an adhesive. Chemical seaming processes include chemical fusion and adhesive seaming. For more information on seaming methods, *Technical Guidance Document: Inspection Techniques for the Fabrication of Geomembrane Field Seams* (U.S. EPA, 1991c), contains a full chapter on each of the traditional seaming methods and additional discussion of emerging techniques, such as ultrasonic, electrical conduction, and magnetic energy source methods.

Consistent quality in fabricating field seams is paramount to liner performance. Conditions that could affect seaming should be monitored and controlled during installation. Factors influencing seam construction and performance include: ambient temperature, relative humidity, wind uplift, changes in geomembrane temperature, subsurface water content, type of supporting surface used, skill of the seaming crew, quality and consistency of chemical or welding materials, preparation of liner surfaces to be joined, moisture at the seam interface, and cleanliness of the seam interface.

[12] ASTM D-1004, Standard Test Method for Initial Tear Resistance of Plastic Film and Sheeting.

[13] ASTM D-413, Standard Test Methods for Rubber Property-Adhesion to Flexible Substrate.

To help control some of these factors, no more than the amount of sheeting that can be used during a shift or a work day should be deployed at one time. To prevent erosion of the underlying soil surface or washout of the geomembrane, proper storm water control measures should be employed. Ambient temperature can become a concern, if the geomembrane liner has a high percentage of carbon black. Although the carbon black will help to prevent damage resulting from ultraviolet radiation, because its dark color absorbs heat, it can increase the ambient temperature of the geomembrane, making installation more complicated. To avoid surface moisture or high subsurface water content, geomembranes should not be deployed when the subgrade is wet.

Regardless of how well a geomembrane liner is designed, its ability to meet performance standards depends on proper quality assurance and quality control during installation. Geomembrane sheets and seams are subject to tearing and puncture during installation; punctures or tears can result from contact with jagged edges or underlying materials or by applying stresses greater than the geomembrane sheet can handle. Proper quality assurance and quality control can help minimize the occurrence of pinhole or seam leaks. For example, properly preparing the underlying layer and ensuring that the gravel is of an acceptable size reduces the potential for punctures.

Protection and Backfilling

Geomembrane liners that can be damaged by exposure to weather or work activities should be covered with a layer of soil or a geosynthetic as soon as possible after quality assurance activities associated with geomembrane testing are completed. If the backfill layer is a soil material, it will typically be a drainage material like sand or gravel. If the cover layer is a geosynthetic, it will typically be a geonet or geocomposite drain placed directly over the geomembrane. Careful placement of backfill materials is critical to avoid puncturing or tearing the geomembrane material.

For soil covers, three considerations determine the amount of slack to be placed in the underlying geomembrane. These considerations include selecting the appropriate type of soil, using the proper type of equipment, and establishing a placement procedure for the soil. When selecting a soil for backfilling, characteristics to consider include particle size, hardness, and angularity, as each of these can affect the potential for tearing or puncturing the liner. To prevent wrinkling, soil covers should be placed over the geomembrane in such a way that construction vehicles do not drive directly on the liner. Care should be taken not to push heavy loads of soil over the geomembrane in a continuous manner. Forward pushing can cause localized wrinkles to develop and overturn in the direction of movement. Overturned wrinkles create sharp creases and localized stress in the liner and can lead to premature failure. A recommended method for placing soil involves continually placing small amounts of soil or drainage material and working outward over the toe of the previously placed material.

Another recommended method involves placing soil over the liner with a large backhoe and spreading it with a bulldozer or similar equipment. If a predetermined amount of slack is to be placed in the geomembrane, the temperature of the liner becomes an important factor, as it will effect the ability of the liner to contract and expand. Although the recommended methods for covering geomembrane liners with soil can take more time than backfilling with larger amounts of soil, these methods are designed to prevent damage caused by covering the liner with too much soil too quickly. In the long run, preventing premature liner failure can be faster and more cost-effective than having to repair a damaged liner.

The types of geosynthetics that are often used as protective covering include geotextiles and geonets. Geogrids and drainage geocomposites can be used for cover soil reinforcement on slopes. The appendix at the end of this chapter provides additional information on geosynthetic materials. For geosynthetic protective covers, as with soil backfilling, to prevent tearing or puncturing, most construction vehicles should not be permitted to move directly on the geomembrane. Some possible exceptions include small, 4-wheel, all terrain vehicles or other types of low ground pressure equipment. Even with these types of vehicles, drivers should take extreme care to avoid movements, such as sudden starts, stops, and turns, which can damage the geomembrane. Seaming-related equipment should be allowed on the geomembrane liner, as long as it does not damage the liner. Geosynthetic materials are placed directly on the liner and are not bonded to it.

Testing During Construction

Testing during construction enables assessment of the integrity of the seams connecting the geomembrane panels. Tests performed on the geomembrane seams are categorized as either destructive or nondestructive.

Destructive testing. Destructive testing refers to removing a sample from the liner seam or sheet and performing tests on the sample. For liner seams, destructive testing includes shear testing and peel testing; for liner sheets, it involves tensile testing. While quality control procedures often require destructive testing prior to construction, in order to ensure that the installed seams and sheets meet performance standards, destructive testing should be performed during construction also. For increased quality assurance, it is recommended that peel and shear tests on samples from the installed geomembrane be performed by an independent laboratory. Testing methods for shear testing, peel testing, and tensile testing vary for different geomembrane liner types.

Determining the number of samples to take is a difficult step. Taking too few samples results in a poor statistical representation of the geomembrane quality. On the other hand, taking too many samples requires additional costs and increases the potential for defects. Defects can result from the repair patches used to cover the areas from which samples were taken.

A common sampling strategy is “fixed increment sampling” where samples are taken at a fixed increment along the length of the geomembrane. Increments range from 80 to 300 m (250 to 1,000 ft). The type of welding, such as extrusion or fusion welding, used to connect the seams and the type of geomembrane liner can also help determine the appropriate sampling interval. For example, extrusion seams on HDPE require grinding prior to welding and if extensive grinding occurs, the strength of the HDPE might decrease. In such cases, sampling at closer intervals, such as 90 to 120 m (300 to 400 ft), might provide a more accurate description of material properties. If the seam is a dual hot edge seam, both the inner and outer seams might need to be sampled and tested.

If test results for the seam or sheet samples do not meet the acceptance criteria for the destructive tests, you should continue testing the area surrounding the rejected sample to determine the limits of the low quality seam. Once the area of low quality has been identified, then corrective measures, such as seaming a cap over the length of the seam or reseaming the affected area, might be necessary.

Nondestructive testing. Unlike destructive tests, which examine samples taken from the geomembrane liner in the containment area, nondestructive tests are designed to evaluate the integrity of larger portions of geomembrane seams without removing pieces of the geomembrane for testing. Common nondestructive testing methods include: the probe test, air lance, vacuum box, ultrasonic methods (pulse echo, shadow, and impedance planes), electrical spark test, pressurized dual seam, and electrical resistivity. You should select the test method most appropriate for the material and seaming method. If sections of a seam fail to meet the acceptable criteria of the appropriate nondestructive test, then those sections need to be delineated and patched, reseamed, or retested. If repairing such sections results in large patches or areas of reseaming, then destructive test methods are recommended to verify the integrity of such pieces.

C. Geosynthetic Clay Liners

If a risk evaluation recommended the use of a single liner, another option to consider is a geosynthetic clay liner (GCL). GCLs are factory-manufactured, hydraulic barriers typically consisting of bentonite clay (or other very low permeability materials), supported by geotextiles or geomembranes held together by needling, stitching, or chemical adhesives. GCLs can be used to augment or replace compacted clay liners or geomembranes, or they can be used in a composite manner to augment the more traditional compacted clay or geomembrane materials. GCLs are typically used in areas where clay is not readily available or where conserving air space is an important factor. As GCLs do not have the level of long-term field performance data that geomembranes or compacted clay liners do, states might request a demonstration that performance of the GCL design will be comparable to that of compacted clay or geomembrane liners.

What are the mass per unit area and hydraulic conductivity recommendations for geosynthetic clay liners?

Geosynthetic clay liners are often designed to perform the same function as compacted clay and geomembrane liner components. For geosynthetic clay liners, you should design for a minimum of 3.7 kg/m^2 (0.75 lb/ft^2) dry weight (oven dried at 105°C) of bentonite clay with a hydrated hydraulic conductivity of no more than 5 x 10^{-9} cm/sec (2 x 10^{-9} in/sec). It is important to follow manufacturer specifications for proper GCL installation.

What issues should be considered in the design of a geosynthetic clay liner?

Factors to consider in GCL design are the specific material properties needed for the liner and the chemical interaction or compatibility of the waste with the GCL. When considering material properties, it is important to keep in mind that bentonite has a low shear strength when it is hydrated. Manufacturers have developed products designed to increase shear strength.

Materials Selection and Properties

For an effective GCL design, material properties should be clearly defined in the specifications used during both manufacture and construction. The properties that should be specified include: type of bonds, thickness, moisture content, mass per unit area, shear strength, and tensile strength. Each of these properties is described below.

Type of bonds. Geosynthetic clay liners are available with a variety of bonding designs, which include a combination of clay, adhesives, and geomembranes or geotextiles. The type of adhesives, geotextiles, and geomembranes used as components of GCLs varies widely. One type of available GCL design uses a bentonite clay mixed with an adhesive bound on each side by geotextiles. A variation on this design involves stitching the upper and lower geotextiles together through the clay layer. Alternatively, another option is to use a GCL where geotextiles on each side of adhesive or nonadhesive bentonite clay are connected by needle punching. A fourth variation uses a clay mixed with an adhesive bound to a geomembrane on one side; the geomembrane can be either the lower or the upper surface. Figure 3 displays cross section sketches of the four variations of GCL bonds. While these options describe GCLs available at the time of this Guide, emerging technologies in GCL designs should also be reviewed and considered.

Thickness. The thickness of the various available GCL products ranges from 4 to 6 mm (160 to 320 mil). Thickness measurements are product dependent. Some GCLs can be quality controlled for thickness while others cannot.

Moisture content. GCLs are delivered to the job site at moisture contents ranging from 5 to 23 percent, referred to as the "dry" state. GCLs are delivered dry to prevent premature hydration, which can cause unwanted variations in the thickness of the clay component as a result of uneven swelling.

Stability and shear strength. GCLs should be manufactured and selected to meet the shear strength requirements specified in design plans. In this context, shear strength is the ability of two layers to resist forces moving them in opposite directions. Since hydrated bentonite clay has low shear strength, bentonite clay can be placed between geotextiles and stitch bonded or needle- punched to provide additional stability. For example, a GCL with geotextiles supported by stitch bonding has greater internal resistance to shear in the clay layer than a GCL without any stitching. Needle-punched GCLs tend to provide greater resistance than stitch-bonded GCLs and can also provide increased friction resistance against an adjoining layer, because they require the use of nonwoven geotextiles. Increased friction is an important consideration on side slopes.

Mass per unit area. Mass per unit area refers to the bentonite content of a GCL. It is important to distribute bentonite evenly throughout the GCL in order to meet desired hydraulic conductivity specifications. All GCL products available in North America use a sodium bentonite clay with a mass per unit area ranging from 3.2 to 6.0 kg/m^2 (0.66 to 1.2 lb/ft^2), as manufactured.

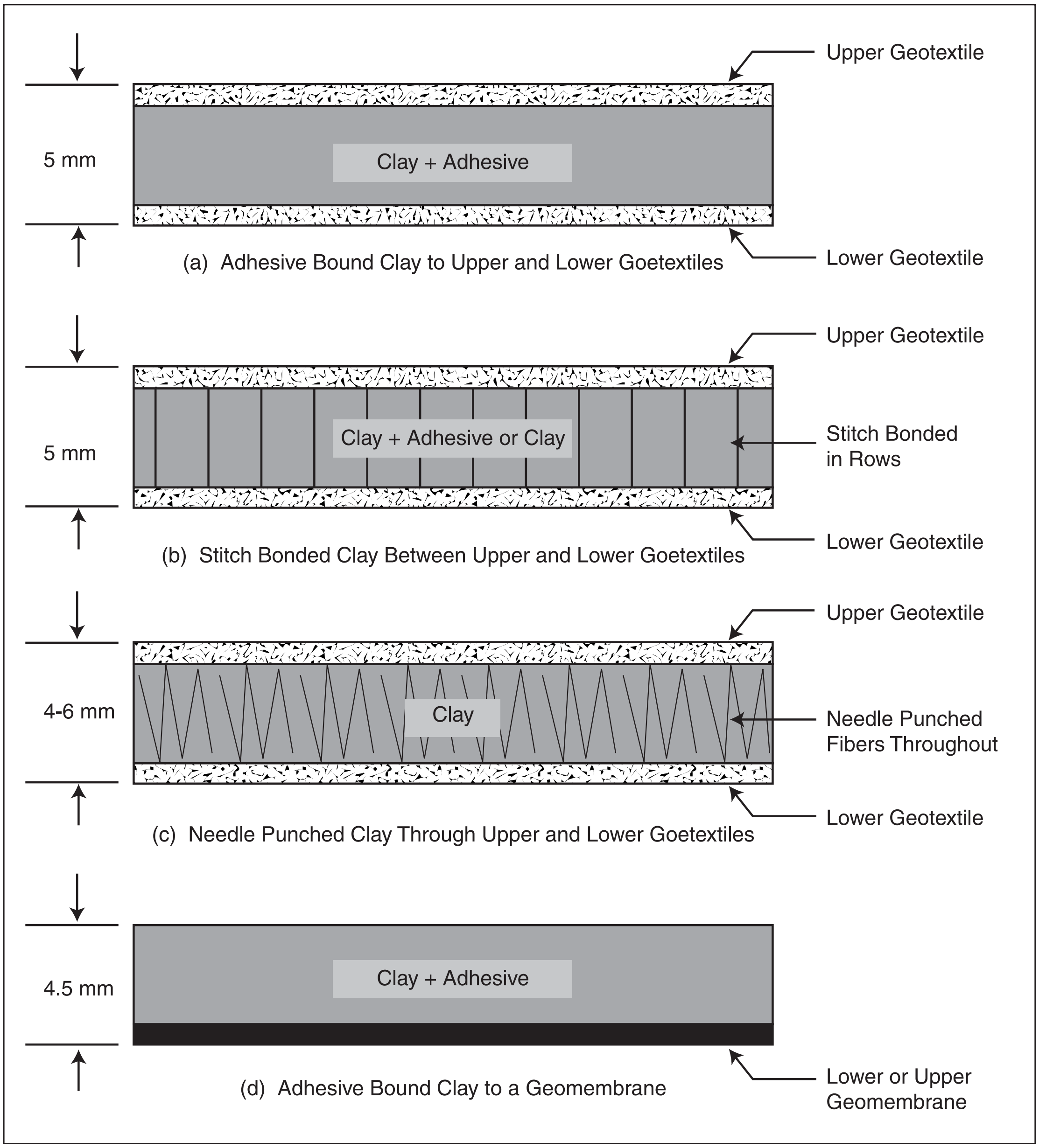
Interaction With Waste

During the selection process for a GCL liner, you should evaluate the chemical compatibility of the liner materials with the types of waste that are expected to be placed in the unit. Certain chemicals, such as calcium, can have an adverse effect on GCLs, resulting in a loss of liner integrity. Specific information on GCL compatibilities should be available from the manufacturer.

What issues should be considered in the construction of a geosynthetic clay liner?

Prior to and during construction, it is recommended that a qualified professional should prepare construction specifications for the GCL. In these specifications, procedures for shipping and storing materials, as well as performing acceptance testing on delivered

Figure 3
Four Variations of GCL Bonding Methods



Source: U.S. EPA, 1993c.

materials, should be identified. The specifications should also address methods for subgrade preparation, joining panels, repairing sections, and protective backfilling.

Shipment, Handling, and Site Storage

GCLs are manufactured in widths of approximately 2 to 5 m (7 to 17 ft) and lengths of 30 to 60 m (100 to 200 ft). Directly after manufacturing, GCLs are rolled around a core and covered with a thin plastic protective covering. This waterproof covering serves to protect the material from premature hydration. GCLs should be stored at the factory with these protective coverings. Typical storage lengths range from a few days to 6 months. To ensure protection of the plastic covering and the rolls themselves during loading and unloading, it is recommended that qualified professionals specify the equipment needed at the site to lift and deploy the rolls properly.

To reduce the potential for accidental damage or for GCLs to absorb moisture at the site, you should try to arrange for "just-in-time-delivery" for GCLs transported from the factory to the field. Even with "just-in-time-delivery," it might be necessary to store GCLs for short periods of time at the site. Often the rolls can be delivered in trailers, which can then serve as temporary storage. To help protect the GCLs prior to deployment, you should use wooden pallets to keep the rolls off the ground, placing heavy, waterproof tarps over the GCL rolls to protect them from precipitation, and using sandbags to help keep the tarps in place.

Manufacturer specifications should also indicate how high rolls of GCLs can be stacked horizontally during storage. Overstacking can cause compression of the core around which the GCL is wrapped. A damaged core makes deployment more difficult and can lead to other problems. For example, rolls are sometimes handled by a fork lift with a stinger attached. The stinger is a long tapered rod that fits inside the core. If the core is crushed, the stinger can damage the liner during deployment.

Acceptance and Conformance Testing

Acceptance and conformance testing is recommended either upon delivery of the GCL rolls or at the manufacturer's facility prior to delivery. Conformance test samples are used to ensure that the GCL meets the project plans and specifications. GCLs should be rewrapped and replaced in dry storage areas immediately after test samples are removed. Liner specifications should prescribe sampling frequencies based on either total area or on number of rolls. Since variability in GCLs can exist between individual rolls, it is important for acceptance and conformance testing to account for this. Conformance testing can include the following.

Mass per unit area test. The purpose of evaluating mass per unit area is to ensure an even distribution of bentonite throughout the GCL panel. Although mass per unit area varies from manufacturer to manufacturer, a typical minimum value for oven dry weight is 3.7 kg/m^2 (0.75 lb/ft^2). Mass per unit area should be tested using ASTM D-5993.[14] This test measures the mass of bentonite per unit area of GCL. Sampling frequencies should be determined using ASTM D- 4354.[15]

Free swell test. Free swell refers to the ability of the clay to absorb liquid. Either ASTM D-5890 or GRI-GCL1, a test method developed by the Geosynthetic Research Institute, can be used to evaluate the free swell of the material.[16]

[14] ASTM D-5993, Standard Test Method for Measuring Mass per Unit Area of Geosynthetic Clay Liners.

[15] ASTM D-4354, Standard Practice for Sampling of Geosynthetics for Testing.

[16] ASTM D-5890, Test Method for Swell Index of Clay Mineral Components of Geosynthetic Clay Liners. GRI-GCL1, Swell Measurement of the Clay Component of Geosynthetic Clay Liners.

Direct shear test. Shear strength of the GCLs can be evaluated using ASTM D-5321.[17] The sampling frequency for this performance-oriented test is often based on area, such as one test per 10,000 m^2 (100,000 ft^2).

Hydraulic conductivity test. Either ASTM D-5084 (modified) or GRI-GCL2 will measure the ease with which liquids can move through the GCL.[18]

Other tests. Testing of any geotextiles or geomembranes should be made on the original rolls of the geotextiles or geomembranes and before they are fabricated into the GCL product. Once these materials have been made part of the GCL product, their properties can change as a result of any needling, stitching, or gluing. Additionally, any peel tests performed on needle punched or stitch bonded GCLs should use the modified ASTM D-413 with a recommended sampling frequency of one test per 2,000 m^2 (20,000 ft^2).[19]

Subgrade Preparation

Because the GCL layer is relatively thin, the first foot of soil underlying the GCL should have a hydraulic conductivity of 1×10^{-5} cm/sec or less. Proper subgrade preparation is essential to prevent damage to the GCL layer as it is installed. This includes clearing away any roots or large particles that could potentially puncture the GCL and its geotextile or geomembrane components. The soil subgrade should be of the specified grading, moisture content, and density required by the installer and approved by a construction quality assurance engineer for placement of the GCL. Construction equipment deploying the rolls should not deform or rut the soil subgrade excessively. To help ensure this, the soil subgrade should be smooth rolled with a smooth-wheel roller and maintained in a smooth condition prior to deployment.

Joining Panels

GCLs are typically joined by overlapping panels, without sewing or mechanically connecting pieces together. To ensure proper joints, you should specify minimum and maximum overlap distances. Typical overlap distances range from 150 to 300 mm (6 to 12 in.). For some GCLs, such as needle punched GCLs with nonwoven geotextiles, it might be necessary to place bentonite on the area of overlap. If this is necessary, you should take steps to prevent fugitive bentonite particles from coming into contact with the leachate collection system, as they can cause physical clogging.

Repair of Sections Damaged During Liner Placement

During installation, GCLs might incur some damage to either the clay component or to any geotextiles or geomembranes. For damage to geotextile or geomembrane components, repairs include patching using geotextile or geomembrane materials. If the clay component is disturbed, a patch made from the same GCL product should be used to perform any repairs.

Protective Backfilling

As soon as possible after completion of quality assurance and quality control activities, you should cover GCLs with either a soil layer or a geosynthetic layer to prevent hydration. The soil layer can be a compacted clay liner or a layer of coarse drainage material. The geosynthetic layer is typically a

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[17] ASTM D-5321, Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method.

[18] ASTM D-5084, Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.
GRI-GCL2, Permeability of Geosynthetic Clay Liners (GCLs).

[19] ASTM D-413, Standard Test Methods for Rubber Property-Adhesion to Flexible Substrate.

geomembrane; however, depending on site-specific designs, it can be a geotextile. As noted earlier, premature hydration before covering can lead to uneven swelling, resulting in a GCL with varied thickness. Therefore, a GCL should be covered with its subsequent soil or geosynthetic layer before a rainfall or snowfall occurs. Premature hydration is less of a concern for GCLs, where the geosynthetic components are needle punched or stitch bonded, because these types of connections can better limit clay expansion.

III. Composite Liners

A composite liner consists of both a geomembrane liner and natural soil. The geomembrane forms the upper component with the natural soil being the lower component. The ususal variations are:

- Geomembrane over compacted clay liner (GM/CCL).
- Geomembrane over geosynthetic clay liner (GM/GCL).
- Geomembrane over geosynthetic clay liner over compacted clay liner (GM/GCL/CCL).

A composite liner provides an effective hydraulic barrier by combining the complementary properties of the two different liners into one system. The geomembrane provides a highly impermeable layer to maximize leachate collection and removal. The natural soil liner serves as a backup in the event of any leakage from the geomembrane. With a composite liner design, you should construct a leachate collection and removal system above the geomembrane. Information on design and construction of leachate collection and removal systems is provided in Section V below.

What are the thickness and hydraulic conductivity recommendations for composite liners?

Each component of the composite liner should follow the recommendations for geomembranes, geosynthetic clay liners, and compacted clay liners described earlier. Geomembrane liners should have a minimum thickness of 30 mil, except for HDPE liners, which should have a minimum thickness of 60 mil. Similarly, compacted clay liners should be at least 2 feet thick and are typically 2 to 5 feet thick. For compacted clay liners and geosynthetic clay liners, you should use materials with maximum hydraulic conductivities of 1×10^{-7} cm/sec (4×10^{-8} in/sec) and 5×10^{-9} cm/sec (2×10^{-9} in/sec), respectively.

What issues should be considered in the design of a composite liner?

As a starting point, you should follow the design considerations discussed previously for single liners. In addition, to achieve the benefits of a combined liner system, you should install the geomembrane to ensure good contact with the compacted clay layer. The uniformity of contact between the geomembrane and the compacted clay layer helps control the flow of leachate. Porous material, such as drainage sand or a geonet, should not be placed between the geomembrane and the clay layer. Porous materials will create a layer of higher hydraulic conductivity, which will increase the amount of leakage below any geomembrane imperfection.

You should consider the friction or shear strength between a compacted clay layer and a geomembrane. The friction or shear stress at this surface is often low and can form a weak plane on which sliding can occur.

ASTM D-5321 provides a test method for determining the friction coefficient of soil and geomembranes.[20] When using bentonite-amended soils, it is important to account for how the percentage of bentonite added and the degree of saturation affect interface friction. To provide for stable slopes, it is important to control both the bentonite and moisture contents. A textured geomembrane can increase the friction with the clay layer and improve stability.

What issues should be considered in the construction of a composite liner?

To achieve good composite bonding, the geomembrane and the compacted clay layer should have good hydraulic contact. To improve good contact, you should smooth-roll the surface of the compacted clay layer using a smooth, steel-drummed roller and remove any stones. In addition, you should place and backfill the geomembrane so as to minimize wrinkles.

The placement of geomembranes onto a compacted clay layer poses a challenge, because workers cannot drive heavy machines over the clay surface without potentially damaging the compacted clay component. Even inappropriate footwear can leave imprints in the clay layer. It might be possible to drive some types of low ground pressure equipment or small, 4-wheel, all terrain vehicles over the clay surface, but drivers should take extreme care to avoid movements, such as sudden starts, stops, and turns, that could damage the surface. To avoid damaging the clay layer, it is recommended that you unroll geomembranes by lifting the rolls onto jacks at a cell side and pulling down on the geomembrane manually. Also, the entire roll with its core can be unrolled onto the cell (with auxiliary support using ropes on embankments).

To minimize desiccation of the compacted clay layer, you should place the geomembrane over the clay layer as soon as possible. Additional cover materials should also be placed over the geomembrane. Exposed geomembranes absorb heat, and high temperatures can dry out and crack an underlying compacted clay layer. Daily cyclic changes in temperature can draw water from the clay layer and cause this water to condense on the underside of the geomembrane. This withdrawal of water can lead to desiccation cracking and potential interface stability concerns.

IV. Double Liners (Primary and Secondary Lined Systems)

In a double-lined waste management unit, there are two distinct liners—one primary (top) liner and one secondary (bottom) liner. Each liner might consist of compacted clay, a geomembrane, or a composite (consisting of a geomembrane and a compacted clay layer or GCL). Above the primary liner, it is recommended that you construct a leachate collection and removal system to collect and convey liquids out of the waste management unit and to control the depth of liquids above the primary liner. In addition, you should place a leak detection, collection, and removal system between the primary and secondary liner. This leak detection system will provide leak warning, as well as collect and remove any liquid or leachate that has escaped the primary liner. See section V below for information on the design of leachate collection and removal systems and leak detection, collection, and removal systems.

[20] ASTM D-5321, Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method.

What are the thickness and hydraulic conductivity recommendations for double liners?

Each component of the double liner should follow the recommendations for geomembranes, compacted clay liners, or composite liners described earlier. Geomembrane liners should have a minimum thickness of 30 mil, except for HDPE liners, which should have a minimum thickness of 60 mil. Similarly, compacted clay liners should be at least 2 feet thick and are typically 2 to 5 feet thick. For compacted clay liners and geosynthetic clay liners, use materials with maximum hydraulic conductivities of 1 x 10^{-7} cm/sec (4 x 10^{-8} in/sec) and 5 x 10^{-9} cm/sec (2 x 10^{-9} in/sec), respectively.

What issues should be considered in the design and construction of a double liner?

Like composite liners, double liners are composed of a combination of single liners. When planning to design and construct a double liner, you should consult the sections on composite and single liners first. In addition, you should consult the sections on leachate collection and removal systems and leak detection systems.

V. Leachate Collection and Leak Detection Systems

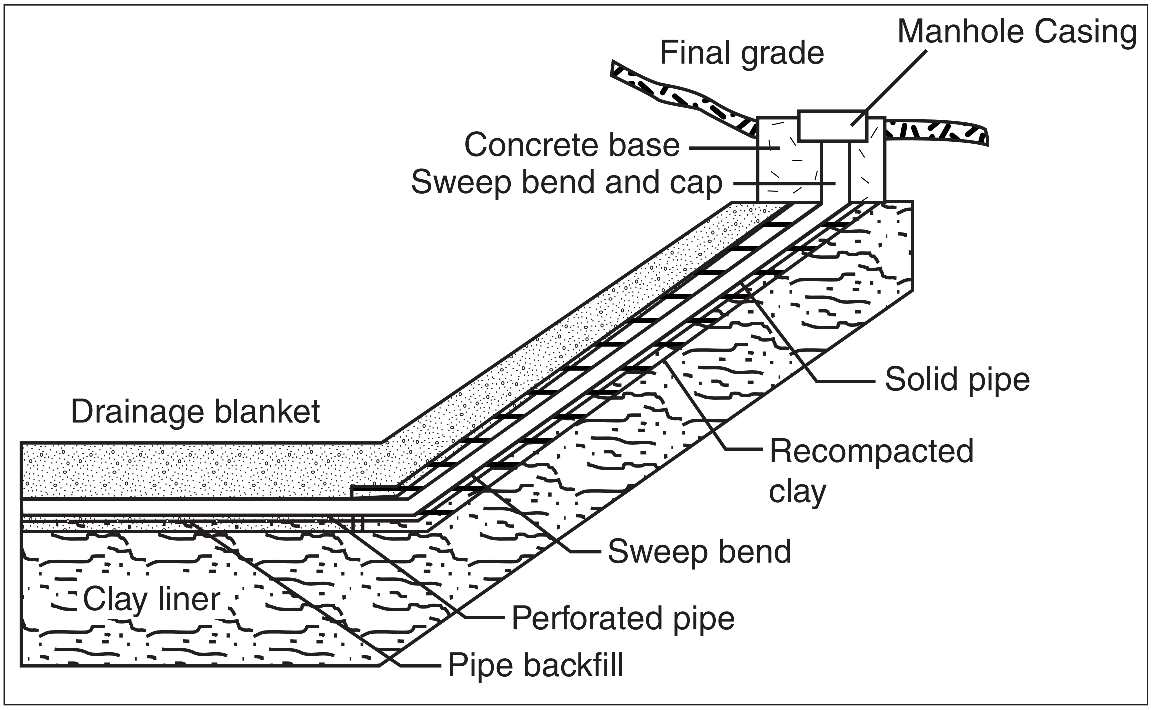
One of the most important functions of a waste management unit is controlling leachate and preventing contamination of the underlying ground water. Both leachate collection and removal systems and leak detection systems serve this purpose. You should consult with the state agency too determine if such systems are required. The primary function of a leachate collection and removal system is to collect and convey leachate out of a unit and to control the depth of leachate above a liner. The primary function of a leak detection system is to detect leachate that has escaped the primary liner. A leak detection system refers to drainage material located below the primary liner and above a secondary liner (if there is one); it acts as a secondary leachate collection and removal system. After the leachate has been removed and collected, a leachate treatment system might be incorporated to process the leachate and remove harmful constituents.

The information in this section on leachate collection and leak detection systems is applicable if the unit is a landfill or a waste pile. Surface impoundments, which manage liquid wastes, usually will not have leachate collection and removal systems unless they will be closed in-place as landfills; they might have leak detection systems to detect liquid wastes that have escaped the primary liner. Leachate collection or leak detection systems generally are not used with land application.

A. Leachate Collection System

A typical leachate collection system includes a drainage layer, collection pipes, a removal system, and a protective filter layer. Leachate collection systems are designed to collect leachate for treatment or alternate disposal and to reduce the buildup of leachate above the liner system. Figure 4 shows a cross section of a typical leachate collection system showing access to pipes for cleaning.

Figure 4
Typical Leachate Collection System



Source: U.S. EPA, 1995b

What are the recommendations for leachate collection and removal systems?

You should design a leachate collection and removal system to maintain less than 30 cm (12 in.) depth of leachate, or "head," above the liner if granular soil or a geosynthetic material is used. The reason for maintaining this level is to prevent excessive leachate from building up above the liner, which could jeopardize the liner's performance. This should be the underlying factor guiding the design, construction, and operation of the leachate collection and removal system.

You should design a leachate collection and removal system capable of controlling the estimated volume of leachate. To determine potential leachate generation, you should use water balance equations or models. The most commonly used method to estimate leachate generation is EPA's Hydrogeologic Evaluation of Landfill Performance (HELP) model.[21] This model uses weather, soil, and waste management unit design data to determine leachate generation rates.

What issues should be considered in the design of a leachate collection and removal system?

You should design a leachate collection and removal system to include the following elements: a low-permeability base, a high-permeability drainage layer, perforated leachate collection pipes, a protective filter layer, and a leachate removal system. During

[21] Available on the CD-ROM version of the Guide, as well as from the U.S. Army Corps of Engineers Web site **<www.wes.army.mil/el/elmodels/index.html#landfill>**

design, you should consider the stability of the base, the transmissivity of the drainage layers, and the strength of the collection pipes. It is also prudent to consider methods to minimize physical, biological, and chemical clogging within the system.

Low-Permeability Base

A leachate collection system is placed over the unit's liner system. The bottom liner should have a minimum slope of 2 percent to allow the leachate collection system to gravity flow to a collection sump. This grade is necessary to provide proper leachate drainage throughout the operation, closure, and post-closure of the unit. Estimates of foundation soil settlement should include this 2 percent grade as a post-settlement design.

High-Permeability Drainage Layer

A high-permeability drainage layer consists of drainage materials placed directly over the low-permeability base, at the same minimum 2 percent grade. The drainage materials can be either granular soil or geosynthetic materials. For soil drainage materials, a maximum of 12 inches of materials with a hydraulic conductivity of at least 1 x 10^{-2} cm/sec (4 x 10^{-3} in/sec) is recommended. For this reason, sand and gravel are the most common soil materials used. If the drainage layer is going to incorporate sand or gravel, it should be demonstrated that the layer will have sufficient bearing capacity to withstand the waste load of the full unit. Additionally, if the waste management unit is designed on grades of 15 percent or higher, it should be demonstrated that the soil drainage materials will be stable on the steepest slope in the design.

Geosynthetic drainage materials such as geonets can be used in addition to, or in place of, soil materials. Geonets promote rapid transmission of liquids and are most effective when used in conjunction with a filter layer or geotextile to prevent clogging. Geonets consist of integrally connected parallel sets of plastic ribs overlying similar sets at various angles. Geonets are often used on the side walls of waste management units because of their ease of installation. Figure 5 depicts a typical geonet material configuration.

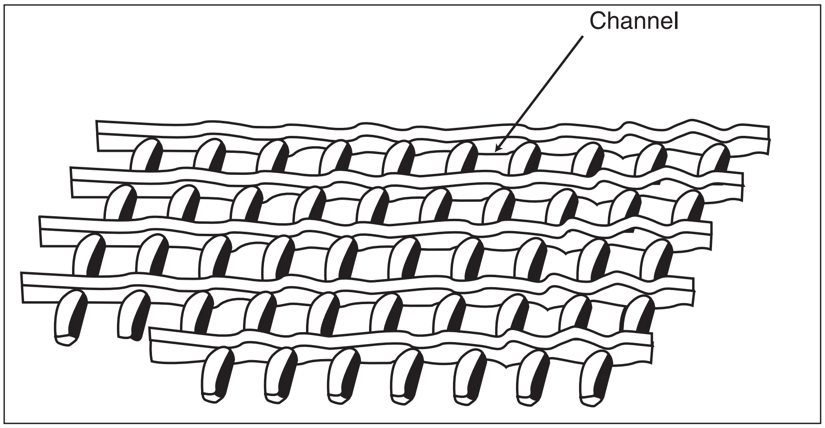
The most critical factor involved with using geonets in a high-permeability drainage layer is the material's ability to transmit fluids under load. The flow rate of a geonet can be evaluated by ASTM D-4716.[22] Several additional measures for determining the transmissivity of geonets are discussed in the *Solid Waste Disposal Facility Criteria: Technical Manual* (U.S. EPA, 1993b).

Perforated Leachate Collection Pipes

Whenever the leachate collection system is a natural soil, a perforated piping system should be located within it to rapidly transmit the leachate to a sump and removal system. Through the piping system, leachate flows gravitationally to a low point where the sump and removal system is located. The design of perforated leachate collection pipes, therefore, should consider necessary flow rates, pipe sizing, and pipe structural strength. After estimating the amount of leachate using the HELP model or a similar water balance model, it is possible to calculate the appropriate pipe diameter and spacing. For the leachate collection system design, you should select piping material that can withstand the anticipated weight of the waste, construction and operating equipment stresses, and foundation settling. Most leachate collection pipes used in modern waste management units are constructed of HDPE. HDPE pipes provide great structural strength, while allowing significant chemical resistance to the many constituents found in leachate. PVC pipes are also used in waste

[22] ASTM D-4716, Standard Test Method for Constant Head Hydraulic Transmissivity (In-Plane Flow) of Geotextiles and Geotextile Related Products.

Figure 5
Typical Geonet Configuration



management units, but they are not as chemically resistant as HDPE pipes.

Protective Filter Layer

To protect the drainage layer and perforated leachate collection piping from clogging, you should place a filter layer over the high-permeability drainage layer. To prevent waste material from moving into the drainage layer, the filter layer should consist of a material with smaller pore space than the drainage layer materials or the perforation openings in the collection pipes. Sand and geotextiles are the two most common materials used for filtration. You should select sand that allows adequate flow of liquids, prevents migration of overlying solids or soils into the drainage layer, and minimizes clogging during the service life. In designing the sand filter, you should consider particle size and hydraulic conductivity. The advantages of using sand materials include common usage, traditional design, and durability.

Any evaluation of geotextile materials should address the same concerns but with a few differences. To begin with, the average pore size of the geotextile should be large enough to allow the finer soil particles to pass but small enough to retain larger soil particles. The number of openings in the geotextile should be large enough that, even if some of the openings clog, the remaining openings will be sufficient to pass the design flow rate. In addition to pore size, geotextile filter specifications should include durability requirements. The advantages of geotextile materials include vertical space savings and easy placement. Chapter 5 of *Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities* (U.S. EPA, 1993c) offers guidance on protection of drainage layers.

Leachate Removal System

Leachate removal often involves housing a sump within the leachate collection drainage layer. A sump is a low point in the liner constructed to collect leachate. Modern waste management unit sumps often consist of prefabricated polyethylene structures supported on a steel plate above the liner. Especially with geomembrane liners, the steel plate serves to support the weight of the sump and protect the liner from puncture. Gravel filled earthen depressions can serve as the sump. Reinforced concrete pipe and concrete flooring also can be used in place of the polyethylene structure but are considerably heavier.

To remove leachate that has collected in the sump, you should use a submersible pump. Ideally, the sump should be placed at a depth of 1 to 1.5 m (3 to 5 ft) to allow enough leachate collection to prevent the pump from running dry. You should consider installing a level control, backup pump, and warning system to ensure proper sump operation. Also consider using a backup pump as an alternate to the primary pump and to assist it during high flow periods. A warning system should be used to indicate pump malfunction.

Standpipes, vertical pipes extending through the waste and cover system, offer one method of removing leachate from a sump without puncturing the liner. Alternatively, you can remove leachate from a sump using pipes that are designed to penetrate the liner. When installing pipe penetrations through the liner, you should proceed with extreme caution to prevent any liner damage that could result in uncontained leachate. Both of these options rely on gravity to direct leachate to a leachate collection pond or to an external pumping station.

Minimizing Clogging

Leachate collection and removal systems are susceptible to physical, biological, and chemical clogging. Physical clogging can occur through the migration of finer-grained materials into coarser-grained materials, thus reducing the hydraulic conductivity of the coarser-grained material. Biological clogging can occur through bacterial growth in the system due to the organic and nutrient materials in leachate. Chemical clogging can be caused by chemical precipitates, such as calcium carbonates, causing blockage or cementation of granular drainage material.

Proper selection of drainage and filter materials is essential to minimize clogging in the high-permeability drainage layer. Soil and geotextile filters can be used to minimize physical clogging of both granular drainage material and leachate collection pipes. When placed above granular drainage material, these filters can also double as an operations layer to prevent sharp waste from damaging the liner or leachate collection and removal systems. To minimize chemical and biological clogging for granular drainage material, the best procedure is to keep the interstices of the granular drainage material as open as possible.

The leachate collection pipes are also susceptible to similar clogging. To prevent this, you should incorporate measures into the design to allow for routine pipe cleaning, using either mechanical or hydraulic methods. The cleaning components can include pipes with a 15 cm (6 in) minimum diameter to facilitate cleaning; access located at major pipe intersections or bends to allow for inspections and cleaning; and valves, ports, or other appurtenances to introduce biocides and cleaning solutions. Also, you should check that the design does not include wrapping perforated leachate collection pipes directly with geotextile filters. If the geotextile becomes clogged, it can block flow into the pipe.

B. Leak Detection System

The leak detection system (LDS) is also known as the secondary leachate collection and removal system. It uses the same drainage and collection components as the primary leachate collection and removal system and identifies, collects, and removes any leakage from the primary system. The LDS should be located directly below the primary liner and above the secondary liner.

What are the recommendations for leak detection systems?

The LDS should be designed to assess the adequacy of the primary liner against leachate leakage; it should cover both the bottom and side walls of a waste management unit. The LDS should be designed to collect leakage through the primary layer and transport it to a sump within 24 hours.

The LDS should allow for monitoring and collection of leachate escaping the primary liner system. You should monitor the LDS on a regular basis. If the volume of leachate detected by the LDS appears to be increasing or is significant, you should consider a closer examination to determine possible remediation measures. A good rule of thumb is that if the LDS indicates a seepage level greater than 20 gallons per acre per day, the system might need closer monitoring or remediation.

C. Leachate Treatment System

Once the leachate has been removed from the unit and collected, you should consider taking measures to characterize the leachate in order to ensure proper management. There are several methods of disposal for leachate, and the treatment strategy will vary according to the disposal method chosen. Leachate disposal options include discharging to or pumping and hauling to a publicly owned treatment works or to an onsite treatment system; treating and discharging to the environment; land application; and natural or mechanical evaporation.

When discharging to or pumping and hauling leachate to a publicly owned treatment works, a typical treatment strategy includes pretreatment. Pretreatment could involve equalization, aeration, sedimentation, pH adjustment, or metals removal.[23] If the plan for leachate disposal does not involve a remote treatment facility, pretreatment alone usually is not sufficient.

There are two categories of leachate treatment, biological and physical/chemical. The most common method of biological treatment is activated sludge. Activated sludge is a "suspended-growth process that uses aerobic microorganisms to biodegrade organic contaminants in leachate."[24] Among physical/chemical treatment techniques, the carbon absorption process and reverse osmosis are the two most common methods. Carbon absorption uses carbon to remove dissolved organics from leachate and is very expensive. Reverse osmosis involves feeding leachate into a tubular chamber whose wall acts as a synthetic membrane, allowing water molecules to pass through but not pollutant molecules, thereby separating clean water from waste constituents.

What are the recommendations for leachate treatment systems?

You should review all applicable federal and state regulations and discharge standards to determine which treatment system will ensure long-term compliance and flexibility for the unit. Site-specific factors will also play a fundamental role in determining the proper leachate treatment system. For some facilities, onsite storage and treatment might not be an option due to space constraints. For other facilities, having a nearby, publicly owned treatment works might make pretreatment and discharge to the treatment works an attractive alternative.

VI. Construction Quality Assurance and Quality Control

Even the best unit design will not translate into a structure that is protective of human health and the environment, if the unit is not properly constructed. Manufacturing quality assurance and manufacturing quality control (MQA and MQC) are also important issues for the overall project; however, they are discussed only briefly here since they are primarily the responsibility of a manufacturer. Nonetheless, it is best to select a manufactur-

[23] Arts, Tom. "Alternative Approaches For Leachate Treatment." *World Wastes*.

[24] Ibid.

er who incorporates appropriate quality assurance and quality control (QA and QC) mechanisms as part of the manufacturing process. The remainder of this section provides a general description of the components of a construction quality assurance and construction quality control (CQA and CQC) program for a project. CQA and CQC are critical factors for waste management units. They are not interchangeable, and the distinction between them should be kept in mind when preparing plans. CQA is third party verification of quality, while CQC consists of in-process measures taken by the contractor or installer to maintain quality. You should establish clear protocols for identifying and addressing issues of concern throughout every stage of construction.

What is manufacturing quality assurance?

The desired characteristics of liner materials should be specified in the unit's contract with the manufacturer. The manufacturer should be responsible for certifying that materials delivered conform to those specifications. MQC implemented to ensure such conformance might take the form of process quality control or computer-aided quality control. If requested, the manufacturer should provide information on the MQC measures used, allow unit personnel or engineers to visit the manufacturing facility, and provide liner samples for testing. It is good practice for the manufacturer to have a dedicated individual in charge of MQC who would work with unit personnel in these areas.

What is construction quality assurance?

CQA is a verification tool employed by the facility manager or regulatory agency, consisting of a planned series of observations and tests designed to ensure that the final product meets project specifications. CQA testing, often referred to as acceptance inspection, provides a measure of the final product quality and its conformance with project plans and specifications. Performing acceptance inspections routinely, as portions of the project become complete, allows early detection and correction of deficiencies, before they become large and costly.

On routine construction projects, CQA is normally the concern of the facility manager and is usually performed by an independent, third-party testing firm. The independence of the testing firm is important, particularly when a facility manager has the capacity to perform the CQA activities. Although the

MQC, MQA, CQC, and CQA

Manufacturing quality control (MQC) is measures taken by the manufacturer to ensure compliance with the material and workmanship specifications of the facility manager.

Manufacturer quality assurance (MQA) is measures taken by facility personnel, or by an impartial party brought in expressly for the purpose, to determine if the manufacturer is in compliance with the specifications of the facility manager.

Construction quality control (CQC) is measures taken by the installer or contractor to ensure compliance with the installation specifications of the facility manager.

Construction quality assurance (CQA) is measures taken by facility personnel, or by an impartial party brought in expressly for the purpose, to determine if the installer or contractor is in compliance with the installation specifications of the facility manager.

facility's in-house CQA personnel might be registered professional engineers, a perception of misrepresentation might arise if CQA is not performed by an independent third party.

The independent party should designate a CQA officer and fully disclose any activities or relationships that the officer has with the facility manager that might impact his or her impartiality or objectivity. If such activities or relationships exist, the CQA officer should describe actions that have been or can be taken to avoid, mitigate, or neutralize the possibility they might affect the CQA officer's objectivity. State regulatory representatives can help evaluate whether these mechanisms are sufficient to ensure acceptable CQA.

What is construction quality control?

CQC is an ongoing process of measuring and controlling the characteristics of the product in order to meet manufacturer's or project specifications. CQC inspections are typically performed by the contractor to provide an in-process measure of construction quality and conformance with the project plans and specifications, thereby allowing the contractor to correct the construction process if the quality of the product is not meeting the specifications and plans. Since CQC is a production tool employed by the manufacturer of materials and by the contractor installing the materials at the site, the Guide does not cover CQC in detail. CQC is performed independently of CQA. For example, while a geomembrane liner installer will perform CQC testing of field seams, the CQA program should require independent testing of those same seams by a third-party inspector.

How can implementation of CQA and CQC plans be ensured?

When preparing to design and construct a waste management unit, regardless of design, you should develop CQA and CQC plans customized to the project. To help the project run smoothly, the CQA plan should be easy to follow. You should organize the CQA plan to reflect the sequence of construction and write it in language that will be familiar to an average field technician. For a more detailed discussion of specific CQA and CQC activities recommended for each type of waste management unit, you should consult *Technical Guidance Document: Quality Assurance and Quality Control for Waste Management Containment Facilities* (U.S. EPA, 1993c). This document provides information to develop comprehensive QA plans and to carry out QC procedures at waste management units.

CQA and CQC plans can be implemented through a series of meetings and inspections, which should be documented thoroughly. Communication among all parties involved in design and construction of a waste management unit is essential to ensuring a quality product. You should define responsibility and authority in written QA and QC plans and ensure that each party involved understands its role. Pre-construction meetings are one way to help clarify roles and responsibilities. During construction, meetings can continue to be useful to help resolve misunderstandings and to identify solutions to unanticipated problems that might develop. Some examples of typical meetings during the course of any construction project include pre-bid meetings, resolution meetings, pre-construction meetings, and progress meetings.

A. Compacted Clay Liner Quality Assurance and Quality Control

Although manufacturing quality control and quality assurance are often the responsibility of the materials manufacturer, in the case of soil components, manufacturing and construction quality control testing can be the responsibility of the facility manager. The CQA and CQC plans should specify procedures for quality assurance and quality control during construction of the compacted clay liners.

How can implementation of QA and QC be ensured for a compacted clay liner?

QC testing is typically performed by the contractor on materials used in construction of the liner. This testing examines material properties such as moisture content, soil density, Atterberg limits, grain size, and laboratory hydraulic conductivity. Additional testing of soil moisture content, density, lift thickness, and hydraulic conductivity helps ensure that the waste management unit has been constructed in accordance with the plans and technical specifications.

CQA testing for soil liners includes the same tests described for QC testing in the paragraph above. Generally, the tests are performed less frequently. CQA testing is performed by an individual or an entity independent of the contractor. Activities of the CQA officer are essential to document quality of construction. The responsibilities of the CQA officer and his or her staff might include communicating with the contractor; interpreting and clarifying project drawings and specifications with the designer, facility manager, and contractor; recommending acceptance or rejection by the facility manager of work completed by the construction contractor; and submitting blind samples, such as duplicates and blanks, for analysis by the contractor's testing staff or independent laboratories.

You should also consider constructing a test pad prior to full-scale construction as a CQA tool. As described earlier in the section on compacted clay liners, pilot construction or test fill of a small-scale test pad can be used to verify that the soil, equipment, and construction procedures can produce a liner that performs according to the construction drawings and specifications.

Specific factors to examine or test during construction of a test fill include: preparation and compaction of foundation material to the required bearing strength; methods of controlling uniformity of the soil material; compactive effort, such as type of equipment and number of passes needed to achieve required soil density and hydraulic conductivity; and lift thickness and placement procedures needed to achieve uniformity of density throughout a lift and prevent boundary effects between lifts or between placements in the same lift. Test pads can also provide a means to evaluate the ability of different types of soil to meet hydraulic conductivity requirements in the field. In addition to allowing an opportunity to evaluate material performance, test pads also allow evaluation of the skill and competence of the construction team, including equipment operators and QC specialists.

B. Geomembrane Liner Quality Assurance and Quality Control

As with the construction of soil liners, installation of geomembrane liners should be in conformance with a CQA and CQC plan. The responsibilities of the CQA personnel for the installation of the geomembrane are generally the same as the responsibilities for the construction of a compacted clay liner, with the addition of certain activities including observations of the liner storage area and liners in storage, and handling of the liner as the panels are positioned in the cell. Geomembrane CQA staff should also observe seam preparation, seam overlap, and materials underlying the liner.

How can implementation of QA and QC be ensured for a geomembrane liner?

Prior to installation, you should work with the geomembrane manufacturer to ensure the labeling system for the geomembrane rolls is clear and logical, allowing easy tracking of the placement of the rolls within the unit. It is important to examine the subgrade surface with both the subgrade contractor and the liner installer to ensure it conforms to specifications.

Once liner installation is underway, CQA staff might be responsible for observations of destructive testing conducted on scrap test welds prior to seaming. Geomembrane CQA staff might also be responsible for sending destructive seam sampling to an independent testing laboratory and reviewing the results for conformance to specifications. Other observations for which the CQA staff are typically responsible include observations of all seams and panels for defects due to manufacturing and handling, and placement and observations of all pipe penetrations through a liner.

Test methods, test parameters, and testing frequencies should be specified in the CQA plan to provide context for any data collected. It is prudent to allow for testing frequency to change, based on the performance of the geomembrane installer. If test results indicate poor workmanship, you should increase testing. If test results indicate high quality installation work, you can consider reducing testing frequencies. When varying testing frequency, you should establish well-defined procedures for modifying testing frequency. It is also important to evaluate testing methods, understand the differences among testing methods, and request those methods appropriate for the material and seaming method be used. Nondestructive testing methods are preferrable when possible to help reduce the number of holes cut into the geomembrane.

Geomembrane CQA staff also should document the results of their observations and prepare reports indicating the types of sampling conducted and sampling results, locations of destructive samples, locations of patches, locations of seams constructed, and any problems encountered. In some cases, they might need to prepare drawings of the liner installation. Record drawing preparation is frequently assigned to the contractor, to a representative of the facility manager, or to the engineer. You should request complete reports from any CQA staff and the installers. To ensure complete CQA documentation, it is important to maintain daily CQA reports and prepare weekly summaries.

C. Geosynthetic Clay Liner Quality Assurance and Quality Control

Construction quality assurance for geosynthetic clay liners is still a developing area; the GCL industry is continuing to establish standardized quality assurance and quality control procedures. The CQA recommendation for GCLs can serve as a starting point. You should check with the GCL manufacturer and installer for more specific information.

How can implementation of QA and QC be ensured for a geosynthetic clay liner?

It is recommended that you develop a detailed CQA plan, including product specifications; shipping, handling, and storage procedures; seaming methods; and placement of overlying material. It is important to work with the manufacturer to verify that the product meets specifications. Upon receipt of the GCL product, you should also verify that it has arrived in good condition.

During construction, CQA staff should ensure that seams are overlapped properly and conform to specifications. CQA staff should also check that panels, not deployed within a short period of time, are stored properly. In addition, as overlying material is placed on the GCL, it is important to restrict vehicle traffic directly on the GCL. You should prohibit direct vehicle traffic, with the exception of small, 4-wheel, all terrain vehicles. Even with the small all-terrain vehicles, drivers should take extreme care to avoid movements, such as sudden starts, stops, and turns, which can damage the GCL.

As part of the CQA documentation, it is important to maintain records of weather conditions, subgrade conditions, and GCL panel locations. Also, you should document any repairs that were necessary or other problems identified and addressed.

D. Leachate Collection System Quality Assurance and Quality Control

Leachate collection system CQC should be performed by the contractor. Similar activities should be performed for CQA by an independent party acting on behalf of the facility manager. The purpose of leachate collection system CQA is to document that the system is constructed in accordance with design specifications.

How can implementation of QA and QC be ensured for a leachate collection system?

Prior to construction, CQA staff should inspect all materials to confirm that they meet the construction plans and specifications. These materials include: geonets; geotextiles; pipes; granular material; mechanical, electrical, and monitoring equipment; concrete forms and reinforcements; and prefabricated structures such as sumps and manholes. The leachate collection system foundation, either a geomembrane or compacted clay liner, should also be inspected, upon its completion, to ensure that it has proper grading and is free of debris and liquids.

During construction, CQA staff should observe and document, as appropriate, the placement and installation of pipes, filter layers, drainage layers, geonets and geotextiles, sumps, and mechanical and electrical equipment. For pipes, observations might include descriptions of pipe bedding material, quality and thickness, as well as the total area covered by the bedding material. Observations of pipe installations should focus on the location, configuration, and grading of the pipes, as well as the quality of connections at joints.

For granular filter layers, CQA activities might include observing and documenting material thickness and quality during placement. For granular drainage layers, CQA might focus on the protection of underlying liners, material thickness, proper overlap with filter fabrics and geonets (if applicable), and documentation of any weather conditions that might affect the overall performance of the drainage layer. For geonets and other geosynthetics, CQA observations should focus on the area of coverage and layout pattern, as well as the overlap between panels. For geonets, CQA staff might want to make sure that the materials do not become clogged by granular material that can be carried over, as a result of either wind or runoff during construction.

Upon completion of construction, each component should be inspected to identify any damage that might have occurred during its installation or during construction of another component. For example, a leachate collection pipe can be crushed during placement of a granular drainage layer. Any damage that does occur should be repaired, and the repairs should be documented in the CQA records.

Designing and Installing Liners Activity List

- ❑ Review the recommended location considerations and operating practices for the unit.
- ❑ Select appropriate liner type—single, composite, or double liner—or in-situ soils, based on risk characterization.
- ❑ Evaluate liner material properties and select appropriate clay, geosynthetic, or combination of materials; consider interactions of liner and soil material with waste.
- ❑ Develop a construction quality assurance (CQA) plan defining staff roles and responsibilities and specifying test methods, storage procedures, and construction protocols.
- ❑ Ensure a stable in-situ soil foundation, for nonengineered liners.
- ❑ Prepare and inspect subgrade for engineered liners.
- ❑ Work with manufacturer to ensure protective shipping, handling, and storage of all materials.
- ❑ Construct a test pad for compacted clay liners.
- ❑ Test compacted clay liner material before and during construction.
- ❑ Preprocess clay material to ensure proper water content, remove oversized particles, and add soil amendments, as applicable.
- ❑ Use proper lift thickness and number of equipment passes to achieve adequate compaction.
- ❑ Protect clay material from drying and cracking.
- ❑ Develop test strips and trial seams to evaluate geomembrane seaming method.
- ❑ Verify integrity of factory and field seams for geomembrane materials before and during construction.
- ❑ Backfill with soil or geosynthetics to protect geomembranes and geosynthetic clay liners during construction.
- ❑ Place backfill materials carefully to avoid damaging the underlying materials.
- ❑ Install geosynthetic clay liner with proper overlap.
- ❑ Patch any damage that occurs during geomembrane or geosynthetic clay liner installation.
- ❑ Design leachate collection and removal system to allow adequate flow and to minimize clogging; include leachate treatment and leak detection systems, as appropriate.
- ❑ Document all CQA activities, including meetings, inspections, and repairs.

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ASTM D-422. 1990. Standard Test Method for Particle-Size Analysis of Soils.

ASTM D-638. 1991. Standard Test Method for Tensile Properties of Plastics.

ASTM D-698. 1991. Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)).

ASTM D-751. 1989. Standard Test Methods for Coated Fabrics.

ASTM D-882. 1991. Standard Test Methods for Tensile Properties of Thin Plastic Sheeting.

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Appendix

Geosynthetic Materials[25]

Geotextiles

Geotextiles form one of the two largest group of geosynthetics. Their rise in growth during the past fifteen years has been nothing short of awesome. They are indeed textiles in the traditional sense, but consist of synthetic fibers rather than natural ones such as cotton, wool, or silk. Thus biodegradation is not a problem. These synthetic fibers are made into a flexible, porous fabric by standard weaving machinery or are matted together in a random, or nonwoven, manner. Some are also knit. The major point is that they are porous to water flow across their manufactured plane and also within their plane, but to a widely varying degree. There are at least 80 specific application areas for geotextiles that have been developed; however, the fabric always performs at least one of five discrete functions:

1. Separation
2. Reinforcement
3. Filtration
4. Drainage
5. Moisture barrier (when impregnated)

Geogrids

Geogrids represent a rapidly growing segment within the geosynthetics area. Rather than being a woven, nonwoven or knit textile (or even a textile-like) fabric, geogrids are plastics formed into a very open, gridlike configuration (i.e., they have large apertures). Geogrids are either stretched in one or two directions for improved physical properties or made on weaving machinery by unique methods. By themselves, there are at least 25 application areas, however, they function almost exclusively as reinforcement materials.

Geonets

Geonets, called geospacers by some, constitute another specialized segment within the geosynthetic area. They are usually formed by a continuous extrusion of parallel sets of polymeric ribs at acute angles to one another. When the ribs are opened, relatively large apertures are formed into a netlike configuration. Their design function is completely within the drainage area where they have been used to convey fluids of all types.

Geomembranes

Geomembranes represent the other largest group of geosynthetics and in dollar volume their sales are probably larger than that of geotextiles. Their growth has been stimulated by governmental regulations originally enacted in 1982. The materials themselves are “impervious” thin sheets of rubber or plastic material used primarily for linings and covers of liquid- or solid-storage facilities. Thus the primary function is always as a liquid or vapor barrier. The range of applications, however, is very great, and at least 30 individual applications in civil engineering have been developed.

Geosynthetic Clay Liners

Geosynthetic clay liners (or GCLs) are the newest subset within geosynthetic materials. They are rolls of factory fabricated thin layers of bentonite clay sandwiched between two geotextiles or bonded to a geomembrane. Structural integrity is maintained by needle punching, stitching or physical bonding. They are seeing use as a composite compo-

[25] Created by Geosynthetic Research Institute. Accessed from the Internet on October 16, 2001 at **<www.drexel.edu/gri/gmat.html>**.

nent beneath a geomembrane or by themselves as primary or secondary liners.

Geopipe (aka Buried Plastic Pipe)

Perhaps the original geosynthetic material still available today is buried plastic pipe. This "orphan" of the Civil Engineering curriculum was included due to an awareness that plastic pipe is being used in all aspects of geotechnical, transportation, and environmental engineering with little design and testing awareness. This is felt to be due to a general lack of formalized training. The critical nature of leachate collection pipes coupled with high compressive loads makes geopipe a bona-fide member of the geosynthetics family. The function is clearly drainage.

Geocomposites

A geocomposite consists of a combination of geotextile and geogrid; or geogrid and geomembrane; or geotextile, geogrid, and geomembrane; or any one of these three materials with another material (e.g., deformed plastic sheets, steel cables, or steel anchors). This exciting area brings out the best creative efforts of the engineer, manufacturer, and contractor. The application areas are numerous and growing steadily. The major functions encompass the entire range of functions listed for geosynthetics discussed previously: separation, reinforcement, filtration, drainage, and liquid barrier.

"Geo-Others"

The general area of geosynthetics has exhibited such innovation that many systems defy categorization. For want of a better phrase, geo-others, describes items such as threaded soil masses, polymeric anchors, and encapsulated soil cells. As with geocomposites their primary function is product-dependent and can be any of the five major functions of geosynthetics.