Seminar Publication

Requirements for Hazardous Waste Landfill Design, Construction, and Closure
3. FLEXIBLE MEMBRANE LINERS

Introduction
This chapter discusses several material and design considerations for flexible membrane liners (FMLs). It highlights some of the problems encountered in designing "bathtub" systems for hazardous waste landfills and describes the impact of proposed regulations on material and design considerations.

Composite Liners: Clay versus Synthetic Components
After a landfill site has been chosen and a basin has been excavated, the basin is lined with one or more layers of water-retaining material (liners) that form a "leachate bathtub." The contained leachate is pumped out through a network of pipes and collector layers. Liners may be constructed of synthetic polymer sheets or of clay. EPA's minimum technology guidance (discussed in Chapter One) relies on a composite liner that utilizes advantages obtained from combining both liner systems.

Understanding the basic hydraulic mechanisms for synthetic liners and clay liners is very important in appreciating the advantages of a composite liner. Clay liners are controlled by Darcy's law \( Q = kIA \) (Darcy's law is discussed in more detail in Chapter Two). In clay liners, the factors that most influence liner performance are hydraulic head and soil permeability. Clay liners have a higher hydraulic conductivity and thickness than do synthetic liners. Additionally, leachate leaking through a clay liner will undergo chemical reactions that reduce the concentration of contaminants in the leachate.

Leakage through a synthetic liner is controlled by Fick's first law, which applies to the process of liquid diffusion through the liner membrane. The diffusion process is similar to flow governed by Darcy's law except it is driven by concentration gradients and not by hydraulic head. Diffusion rates in membranes are very low in comparison to hydraulic flow rates even in clays. In synthetic liners, therefore, the factor that most influences liner performance is penetrations.

Synthetic liners may have imperfect seams or pinholes, which can greatly increase the amount of leachate that leaks out of the landfill.

Clay liners, synthetic liners, or combinations of both are required in landfills. Figure 3-1 depicts the synthetic/composite double liner system that appears in EPA's minimum technology guidance. The system has two synthetic flexible membrane liners (FMLs): the primary FML, which lies between two leachate collection and removal systems (LCRS), and the secondary FML, which overlies a compacted clay liner to form a composite secondary liner. The advantage of the composite liner design is that by putting a fine grain material beneath the membrane, the impact of given penetrations can be reduced by many orders of magnitude (Figure 3-2). In the figure, \( Q_L \) is the inflow rate with gravel and \( Q_C \) is the inflow rate with clay.

Figure 3-3 is a profile of a liner that appeared in an EPA design manual less than a year ago. This system is already dated. Since this system was designed, EPA has changed the minimum hydraulic conductivity in the secondary leachate collection system from \( 1 \times 10^{-2} \) cm/sec to 1 cm/sec to improve detection time. To meet this requirement, either gravel or a net made of synthetic material must be used to build the secondary leachate collection system; in the past, sand was used for this purpose.

Material Considerations
Synthetics are made up of polymers—natural or synthetic compounds of high molecular weight. Different polymeric materials may be used in the construction of FMLs:

- Thermoplastics—polyvinyl chloride (PVC)
- Crystalline thermoplastics—high density polyethylene (HDPE), linear low density polyethylene (LLDPE)
Figure 3-1. Synthetic/composite double liner system.

Figure 3-2. Advantage of composite liner.

- Thermoplastic elastomers—chlorinated polyethylene (CPE), chlorylsulfonated polyethylene (CSPE)
- Elastomers—neoprene, ethylene propylene diene monomer (EPDM)

Typical compositions of polymeric geomembranes are depicted in Table 3-1. As the table shows, the membranes contain various admixtures such as oils and fillers that are added to aid manufacturing of the FML but may affect future performance. In addition, many polymer FMLs will cure once installed, and the strength and elongation characteristics of certain FMLs will change with time. It is important therefore to select polymers for FML construction with care. Chemical compatibility, manufacturing considerations, stress-strain characteristics, sur-
vivability, and permeability are some of the key issues that must be considered.

**Chemical Compatibility**

The chemical compatibility of a FML with waste leachate is an important material consideration. Chemical compatibility and EPA Method 9090 tests must be performed on the synthetics that will be used to construct FMLs. (EPA Method 9090 tests are discussed in more detail in Chapter Nine.) Unfortunately, there usually is a lag period between the time these tests are performed and the actual construction of a facility. It is very rare that at the time of the 9090 test, enough material is purchased to construct the liner. This means that the material used for testing is not typically from the same production lot as the synthetics installed in the field.

The molecular structure of different polymers can be analyzed through differential scanning calorimeter or thermogravimetric testing. This testing or "fingerprinting" can ensure that the same material used for the 9090 test was used in the field. Figure 3-4 was provided by a HDPE manufacturer, and the fingerprints depicted are all from high density polyethylenes. Chemical compatibility of extrusion welding rods with polyethylene sheets is also a concern.

**Manufacturing Considerations**

Polyethylene sheets are produced in various ways:

- Extrusion—HDPE
- Calendering—PVC
- Spraying—Urethane

In general, manufacturers are producing high quality polyethylene sheets. However, the compatibility of extrusion welding rods and high density polyethylene sheets can be a problem. Some manufacturing processes can cause high density polyethylene to crease. When this material creases, stress fractures will result. If the material is taken into the field to be placed, abrasion damage will occur on the creases. Manufacturers have been working to resolve this problem and, for the most part, sheets of acceptable quality are now being produced.

**Stress-Strain Characteristics**

Table 3-2 depicts typical mechanical properties of HDPE, CPE, and PVC. Tensile strength is a

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Table 3-1. Basic Composition of Polymeric Geomembrane

<table>
<thead>
<tr>
<th>Component</th>
<th>Crosslinked</th>
<th>Thermoplastic</th>
<th>Semicrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer or alloy</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Oil or plasticizer</td>
<td>5-40</td>
<td>5-65</td>
<td>0-10</td>
</tr>
<tr>
<td>Fillers:</td>
<td>5-40</td>
<td>5-40</td>
<td>2-5</td>
</tr>
<tr>
<td>Carbon Black</td>
<td>5-40</td>
<td>5-40</td>
<td></td>
</tr>
<tr>
<td>Inorganics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antidegradants</td>
<td>1-2</td>
<td>1-2</td>
<td></td>
</tr>
<tr>
<td>Crosslinking system:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inorganic system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur system</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

fundamental design consideration. Figure 3-5 shows the uniaxial stress-strain performance of HDPE, CPE, and PVC. As 600, 800, 1,100, and 1,300 percent strain is developed, the samples fail. When biaxial tension is applied to HDPE, the material fails at strains less than 20 percent. In fact, HDPE can fail at strains much less than other flexible membranes when subjected to biaxial tensions common in the field.

Another stress-strain consideration is that high density polyethylene, a material used frequently at hazardous waste facilities, has a high degree of thermal coefficient of expansion - three to four times that of other flexible membranes. This means that during the course of a day (particularly in the summer), 100-degrees-Fahrenheit (°F) variations in the temperature of the sheeting are routinely measured. A 600-foot long panel, for example, may grow 6 feet during a day.

Survivability

Various tests may be used to determine the survivability of unexposed polymeric geomembranes (Table 3-3). Puncture tests frequently are used to estimate the survivability of FMLs in the field. During a puncture test, a 5/16 inch steel rod with rounded edges is pushed down through the membrane. A very flexible membrane that has a high strain capacity under biaxial tension may allow that rod to penetrate almost to the bottom of the chamber rupture. Such a membrane has a very low penetration force but a very high penetration elongation, and may have great survivability in the field. High density polyethylene will give a very high penetration force, but have very high brittle failure. Thus, puncture data may not properly predict field survivability.

Permeability

Permeability of a FML is evaluated using the Water Vapor Transmission test (ASTM E96). A sample of the membrane is placed on top of a small aluminum cup containing a small amount of water. The cup is then placed in a controlled humidity and temperature chamber. The humidity in the chamber is typically 20 percent relative humidity, while the humidity in the cup is 100 percent. Thus, a concentration gradient is set up across the membrane. Moisture diffuses through the membrane and with time the liquid level in the cup is reduced. The rate at which moisture is moving through the membrane is measured. From that rate, the permeability of the membrane is calculated with the simple diffusion equation (Fick's first law). It is important to remember that even if a liner is installed correctly with no holes, penetrations, punctures, or defects, liquid will still diffuse through the membrane.

Design Elements

A number of design elements must be considered in the construction of flexible membrane liners: (1) minimum technology guidance, (2) stress considerations, (3) structural details, and (4) panel fabrication.

Minimum Technology Guidance

EPA has set minimum technology guidance for the design of landfill and surface impoundment liners to achieve de minimis leakage. De minimis leakage is 1 gallon per acre per day. Flexible membrane liners must be a minimum of 30 mils thick, or 45 mils thick if exposed for more than 30 days. There may, however, be local variations in the requirement of minimum thickness, and these variations can have an impact on costs. For example, membranes cost approximately $0.01 per mil per square foot, so that increasing the required thickness of the FML from 30 mils to 60 mils, will increase the price $.30 cents per square foot or $12,000 per acre.

Stress

Stress considerations must be considered for side slopes and the bottom of a landfill. For side slopes, self-weight (the weight of the membrane itself) and waste settlement must be considered; for the bottom of the facility, localized settlement and normal compression must be considered.

The primary FML must be able to support its own weight on the side slopes. In order to calculate self-weight, the FML specific gravity, friction angle, FML thickness, and FML yield stress must be known (Figure 3-6).

Waste settlement is another consideration. As waste settles in the landfill, a downward force will act on the primary FML. A low friction component between the FML and underlying material prevents that force from being transferred to the underlying material, putting tension on the primary FML. A 12-inch direct shear test is used to measure the friction angle between the FML and underlying material.

An example of the effects of waste settlement can be illustrated by a recent incident at a hazardous waste landfill facility in California. At this facility, waste settlement led to sliding of the waste, causing the standpipes (used to monitor secondary leachate collection sumps) to move 60 to 90 feet downslope in 1 day. Because there was a very low coefficient of friction between the primary liner and the geonet, the waste (which was deposited in a canyon) slid down the canyon. There was also a failure zone between the secondary liner and the clay. A two-
Table 3.2. Typical Mechanical Properties

<table>
<thead>
<tr>
<th></th>
<th>HDPE</th>
<th>CPE</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, gm/cm³</td>
<td>&gt;1.3</td>
<td>1.3 - 1.37</td>
<td>1.24 - 1.3</td>
</tr>
<tr>
<td>Thermal coefficient of expansion</td>
<td>12.5 x 10⁻⁵</td>
<td>4 x 10⁻⁵</td>
<td>3 x 10⁻⁵</td>
</tr>
<tr>
<td>Tensile strength, psi</td>
<td>4800</td>
<td>1800</td>
<td>2200</td>
</tr>
<tr>
<td>Puncture, lb/mil</td>
<td>2.8</td>
<td>1.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Dimensional slope stability analysis at the site indicated a factor of safety greater than one. A three-dimensional slope stability analysis, however, showed the safety factor had dropped below one. Three-dimensional slope stability analyses should therefore be considered with canyon and trench landfills.

Since more trenches are being used in double FML landfills, the impact of waste settlement along such trenches should be considered. Figure 3-7 is a simple evaluation of the impact of waste settlement along trenches on the FML. Settlements along trenches will cause strain in the membrane, even if the trench is a very minor ditch. Recalling that when biaxial tension is applied to high density polyethylene, the material fails at a 16 to 17 percent strain, it is possible that the membrane will fail at a moderate settlement ratio.

Another consideration is the normal load placed on the membranes as waste is piled higher. Many of the new materials on the market, particularly some of the linear low density polyethylene (LLDPE) liners, will take a tremendous amount of normal load without failure. The high density polyethylenes, on the other hand, have a tendency to high brittle failure.

**Structural Details**

Double liner systems are more prone to defects in the structural details (anchorage, access ramps, collection standpipes, and penetrations) than single liner systems.
<table>
<thead>
<tr>
<th>Property</th>
<th>Membrane Liner Without Fabric Reinforcement</th>
<th>Fabric Reinforced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatiles</td>
<td>MTM-1\textsuperscript{a}</td>
<td>MTM-1\textsuperscript{a} (on salvage and reinforced sheathing)</td>
</tr>
<tr>
<td>Extractables</td>
<td>MTM-2\textsuperscript{a}</td>
<td>MTM-2\textsuperscript{a} (on salvage and reinforced sheathing)</td>
</tr>
<tr>
<td>Ash</td>
<td>ASTM D297, Section 34</td>
<td>ASTM D297, Section 34 (on salvage)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>ASTM D792, Method A</td>
<td>ASTM D792, Method A (on salvage)</td>
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<tr>
<td>Thermal analysis:</td>
<td></td>
<td></td>
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<tr>
<td>Differential scanning</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calorimetry (DSC)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Thermogravimetry (TGA)</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Physical Properties</td>
<td></td>
<td></td>
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<tr>
<td>Thickness - total</td>
<td>ASTM D838</td>
<td>ASTM D751, Section 6</td>
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<td>Coating over fabric</td>
<td>NA</td>
<td>Optical method</td>
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<tr>
<td>Tensile properties</td>
<td>ASTM D882, ASTM D638</td>
<td>ASTM D751, Method A</td>
</tr>
<tr>
<td>Tear resistance</td>
<td>ASTM D1004 (modified)</td>
<td>ASTM D751, Method A</td>
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<tr>
<td>Modulus of elasticity</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Hardness</td>
<td>ASTM D882, Method A</td>
<td>ASTM D751, Method A</td>
</tr>
<tr>
<td>Puncture resistance</td>
<td>FTMS 101B, Method 2055</td>
<td>FTMS 101B, Method 2055</td>
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<tr>
<td>Hydrostatic resistance</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Seam strength:</td>
<td></td>
<td></td>
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<tr>
<td>In shear</td>
<td>ASTM D882, Method A (modified)</td>
<td>ASTM D751, Method A (modified)</td>
</tr>
<tr>
<td>In peel</td>
<td>ASTM D413, Mach Method Type 1 (modified)</td>
<td>ASTM D413, Mach Method Type 1 (modified)</td>
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<tr>
<td>Ply adhesion</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Environmental and Aging Effects</td>
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<td>Ozone cracking</td>
<td>ASTM D1149</td>
<td>ASTM D1149</td>
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<tr>
<td>Environmental stress</td>
<td>NA</td>
<td>ASTM D1693</td>
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<tr>
<td>cracking</td>
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<tr>
<td>Low temperature testing</td>
<td>ASTM D1790</td>
<td>ASTM D1790</td>
</tr>
<tr>
<td>Tensile properties at</td>
<td>ASTM D838 (modified)</td>
<td>ASTM D751 Method B (modified)</td>
</tr>
<tr>
<td>elevated temperature</td>
<td>ASTMD 412 (modified)</td>
<td>ASTMD 412 (modified)</td>
</tr>
<tr>
<td>Dimensional stability</td>
<td>ASTM D1204</td>
<td>ASTM D1204</td>
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Table 3-3. Test Methods for Unexposed Polymeric Geomembranes (continued)

<table>
<thead>
<tr>
<th>Property</th>
<th>Membrane Liner Without Fabric Reinforcement</th>
<th>Fabric Reinforced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermoplastic</td>
<td>Crosslinked</td>
</tr>
<tr>
<td>Air-oven aging</td>
<td>ASTM D573 (modified)</td>
<td>ASTM D573 (modified)</td>
</tr>
<tr>
<td>Water absorption</td>
<td>ASTM D570</td>
<td>ASTM D471</td>
</tr>
<tr>
<td>Immersion in standard</td>
<td>ASTM D471, D543</td>
<td>ASTM D471</td>
</tr>
<tr>
<td>Immersion in waste</td>
<td>EPA 9090</td>
<td>EPA 9090</td>
</tr>
<tr>
<td>liquids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil burial</td>
<td>ASTM D3083</td>
<td>ASTM D3083</td>
</tr>
<tr>
<td>Outdoor exposure</td>
<td>ASTM D4364</td>
<td>ASTM D4364</td>
</tr>
<tr>
<td>Tub test</td>
<td>b</td>
<td>b</td>
</tr>
</tbody>
</table>

*See reference (8).
*See reference (12).
NA = not applicable.
Source: Haco, 1997

Cell Component: FLEXIBLE MEMBRANE LINER

Consideration: TENSILE STRESS - LINER WEIGHT; EVALUATE ABILITY OF FLM TO SUPPORT ITS OWN WEIGHT ON THE GIRDER SLICES.

Required Material Properties | Range | Test | Standard |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FLM SPECIFIC GRAVITY, G</td>
<td>&lt;1.30</td>
<td>G</td>
<td>ASTM D2292</td>
</tr>
<tr>
<td>FLEXION ANGLE</td>
<td>10° to 45°</td>
<td>DRY TEST</td>
<td>ASTM D4893</td>
</tr>
<tr>
<td>FLM THICKNESS, t</td>
<td>0.10 to 0.20 in.</td>
<td>TENSILE</td>
<td>ASTM D5818</td>
</tr>
<tr>
<td>FLM YIELD STRESS, GY</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Analysis Procedure:

1. Calculate FLM Tensile Force, T

   \[ T = \frac{W \cdot \sin \beta \cdot \cos \beta}{10} \]

   \[ W = \frac{1}{2} \cdot F \cdot L \cdot \sin \beta \]

2. Calculate FLM Tensile Stress, G

   \[ G = \frac{F}{A} \]

3. Obtain Laboratory FLM YIELD STRESS, GY

4. Calculate Design Ratio

   \[ DR = \frac{GY}{G} \]

Example:

Given:

1. FLM SPECIFIC GRAVITY, G = 0.943
2. FLEXION ANGLE
3. FLM THICKNESS, t = 0.10 in.
4. \( \beta = 30° \)

(1) Calculate FLM Tensile Force, T

\[ T = \frac{7.0 \cdot \cos 30° \cdot \sin 30°}{10} = 1.75 \text{ kN/m} \]

(2) Calculate FLM Tensile Stress, G

\[ G = 12.0 / (1 \times 12) = 1.00 \text{ kN/m}^2 \]

(3) Obtain Laboratory FLM YIELD STRESS, GY

(4) Calculate Design Ratio

\[ DR = \frac{20}{1.00} = 20 \]

Example No. 514

Figure 3-6. Calculation of self-weight.
Anchorage
Anchor trenches can cause FMLs to fail in one of two ways: by ripping or by pulling out. The pullout mode is easier to correct. It is possible to calculate pullout capacity for FMLs placed in various anchorage configurations (Figures 3-8 and 3-9). In the "V" anchor configuration, resistance can be increased by increasing the "V" angle. A drawback to using the "V" design for getting an accurate estimate of pullout capacity is that it uses more space. The concrete trench is not presently used.

Ramps
Most facilities have access ramps (Figure 3-10), which are used by trucks during construction and by trucks bringing waste into the facility. Figure 3-11 depicts a cross section of a typical access ramp. The double FML integrity must be maintained over the entire surface of the ramp. Because ramps can fail due to traffic-induced sliding, roadway considerations, and drainage, these three factors must be considered during the design and construction of access ramps.

The weight of the roadway, the weight of a vehicle on the roadway, and the vehicle braking force all must be considered when evaluating the potential for slippage due to traffic (Figure 3-12). The vehicle braking force should be much larger than the dead weight of the vehicles that will use it. Wheelloads also have an impact on the double FML system and the two leachate collection systems below the roadway. Trucks with maximum axle loads (some much higher than the legal highway loads) and 90 psi tires should be able to use the ramps. Figure 3-13 illustrates how to verify that wheel contact loading will not damage the FML. Swells or small drains may be constructed along the inboard side of a roadway to ensure that the ramp will adequately drain water from the roadway. Figure 3-14 illustrates how to verify that a ramp will drain water adequately. The liner system, which must be protected from tires, should be armored in the area of the drainage swells. A sand subgrade contained by a geotextile beneath the roadway can prevent local sloughing and local slope failures along the side of the roadway where the drains are located. The sand subgrade tied together with geotextile layers forms, basically, 800-foot long sandbags stacked on top of one another.

Vertical Standpipes
Landfills have two leachate collection and removal systems (LCRSs): a primary LCRS and a secondary LCRS. Any leachate that penetrates the primary
Figure 3-8. Calculation of anchor capacity.

system and enters the secondary system must be removed. Vertical standpipes (Figure 3-15) are used to access the primary leachate collection sumps. As waste settles over time, downdrag forces can have an impact on standpipes. Those downdrag forces can lead to puncture of the primary FML beneath the standpipe. Figure 3-16 illustrates how to verify that downdrag induced settlement of standpipes will not cause the underlying leachate collection system to fail.

To reduce the amount of downdrag force on the waste pile, standpipes can be coated with viscous or low friction coating. Standpipes can be encapsulated with multiple layers of HDPE. This material has a very low coefficient of friction that helps reduce the amount of downdrag force on the waste piles. Figure 3-17 illustrates how to evaluate the potential downdrag forces acting on standpipes and how to compare coatings for reducing these forces.

Downdrag forces also affect the foundation or subgrade beneath the standpipe. If the foundation is rigid, poured concrete, there is a potential for significant strain gradients. A flexible foundation will provide a more gradual transition and spread the distribution of contact pressures over a larger portion of the FML than will a rigid foundation (Figure 3-18). To soften rigid foundations, encapsulated steel plates may be installed beneath the foundation, as shown in Figure 3-15.

Standpipe Penetrations

The secondary leachate collection system is accessed by collection standpipes that must penetrate the primary liner. There are two methods of making these penetrations: rigid or flexible (Figure 3-19). In the rigid penetrations, concrete anchor blocks are set behind the pipe with the membranes anchored to the concrete. Flexible penetrations are preferred since these allow the pipe to move without damaging the
Figure 3-9. Forces and variables—anchor analysis.

liner. In either case, standpipes should not be welded to the liners. If a vehicle hits a pipe, there is a high potential for creating major tears in the liner at depth.
Wind Damage

During the installation of FMLs, care must be taken to avoid damage from wind. Figure 3-20 shows maximum wind speeds in the United States. Designers should determine if wind will affect an
installation and, if so, how many sandbags will be needed to anchor the FML panels as they are being placed in the field. Figure 3-21 shows how to calculate the required sandbag spacing for FML panels during placements. Wind-uplift pressure must be known to make this calculation. Using the data in Table 3-4, the uplift pressures acting on the membranes may be calculated.

Surface Impoundments versus Landfills
There are significant differences in structural considerations between landfills and surface impoundments. First, liners used in surface impoundments have a long-term exposure to the waste and to sunlight. In addition, surface impoundments have a potential for gas in the leachate collection and removal system because there will always be the potential for organic material beneath the system.

Long-term exposure can be stopped using either soil or a nonwoven fabric to cover the membrane in a surface impoundment. Figure 3-22 illustrates how to calculate the stability of a soil cover over the membrane. Another option is to drape a heavy, nonwoven fabric with base anchors in it over the membrane. This nonwoven material is cheaper, safer, and more readily repaired than a soil cover.

Gas or liquid generated "whales" can be a serious problem in surface impoundments. Water-induced "whaling" can be a problem in facilities that are located where there is a high water table. Storm water can also enter a collection system through gas vents. Figure 3-23 illustrates two gas vent designs in which the vent is placed higher than the maximum overflow level. If excess water in the leachate collectors is causing whaling, the perimeter should be checked to determine where water is entering. To repair a water-generated whale, the excess water should be pumped out of the sump and its source.
Figure 3.13. Calculation of wheel loading capacity.

stopped. If there is gas in the whale (liner is inflated and visible above the water surface), the facility must be rebuilt from scratch.

Panel Fabrication

The final design aspect to consider is the FML panel layout of the facility. Three factors should be considered when designing a FML panel layout: (1) seams should run up and down on the slope, not horizontally; (2) the field seam length should be minimized whenever possible; and (3) there should be no penetration of a FML below the top of the waste.

Panels must be properly identified to know where they fit in the facility. Figure 3.24 depicts the panel-seam identification scheme used for this purpose. This numbering scheme also assures a high quality installation, since seam numbers are used to inventory all samples cut from the FML panel during installation. The samples cut from the panels are tested to ensure the installation is of high quality. Quality assurance and the panel-seam identification scheme are discussed in more detail in Chapter Seven.

References


<table>
<thead>
<tr>
<th>Cell Component: RAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consideration: DRAINAGE: VERIFY THAT RAMP WILL ADEQUATELY DRAIN SURFACE WATER FROM ROADWAY.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Required Material Properties</th>
<th>Range</th>
<th>Test</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Plane Flow of LCR, Q</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability, K, of Subbase</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Full HE Rain |

Analysis Procedure:

1. **Estimate Flow Rate, Q**
   
   Q = C IA
   
   WHERE C = 1.0
   
   IA = Rainfall + Area A
   
   HE = Water depth

2. **Estimate Flow Capacity of LCR + Roadway, QCR**
   
   QCR = Q + QIA
   
   WHERE QIA = Area * In-Plane Flow

3. **Calculate Design Rain, QDR**
   
   QDR = Flow Capacity / QCR

4. **Calculate Design Rain, QDR**

Design Ratio: DRmin > 1.5

References:

Example:

- **Example:**
  
  - Ramp Parameters:
    - Width = 18
    - In-Plane = 1.0
    - Subgrade = 2.0
    - Soil Type = Clay
    - Drainage = 3.0
  
  - Surface Water:
    - IA = Rainfall + Area
    - HE = Water depth

  1. **Estimate Flow Rate, Q**
     
     Q = C IA
     
     WHERE C = 1.0

  2. **Estimate Flow Capacity of LCR + Roadway, QCR**
     
     QCR = Q + QIA

  3. **Calculate Design Rain, QDR**

Example No. 42

Figure 3-14. Calculation of ramp drainage capability.
Placing low friction HDPE around a standpipe.
Figure 3-15. Details of standpipe/drain.
Figure 3-16. Verification that downdrag induced settlement will not cause LCR failure.
Figure 3-17. Evaluation of potential downdrag forces on standpipes with and without coating.
Figure 3-18. Standpipe induced strain in FML.
Figure 3-19. Details of rigid and flexible penetrations.
Figure 3-20. Design maximum wind speeds.
**Cell Component:** Flexible Membrane

**Consideration:** Wind Lift: Calculate the required sandbag spacing for FML/FSM panels during placement.

<table>
<thead>
<tr>
<th>Required Material Properties</th>
<th>Range</th>
<th>Test</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible Membrane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Weight</td>
<td>3-200</td>
<td>Density</td>
<td>ASTM D7092</td>
</tr>
</tbody>
</table>

**Analysis Procedures:**

(1) **Determine Ceiling Maximum Wind Speed** $V_{wind}$

- Use one specific data or reference Fig. 2.

(2) **Determine Wind Uplift Pressure, $P_{wind}$**

- Reference Table 6.2 if $V_{wind} \geq P_{wind}$
- Note: Perform linear interpolation for depths < 10 ft.

(3) **Calculate Sand Bag Spacing**

- $W_a$ = Weight of Sandbag
- $T_{trib}$ = Tributary Area

(4) **Calculate Design Ratio**

$$DR = TA / (Tributary\ \text{Field}\ \text{Area})$$

**Design Ratio:**

$DR_{ult-11}$ (Smart-Tech Only)

**References:**

Factory Mutual System

---

**Example:**

- Philadelphia, PA
- Annual Extreme Wind Speed (Fig. 2)
  - $V_{wind} = 80$ mph
- $W_a = 20$ lbs
- FML/FSM = 20 ft to 90 ft
- Sandbag = 50 lbs; 2 per 10 sq. ft.
- Height to FML = 20 ft, 10 ft, 50 ft

(1) **Determine Design Maximum Wind Speed, $V_{wind}$**

$V_{wind} = 50$ mph (Ref. value)

(2) **Determine Wind Uplift Pressure, $P_{wind}$**

**Example No. 6.1**

---

**Table 3-4. Wind-Uplift Forces, PSF (Factory Mutual System)**

<table>
<thead>
<tr>
<th>Height Above Ground (ft)</th>
<th>City, Suburban Areas, Towns, and Wooded Areas</th>
<th>Flat, Open Country, or Open Coastal Belt &gt; 1500 ft from Coast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>0-15</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>50</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>75</td>
<td>14</td>
<td>18</td>
</tr>
</tbody>
</table>

*Uplift pressures in PSF*
Figure 3-22. Calculation of soil cover stability.
Creation of "whales."
Figure 3-23. Gas vent details.
Figure 3-24. Panel-seam Identification scheme.
5. SECURING A COMPLETED LANDFILL

Introduction
This chapter describes the elements in a closure or cap system of a completed landfill, including flexible membrane caps, surface water collection and removal systems, gas control layers, biotic barriers, and vegetative top covers. It also discusses infiltration, erosion control, and long-term aesthetic concerns associated with securing a completed landfill.

Figure 5-1 shows a typical landfill profile designed to meet EPA’s proposed minimum technology guidance (MTG) requirements. The upper subprofile comprises the cap, or cover, and includes the required 2-foot vegetative top cover, 1-foot lateral drainage layer, and low permeability cap of barrier soil (clay), which must be more than 2 feet thick. This three-tier system also includes an optional flexible membrane cap and an optional gas control layer. The guidance originally required a 20-mil thick flexible membrane cap, but EPA currently is proposing a 40 mil minimum.

Flexible Membrane Caps
Flexible membrane caps (FMCs) are placed over the low permeable clay cap and beneath the surface water collection and removal (SWCR) system. FMCs function primarily in keeping surface water off the landfill and increasing the efficiency of the drainage layer. EPA leaves operators with the option of choosing the synthetic material for the FMC that will be most effective for site-specific conditions. In selecting materials, operators should keep in mind several distinctions between flexible membrane liners (FMLs) and FMCs. Unlike a FML, a FMC usually is not exposed to leachate, so chemical compatibility is not an issue. Membrane caps also have low normal stresses acting on them in comparison with FMLs, which generally carry the weight of the landfill. An advantage FMCs have over liners is that they are much easier to repair, because their proximity to the surface of the facility makes them more accessible. FMCs will, however, be subject to greater strains than FMLs due to settlement of the waste.

Surface Water Collection and Removal (SWCR) Systems
The SWCR system is built on top of the flexible membrane cap. The purpose of the SWCR system is to prevent infiltration of surface water into the landfill by containing and systematically removing any liquid that collects within it. Actual design levels of surface water infiltration into the drainage layer can be calculated using the water balance equation or the Hydrologic Evaluation of Landfill Performance (HELP) model. (A more detailed discussion of HELP is contained in Chapter Four.) Figure 5-2 shows the results of two verification studies of the HELP model published by EPA.

Errors in grading the perimeter of the cap often integrates (or cross-connects) the SWCR system with the secondary leak detection and removal system, resulting in a significant amount of water infiltrating the secondary detection system. This situation should be remedied as soon as possible if it occurs. Infiltration of surface water is a particular concern in nuclear and hazardous waste facilities, where gas vent stacks are found. A containment system should be designed to prevent water from entering the system through these vents.

In designing a SWCR system above a FMC, three issues must be considered: (1) cover stability, (2) puncture resistance, and (3) the ability of the closure system to withstand considerable stresses due to the impact of settlement. Figure 5-3 illustrates the effects of these phenomena.

Cover Stability
The stability of the FMC supporting the SWCR system can be affected by the materials used to construct the drainage layer and by the slope of the site. In some new facilities, the drainage layer is a geonet placed on top of the flexible membrane cap,
with the coefficient of friction between those two elements being as low as 8 to 10 degrees. Such low friction could allow the cover to slide. One facility at the Meadowlands in New Jersey is constructed on a high mound having side slopes steeper than 2:1. In order to ensure adhesion of the membrane to the side slopes of the facility, a nonwoven geotextile was bonded to both sides of the FMC. Figures 5-4 and 5-5 give example problems that evaluate the sliding stability of a SWCR system in terms of shear capacities and tensile stress.

**Puncture Resistance**

Flexible membrane caps must resist penetration by construction equipment, rocks, roots, and other natural phenomena. Traffic by operational equipment can cause serious tearing. A geotextile placed on top of or beneath a membrane increases its puncture resistance by three or four times. Figure 5-6 shows the results of puncture tests on several common geotextile/membrane combinations. Remember, however, that a geotextile placed beneath the FMC and the clay layer will destroy the composite action between the two. This will lead to increased infiltration through penetrations in the FMC.

**Impact of Settlement**

The impact of settlement is a major concern in the design of the SWCR system. A number of facilities have settled 6 feet in a single year, and 40 feet or more over a period of years. The Meadowlands site in New Jersey, for example, was built at a height of 95 feet, settled to 40 feet, and then was rebuilt to 135 feet. Uniform settlement can actually be beneficial by compressing the length of the FMC and reducing tensile strains. However, if waste does not settle uniformly it can be caused by interior berms that separate waste cells.

In one current closure site in California, a waste transfer facility with an 18-foot wall is being built within a 30-foot trench on top of a 130-foot high landfill. The waste transfer facility will settle faster than the adjacent area, causing tension at the edge of the trench. Electronic extensometers are proposed at the tension points to check cracking strains in the clay cap and FMC.

Settlements can be estimated, although the margin for error is large. Secure commercial hazardous waste landfills have the smallest displacement, less than 1.5 percent. Displacements at new larger solid waste landfills can be estimated at 15 percent, while older, unregulated facilities with mixed wastes have settlements of up to 60 percent. Figure 5-7 gives an example problem showing how to verify the durability of a FMC under long-term settlement compression.

**Gas Control Layer**

Gas collector systems are installed directly beneath the low permeability clay cap in a hazardous waste landfill. Landfills dedicated to receiving only hazardous wastes are relatively new and gas has never been detected in these systems. It may take 40 years or more for gas to develop in a closed secure hazardous waste landfill facility. Because the long-term effects of gas generation are not known, and
costs are minimal, EPA strongly recommends the use of gas collector systems.

Figure 5-8 shows details from a gas vent pipe system. The two details at the left of the illustration show closeups of the boot seal and flange seals located directly at the interface of the SWCR system with the flexible membrane cap. To keep the vent operating properly, the slope of the closure system should never be less than 2 percent; 5 to 7 percent is preferable. A potential problem with gas collector systems is that a gas venting pipe, if not properly maintained, can allow surface water to drain directly into the landfill waste.

Figure 5-9 illustrates two moisture control options in gas collector systems. Gas collector systems will tolerate a large amount of moisture before air transmissivity is affected. Figure 5-10 shows air and water transmissivity in a needle-punched nonwoven geotextile. Condensates from the gas collector layer that form beneath the clay and flexible membrane
cap also can be taken back into the waste, since most hazardous wastes are deposited very dry.

**Biotic Barriers**

A biotic barrier is a gravel and rock layer designed to prevent the intrusion of burrowing animals into the landfill area. This protection is primarily necessary around the cap but, in some cases, may also be needed at the bottom of the liner. Animals cannot generally penetrate a FMC, but they can widen an existing hole or tear the material where it has wrinkled.

Figure 5-11 shows the gravel filter and cobblestone components of the biotic barrier and their placement in the landfill system. The proposed 1-meter thickness for a biotic barrier should effectively prevent penetration by all but the smallest insects. Note that the biotic barrier also serves as the surface water collection/drainage layer. Biotic barriers used in nuclear caps may be up to 14-feet thick with rocks several feet in diameter. These barriers are designed to prevent disruption of the landfill by humans both now and in the future.

**Vegetative Layer**

The top layer in the landfill profile is the vegetative layer. In the short term, this layer prevents wind and water erosion, minimizes the percolation of surface water into the waste layer, and maximizes evapotranspiration, the loss of water from soil by evaporation and transpiration. The vegetative layer also functions in the long term to enhance aesthetics and to promote a self-sustaining ecosystem on top of the landfill. The latter is of primary importance because facilities may not be maintained for an
Meadowpanda test of sjo-resistant FMC.

indefinite period of time by either government or industry.

Erosion can seriously affect a landfill closure by disrupting the functioning of drainage layers and surface water and leachate collection and removal systems. Heavy erosion could lead to the exposure of the waste itself. For this reason, it is important to predict the amount of erosion that will occur at a site and reinforce the facility accordingly. The Universal Soil Loss Equation shown below can be used to determine soil loss from water erosion:

\[ X = RKSLCP \]

where \( X \) = soil loss

\( R \) = rainfall erosion index

\( K \) = soil erodibility index

\( S \) = slope gradient factor

\( L \) = slope length factor

\( C \) = crop management factor

\( P \) = erosion control practice

Figure 5-12 can be used to find the soil-loss ratio due to the slope of the site as used in the Universal Soil Loss Equation. Loss from wind erosion can be determined by the following equation:

\[ X' = PK'C'L'V' \]

where \( X' \) = annual wind erosion

\( P \) = field roughness factor

\( K' \) = soil erodibility index
**Figure 5-4.** Shear failure for surface water collection and removal system.

**Cell Component:** Surface Water Collection/Removal System

<table>
<thead>
<tr>
<th>Consideration:</th>
<th>Shear Failure</th>
<th>Evaluate sliding stability of cover soil and design ratio against shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Material Properties</td>
<td>Range</td>
<td>Test</td>
</tr>
<tr>
<td>Friction Angle</td>
<td>Cover Soil to SWCR, $\phi_u$</td>
<td>30$^\circ$-45$^\circ$</td>
</tr>
<tr>
<td></td>
<td>SWCR to FMC, $\phi_c$</td>
<td>15$^\circ$-45$^\circ$</td>
</tr>
<tr>
<td></td>
<td>Shear Strength of SWCR, $\tau_{sw}$</td>
<td>100-400</td>
</tr>
</tbody>
</table>

**Analyses Procedure:**

1. **Calculate Design Ratio for Cover**
   
   $DR = \frac{\tan \alpha}{\tan \phi_u}$

2. **Calculate Shear Stress Angle for SWCR System**
   
   $\tau_u = \frac{\tan \phi_u + \tan \alpha}{\tan \phi_u}$

3. **Calculate Design Ratio for SWCR Shear**
   
   $DR = \frac{T_{sw}}{\tau_{sw}}$

**Design Ratio:**

- Cover Shear: $DR > 2.0$
- SWCR Shear: $DR > 5.0$

**References:**

- Minton, S.M. (1965)
- Kargull, L.J. (1962)

**Example:**

1. **Shear:**
   
   - Friction Angle:
     - Cover Soil to SWCR: $40^\circ$
     - SWCR to FMC: $25^\circ$
     - Angle to SWCR: $51^\circ$
   
   - Cover Soil Depth: 4 ft
   
   - Cover Soil Density: 150 lb/ft$^3$
   
   - SWCR Strength: 150 lb/ft$^3$

   - **Calculate Design Ratio for Cover**
     
     $DR = \frac{T_{sw}}{T_{fr}} = \frac{6,800}{2,600} > 2.6$

   - **Calculate Shear Stress Angle for SWCR System**
     
     $\tau_u = \frac{\tan 40^\circ + \tan 51^\circ}{\tan 40^\circ} = 1.07$

   - **Calculate Design Ratio for SWCR Shear**
     
     $DR = \frac{16 \times 144}{223} = 9.6 > 5.0$

**Operators** should contact their local agricultural extension agent or State Department of Transportation to find out what kinds of vegetation will grow under the conditions at the site. The impact of the SWCR system on the soil layer also should be studied before vegetation is chosen. Native grasses usually are the best choice because they already are adapted to the surrounding environment. Sometimes vegetation can overcome adverse conditions, however. At one site in the New Jersey Meadowlands, plants responded to excess surface water by anchoring to the underlying waste through holes in a FMC, creating a sturdy bond between surface plants and underlying material.

For sites on very arid land or on steep slopes, an armoring system, or hardened cap, may be more effective than a vegetative layer for securing a landfill. Operators should not depend on an agricultural layer for protection in areas where vegetation cannot survive. Many States allow
### Cell Component: Surface Water Collection/Removal System

**Consideration:** Tensile Stress; Evaluate ability of SWSR to resist tensile forces resulting from imbalance in shear capacities.

<table>
<thead>
<tr>
<th>Required Material Properties</th>
<th>Range</th>
<th>Test</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Angle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- SWSR to SMC, $\theta_1$</td>
<td>35°-45°</td>
<td>DOWN SHEAR</td>
<td>ASTM D754</td>
</tr>
<tr>
<td>- SMC to SMC, $\theta_2$</td>
<td>10°-20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength of SWSR, $T_{u}$</td>
<td>$300-450$ MPY</td>
<td>DOWN SHEAR</td>
<td>ASTM D754</td>
</tr>
</tbody>
</table>

**Analysis Procedure:**

1. **Calculate Shear Stress Above & Below SWSR**
   \[ T_{u} = \frac{G_u \tan \theta_1 \cos \beta}{\cos \theta_1}, \quad T_{l} = \frac{G_u \tan \theta_2 \cos \beta}{\cos \theta_2} \]

2. **Calculate Tensile in SWSR**
   \[ T_{MAX} = (T_u + T_l) L \]

3. **Calculate Design Ratio**
   \[ DR = \frac{\max(T_u, T_l)}{T_{MAX}} \]

**Example:**

- **Ground Angles**
  - SWSR to SMC, $\theta_1$ = 40°
  - SMC to SMC, $\theta_2$ = 25°
  - Slope Angle, $\theta$ = 3.75°
  - Cover Soil Depth, $D_{c}$ = 14 ft
  - Tensile Strength of SWSR, $T_{u}$ = 400 MPY
  - SWSR Length, $L$ = 200 ft

1. **Calculate Shear Stress Above & Below SWSR**
   \[ G_u = 4500 \text{ MPY}, \quad T_u = \frac{450 \cdot 450 \cdot \tan 40^\circ}{\cos 40^\circ} = 3910 \text{ MPY} \]

2. **Calculate Tensile in SWSR**
   \[ T_{MAX} = (3910 + 3910) \cdot 200 = 38600 \text{ MPY}, \quad 2970 \text{ in/lb} \]

3. **Calculate Design Ratio**
   \[ DR = \frac{400}{2970} = 0.13 \]

**Figure 5-5: Tensile stress for a surface water collection and removal system.**

### Other Considerations

Filter layers, frost penetration, and cap-liner connections are other factors to consider in designing the closure system for a hazardous waste landfill. Before using geotextiles for filter layers in closures, one should conduct pressure tests and clogging tests on the material. Freeze-thaw cycles probably have little effect on membranes, but their impact on clay is still not known. Because of this lack of knowledge, membrane and clay layers should be placed below the frost penetration layer. Figure 5-13 shows frost penetration depths in inches for the continental United States. Finally, a cap membrane should not be welded to the primary flexible membrane liner (see Figure 5-14). Differential settlement in the cap can put tension on the cap membrane. In such a situation, the seam could separate and increase the potential for integration of the surface water collection system into the leak detection system.
Figure 5-6. Puncture and impact resistance of common FMLs.

a. Puncture Resistance

b. Impact Resistance

(Koerner, 1988)
Figure 5-7. The effects of settlement on a flexible membrane cap.
Figure 5-8. Details of a gas vent pipe system.
Figure 5-9. Water traps in a gas collector system.

Figure 5-10. Air and water transmissivity in a needle-punched nonwoven geotextile.

(Koerner, et al, 1984)

Normalized Pressure Ratio

Relative Air Permeability

Relative Water Permeability

0 0.2 0.4 0.6 0.8 1.0

Figure 5-11. Optional biotic barrier layer.
Figure 5-12. Soil erosion due to slope.
Figure 5-13. Regional depth of frost penetration in inches.

Figure 5-14. Geosynthetic cell profile with extrusion welds at FML and FMC junctures.
7. CONSTRUCTION OF FLEXIBLE MEMBRANE LINERS

Introduction
This chapter describes the construction of flexible membrane liners (FMLs), quality control measures that should be taken during construction, and EPA’s construction quality assurance (CQA) program. The CQA program for FMLs is a planned series of activities performed by the owner of a hazardous waste facility to ensure that the flexible membrane liner is constructed as specified in the design. There are five elements to a successful CQA program: (1) responsibility and authority, (2) CQA personnel qualifications, (3) inspection activities, (4) sampling strategies, and (5) documentation. This chapter discusses each of these elements.

Responsibility and Authority
A FML may be manufactured by one company, fabricated by a second company, and installed by a third company. The FML also may be manufactured, fabricated, and installed by the same company. Depending on how the FML is constructed, various individuals will have responsibilities within the construction process. These individuals may include engineers, manufacturers, contractors, and owners. In general, engineers design the components and prepare specifications, manufacturers fabricate the FML, and contractors perform the installation.

Any company that installs a FML should have had past experience with at least 10 million square feet of a similar FML material. Supervisors should have been responsible for installing at least 2 million square feet of the FML material being installed at the facility. Caution should be exercised in selecting firms to install FMLs since many companies have experienced dramatic growth in the last several years and do not have a sufficient number of experienced senior supervisors.

A qualified auditor should be employed to review two key documents: (1) a checklist of requirements for facilities, which will help ensure that all facility requirements are met; and (2) a CQA plan, which will be used during construction to guide observation, inspection, and testing.

Designers are responsible for drawing up general design specifications. These specifications indicate the type of raw polymer and manufactured sheet to be used, as well as the limitations on delivery, storage, installation, and sampling. Some specific high density polyethylene (HDPE) raw polymer and manufactured sheet specifications are:

- Raw Polymer Specifications
  - Density (ASTM D1505)
  - Melt index (ASTM D1238)
  - Carbon black (ASTM D1603)
  - Thermogravimetric analysis (TGA) or differential scanning calorimetry (DSC)

- Manufactured Sheet Specifications
  - Thickness (ASTM D1593)
  - Tensile properties (ASTM D638)
  - Tear resistance (ASTM D1004)
  - Carbon black content (ASTM D1603)
  - Carbon black disp. (ASTM D3015)
  - Dimensional stability (ASTM D1204)
  - Stress crack resistance (ASTM D1693)

Both the design specifications and the CQA plan are reviewed during a preconstruction CQA meeting. This meeting is the most important part of a CQA program.

The preconstruction meeting also is the time to define criteria for "seam acceptance." Seams are the most difficult aspect of field construction. What constitutes an acceptable seam should be defined before the installation gets under way. One technique is to define seam acceptance and verify the
qualifications of the personnel installing the seams at the same time. The installer's seamers produce samples of welds during the preconstruction CQA meeting that are then tested to determine seam acceptability. Samples of "acceptable" seams are retained by both the owner and the installer in case of disputes later on. Agreement on the most appropriate repair method also should be made during the preconstruction CQA meeting. Various repair methods may be used, including capstripping or grinding and rewelding.

CQA Personnel Qualifications

EPA requires that the CQA officer be a professional engineer (PE), or the equivalent, with sufficient practical, technical, and managerial experience. Beyond these basic criteria, the CQA officer must understand the assumptions made in the design of the facility and the installation requirements of the geosynthetics. Finding personnel with the requisite qualifications and actual field experience can be somewhat difficult. To develop field expertise in landfill CQA, some consulting firms routinely assign an inexperienced engineer to work with trained CQA people on a job site and not bill for the inexperienced engineer receiving training. This enables companies to build up a reservoir of experience in a short period of time.

Inspection Activities

Because handling and work in the field can damage the manufactured sheets, care must be taken when shipping, storing, and placing FMLs. At every step, the material should be carefully checked for signs of damage and defects.

Shipping and Storage Considerations

FML panels frequently are fabricated in the factory, rather than on site. The panels must be shipped and stored carefully. High crystalline FML, for example, should not be folded for shipment. White lines, which indicate stress failure, will develop if this material is folded. Flexible membrane liners that can be folded should be placed on pallets when being shipped to the field. All FMLs should be covered during shipment. Each shipping roll should be identified properly with name of manufacturer/fabricator, product type and thickness, manufacturer batch code, date of manufacture, physical dimensions, panel number, and directions for unfolding.

Proper onsite storage also must be provided for these materials. All FMLs should be stored in a secure area, away from dirt, dust, water, and extreme heat. In addition, they should be placed where people and animals cannot disturb them. Proper storage prevents heat-induced bonding of the rolled membrane (blocking), and loss of plasticizer or curing of the polymer, which could cause embrittlement of the membrane and subsequent seaming problems.

Bedding Considerations

Before placing the membrane, bedding preparations must be completed. Adequate compaction (90 percent by modified proctor equipment; 95 percent by standard proctor equipment) is a must. The landfill surface must be free of rocks, roots, and water. The subgrades should be rolled smooth and should be free from desiccation cracks. The use of herbicides can also affect bedding. Only chemically compatible herbicides should be used, particularly in surface impoundments. Many herbicides have hydrocarbon carriers that will react with the membranes and destroy them.

FML Panel Placement

Prior to unfolding or unrolling, each panel should be inspected carefully for defects. If no defects are found, the panels may be unrolled. The delivery ticket should describe how to unroll each panel. Starting with the unrolling process, care should be taken to minimize sliding of the panel. A proper overlap for welding should be allowed as each panel is placed. The amount of panel placed should be limited to that which can be seamed in 1 day.

Seaming and Seam Repair

After the panels have been inspected for defects, they must be seamed by a qualified seamer. The membrane must be clean for the seaming process and there must be a firm foundation beneath the seam. Figure 7-1 shows the configuration of several types of seams.

The most important seam repair criterion is that any defective seam must be bounded by areas that pass fitness structure tests. Everything between such areas must be repaired. The repair method should be determined and agreed upon in advance, and following a repair, a careful visual inspection should be performed to ensure the repair is successful.

Weather and Anchorage Criteria

Weather is an additional consideration when installing a FML. From the seaming standpoint, it is important not to expose the liner materials to rain or dust. Any time the temperature drops below 50°F, the installer should take precautions for temperature. For example, preheaters with the chambers around them may be used in cold weather to keep the FML warm. There also should be no excessive wind, because it is very difficult to weld under windy conditions.

In addition, FML panels should be anchored as soon as possible. The anchor trench may remain open for
understand the liabilities, the risks, and the problems associated with landfill liner failure.

**Sampling Strategies**

In a CQA program, there are three sampling frequency criteria: (1) continuous (100 percent), (2) judgmental, and (3) statistical. Every FML seam should be tested over 100 percent of its length. Any time a seaming operation begins, a sample should be cut for testing. A sample also should be taken any time a seaming operation is significantly modified (by using a new seamer or a new factory extrusion rod, or by making a major adjustment to the equipment).

**Continuous (100 Percent) Testing**

There are three types of continuous tests: visual, destruct (DT), and nondestruct (NDT). **Visual inspection** must be done on all seams, and **DT tests** must be done on all startup seams.

There are several types of nondestruct (NDT) seam tests (see Table 7-1). The actual NDT test depends on the seam type and membrane polymer. An **air lance** (a low pressure blast of air focused on the edge of the seam) can be used on polyvinyl chloride (PVC), chlorinated polyethylene (CPE), and other flexible liner materials. If there is a loose bond, the air lance will pop the seam open.

In a **mechanical point stress test**, a screwdriver or a pick is pressed into the edge of the seam to detect a weak bond location. In a **vacuum chamber test**, the worker applies soapy water to the seam. The vacuum chamber is then moved over the seam. If there is a hole, the vacuum draws air from beneath the membrane, causing a bubble to occur. The chamber should not be moved too quickly across the seam. To be effective, the vacuum box should remain on each portion of the seam at least 15 seconds before it is moved. Otherwise, it may not detect any leaks.

The **pressurized dual seam test** checks air retention under pressure. This test is used with double hot air or wedge seams that have two parallel welds with an air space between them, so that air pressure can be applied between the welds. Approximately 30 psi is applied for 5 minutes with a successful seam losing no more than 1 psi in that time. This seam cannot be used in sumps or areas in which there is limited space for the equipment to operate.

**Ultrasonic equipment** also may be used in a variety of seam tests. This equipment measures the energy transfer across a seam using two rollers: one that transmits a high frequency signal, and one that receives it. An oscilloscope shows the signal being received. An anomaly in the signal indicates some change in properties, typically a void caused by the

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**Figure 7-1. Configurations of field geomembrane seams.**

several days after installation of a panel. However, the anchor trench must be filled when the panel is at its coolest temperature and is, therefore, shortest in length. This will occur early in the morning.

**Additional Polymer Components**

Polymer components, such as geotextiles, geonets, and geogrids, must be carefully inspected, as there is no CQA program for these components. Chapter Four discusses polymer components in more detail. To date, CQA activities have focused on FMLs, and there is no way to "fingerprint" other materials to determine their characteristic properties over the long term. Fingerprinting refers to the evaluation of the molecular structure of the polymer. For example, some geonets sold on the market use air-entrained polymers to create "foamed" geonets with greater thicknesses. Over time, however, the air-in the entrained bubbles diffuses through the polymer and the drainage net goes flat. When loads are left on these geonets for testing purposes, it is possible to observe orders-of-magnitude reductions in the capacity of these materials by the 30th day of testing.

Geotextiles, geogrids, and geonets all should be purchased from companies that have instituted quality control procedures at their plants and
presence of water). Ultrasonic equipment, however, will not detect a tacked, low-strength seam or dirt contamination, and the tests are very operator-dependent.

Judgmental Testing
Judgmental testing involves a reasonable assessment of seam strength by a trained operator or CQA inspector. Judgmental testing is required when a visual inspection detects factors such as apparent dirt, debris, grinding, or moisture that may affect seam quality.

Statistical Testing
True statistical testing is not used in evaluating seams; however, a minimum of one DT every 500 feet of seam, with a minimum of one test per seam, is required. Sumps or ramps, however, may have seams that are very short, and samples should not be cut from these seams unless they appear defective. In
Table 7-1. Overview of Nondestructive Geomembrane Seam Tests

<table>
<thead>
<tr>
<th>Nondestructive Test Method</th>
<th>Primary User</th>
<th>Cost of Equipment ($)</th>
<th>General Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contractor</td>
<td>Design Engr.</td>
<td>Speed of Tests</td>
</tr>
<tr>
<td></td>
<td>Third Party Inspector</td>
<td></td>
<td>Cost of Tests</td>
</tr>
<tr>
<td>1. Air lance</td>
<td>Yes</td>
<td>--</td>
<td>Fast</td>
</tr>
<tr>
<td>2. Mechanical point (pick)</td>
<td>Yes</td>
<td>--</td>
<td>Fast</td>
</tr>
<tr>
<td>3. Vacuum chamber (negative</td>
<td>Yes</td>
<td>Yes</td>
<td>Slow</td>
</tr>
<tr>
<td>4. Dual seam (positive</td>
<td>Yes</td>
<td>Yes</td>
<td>Fast</td>
</tr>
<tr>
<td>5. Ultrasonic pulse echo</td>
<td>--</td>
<td>Yes</td>
<td>Mod.</td>
</tr>
<tr>
<td>6. Ultrasonic impedance</td>
<td>--</td>
<td>Yes</td>
<td>Mod.</td>
</tr>
<tr>
<td>7. Ultrasonic shadow</td>
<td>--</td>
<td>Yes</td>
<td>Mod.</td>
</tr>
</tbody>
</table>


In addition, a minimum of one DT test should be done per shift.

There are no outlier criteria for statistical testing of seams. In other words, no failure is acceptable. Typically two tests, a shear test and a peel test, are performed on a DT sample (Figure 7-2). The shear test measures the continuity of tensile strength in a membrane. It is not, however, a good indicator of seam quality. The peel test provides a good indication of the quality of a weld because it works on one face of a weld. A poor quality weld will fail very quickly in a peel test.

In a shear test, pulling occurs in the plane of the weld. This is comparable to grabbing onto the formica on a desk top and trying to pull the formica off horizontally. The bond is being sheared. The peel test, on the other hand, is a true test of bond quality. This test is comparable to getting beneath the formica at one corner of a desk top and peeling up.

**Documentation**

Documentation is a very important part of the CQA process. Documents must be maintained throughout FML placement, inspection, and testing. A FML panel placement log (Figure 7-3), which details the panel identity, subgrade conditions, panel conditions, and seam details, should be kept for every panel that is placed. This form is filled out on site and typically carries three signatures: the engineer's, the installer's, and the regulatory agency's onsite coordinator's (if appropriate).

In addition, all inspection documents (e.g., information on repairs, test sites, etc.) must be carefully maintained. Every repair must be logged (Figure 7-4). Permits should never be issued to a facility whose records do not clearly document all repairs.

During testing, samples must be identified by seam number and location along the seam. A geomembrane seam test log is depicted in Figure 7-5. This log indicates the seam number and length, the test methods performed, the location and date of the test, and the person who performed the test.

At the completion of a FML construction, an as-built record of the landfill construction should be produced that provides reviewers with an idea of the quality of work performed in the construction, as well as where problems occurred. This record should contain true panel dimensions, location of repairs, and location of penetrations.
Dirt within an extruded seam.
Figure 7-2. Seam strength tests.

Figure 7-3. Panel placement log.
### Geomembrane Repair Log

<table>
<thead>
<tr>
<th>Date</th>
<th>Seam</th>
<th>Panels</th>
<th>Location</th>
<th>Material Type</th>
<th>Description of Damage</th>
<th>Type of Repair</th>
<th>Repair Test Type</th>
<th>Tested By</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

**Figure 7-4. Geomembrane repair log.**
<table>
<thead>
<tr>
<th>Seam No.</th>
<th>Seam Length</th>
<th>Visual Inspect</th>
<th>Air Temp.</th>
<th>Test Method</th>
<th>Pressure Init/Final</th>
<th>Peel Test</th>
<th>Shear Test</th>
<th>Location</th>
<th>Date</th>
<th>Tested By</th>
</tr>
</thead>
</table>

Figure 7-8. Geomembrane seam test log.