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Minimum Technology Guidance on Double Liner Systems for Landfills and Surface Impoundments-- Design, Construction, and Operation

Second version

May 24,1985

Minimum Technology Guidance on Double Liner Systems for Landfills and Surface Impoundments

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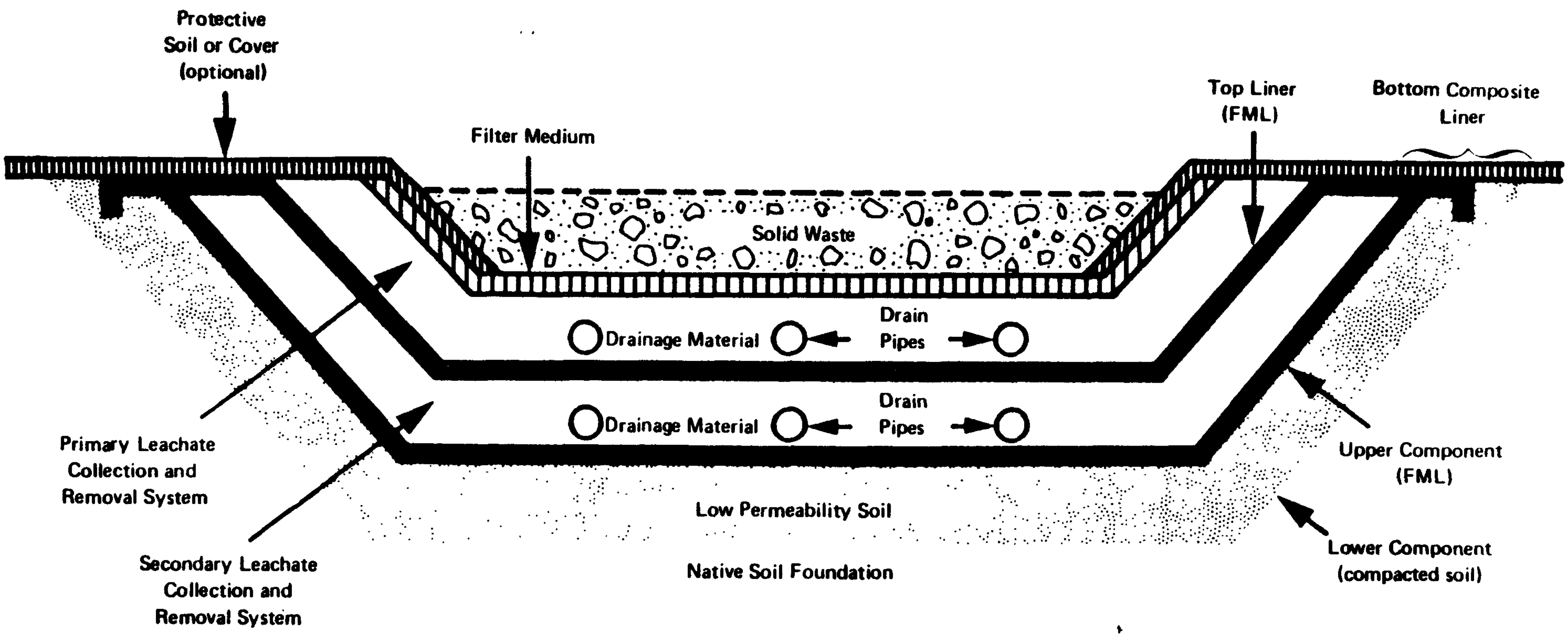
Introduction

On November 8, 1984, the President signed into law the Hazardous and Solid Waste Amendments of 1984 (HSWA). Under Sections 3004(o) and 3015 of the HSWA certain landfills and surface impoundments are required to have "two or more liners and a leachate collection system above (in the case of a landfill) and between such liners," unless the conditions for a statutory variance are met. Section 3004(o)(5)(B) allows the use of a particular type of liner design pending the issuance of EPA regulations or guidance documents (through the notice and comment process) implementing the double liner requirement in Section 3004(o). This guidance document is intended to provide guidance on designs in addition to the design set out in Section 3004(o)(5)(B) that the Agency believes meet the requirements of §§3004(o) and 3015 of the HSWA and are protective of human health and the environment. This document identifies two such double liner systems.

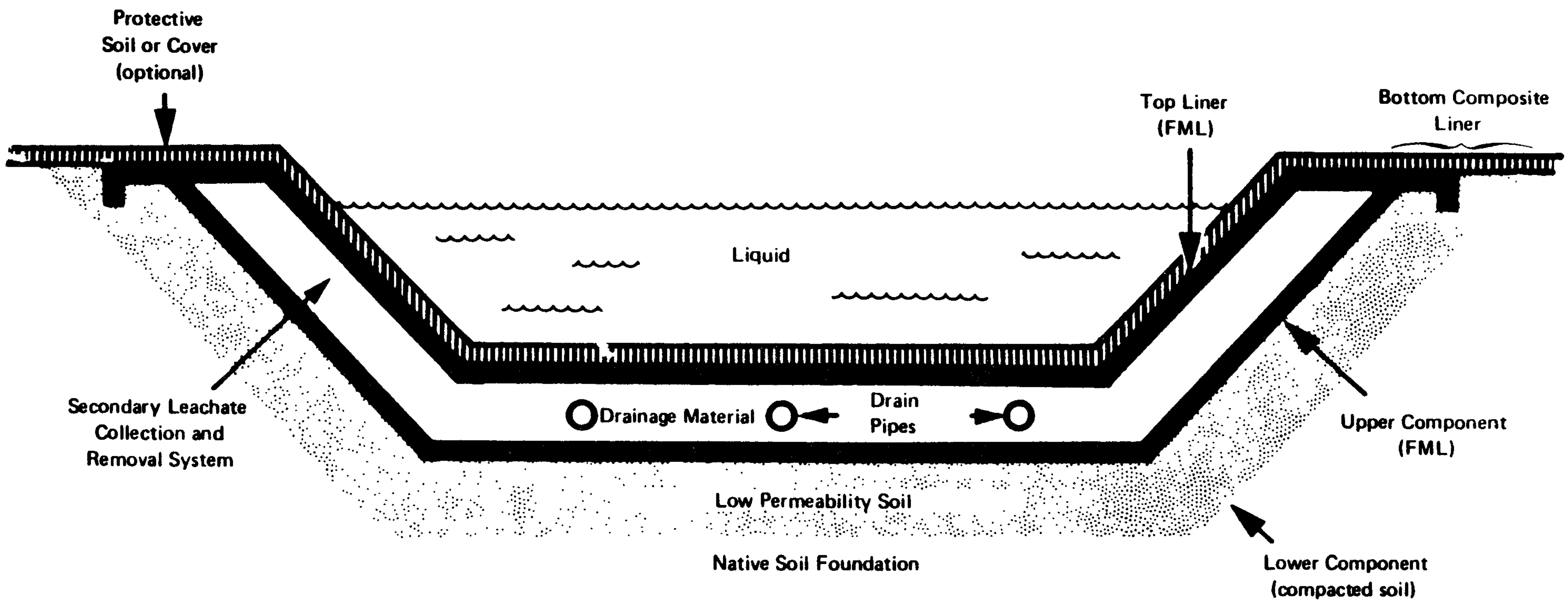
The first double liner system includes a top liner and a composite bottom liner (Figures 1 & 2). The top liner is designed, operated, and constructed of materials to prevent the migration of any hazardous constituents into such liner during the period the facility remains in operation (including a 30-year post-closure monitoring period). The top liner is a flexible membrane liner (FML), which is addressed in this guidance in some detail. The bottom liner consists of two components that are intended to function as one system, hence, the term "composite" liner. Like the top liner, the upper component of the bottom liner is designed, operated, and constructed to prevent the migration of any constituent into this component during the period of facility operation, including the post-closure monitoring period. The upper component of the composite liner is also a flexible membrane liner (FML). The lower component of the bottom liner is designed, operated, and constructed to

FIGURE 1
SCHEMATIC OF AN FML/COMPOSITE DOUBLE LINER SYSTEM FOR A LANDFILL



(Not to Scale)

FIGURE 2
SCHEMATIC OF AN FML/COMPOSITE DOUBLE LINER SYSTEM FOR A SURFACE IMPOUNDMENT



Note: Primary leachate collection system not used in surface impoundment.

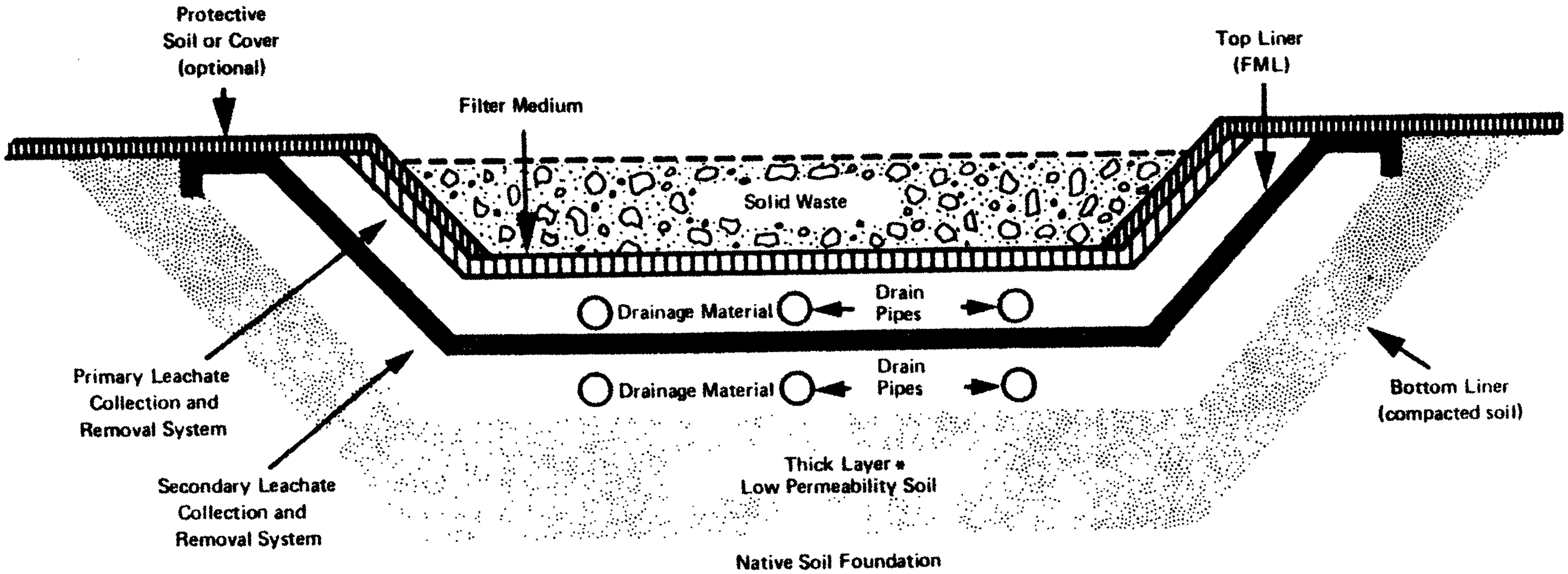
(Not to Scale)

minimize the migration of any constituent through the upper component if a breach in the upper component were to occur prior to the end of facility operation, including the post-closure monitoring period. The lower component of the composite bottom liner is a compacted soil that should meet technical requirements set forth in this document.

The second design includes the performance standard from Section 3004(o)(5)(B) This double liner system includes a top liner designed, constructed, and operated of materials to prevent the migration of any constituent into such liner during the period the facility remains in operation (including a 30-year post-closure monitoring period), and a lower liner designed, operated, and constructed to prevent the migration of any constituent through the liner during this period (Figures 3 & 4). The top liner in this design is an FML and the bottom liner is a compacted low permeability soil. Section 3004(o)(5)(B) provides that a three-foot thick liner of recompacted clay or other natural material will satisfy the lower liner requirement. Because EPA believes that three feet of clay or other natural material will not prevent migration in most cases, this document provides guidance on what the Agency believes is an adequate lower liner. The Agency interprets the term "natural material" to mean any naturally occurring soil that can be compacted, without man made additives, into a liner with a permeability of 1 X 10^{-7}cm/sec or less.

Although both of these double liner system designs are acceptable, this guidance contains more information on the first design than the second. The second design is more dependent on site specific characteristics, such as the amount of annual rainfall, than the first design. Also, the second design requires a series of assumptions on leakage rates, flow characteristics, and other factors. Therefore, the specificity of guidance that is given on the second double liner system design is more limited.

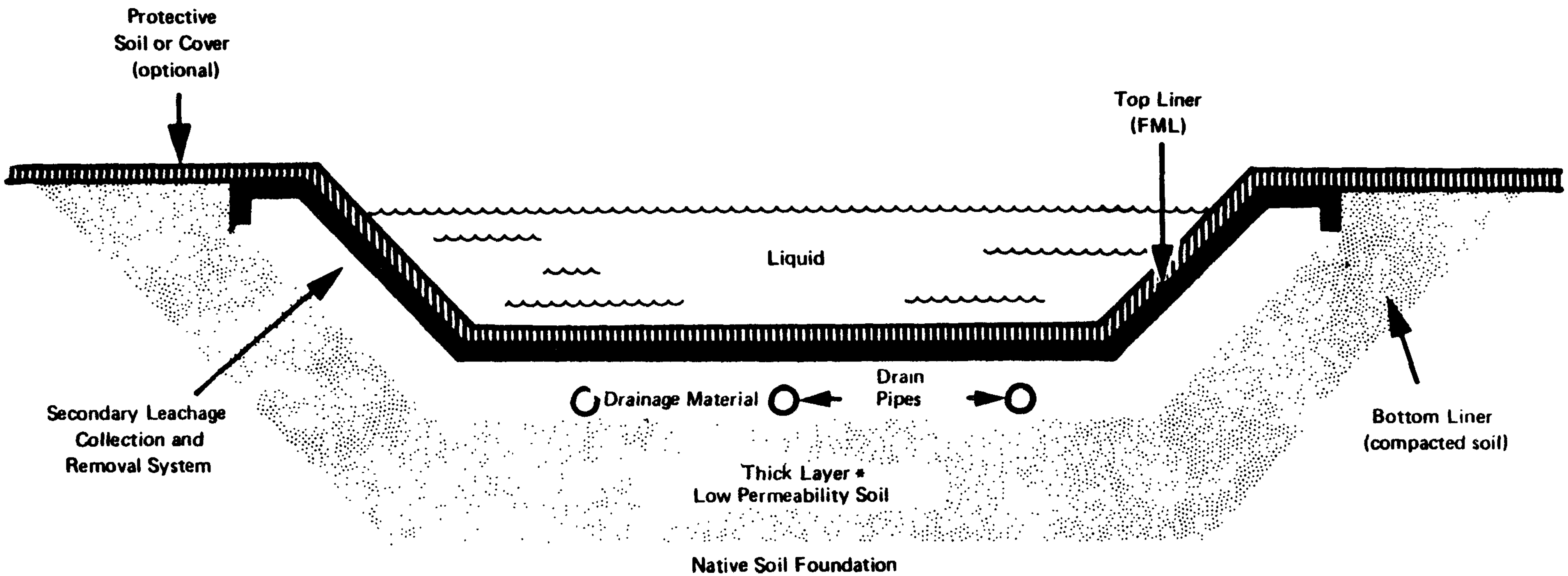
FIGURE 3
SCHEMATIC OF AN FML/COMPACTED SOIL DOUBLE LINER SYSTEM FOR A LANDFILL



(Not to Scale)

* Thickness to be determined by break through time.

FIGURE 4
SCHEMATIC OF AN FML/COMPACTED SOIL DOUBLE LINER SYSTEM
FOR A SURFACE IMPOUNDMENT



* Thickness to be determined by breakthrough time.

Note: Primary leachate collection system not used in surface impoundment.

(Not to Scale)

The double liner system set out in Section 3004(o)(5)(B) and the two double liner systems discussed in this guidance are not the only double liner systems that may be used to comply with the minimum technology requirements of HSWA. Other double liner systems, depending on their design, operation, location, and waste types to be received, may be acceptable. Alternative double liner systems may include other amended soil materials with man made products or natural materials such as soil cement, lime/soil mixture, or fly ash/soil mixture. However, an owner/operator choosing to install an alternative double liner system should confer with the Agency during the design and construction of the system in order for EPA to ascertain whether the system will meet the minimum technology requirements of HSWA.

For example, an owner/operator of an interim status landfill or surface impoundment who wants to install one of the two double liner systems described in this guidance below the ground-water table should request review of the design plans prior to construction. Liner and leachate collection system installation below the ground-water table involves many site-specific considerations. Such systems are not specifically discussed in this guidance. Owners and operators choosing the design in §3004(o)(5)(B) or one of the two designs that are discussed in this guidance (particularly the FML/composite design) should be able to proceed with construction with substantially less Agency interaction. (This is likely to be the case for both interim status and permitted units.)

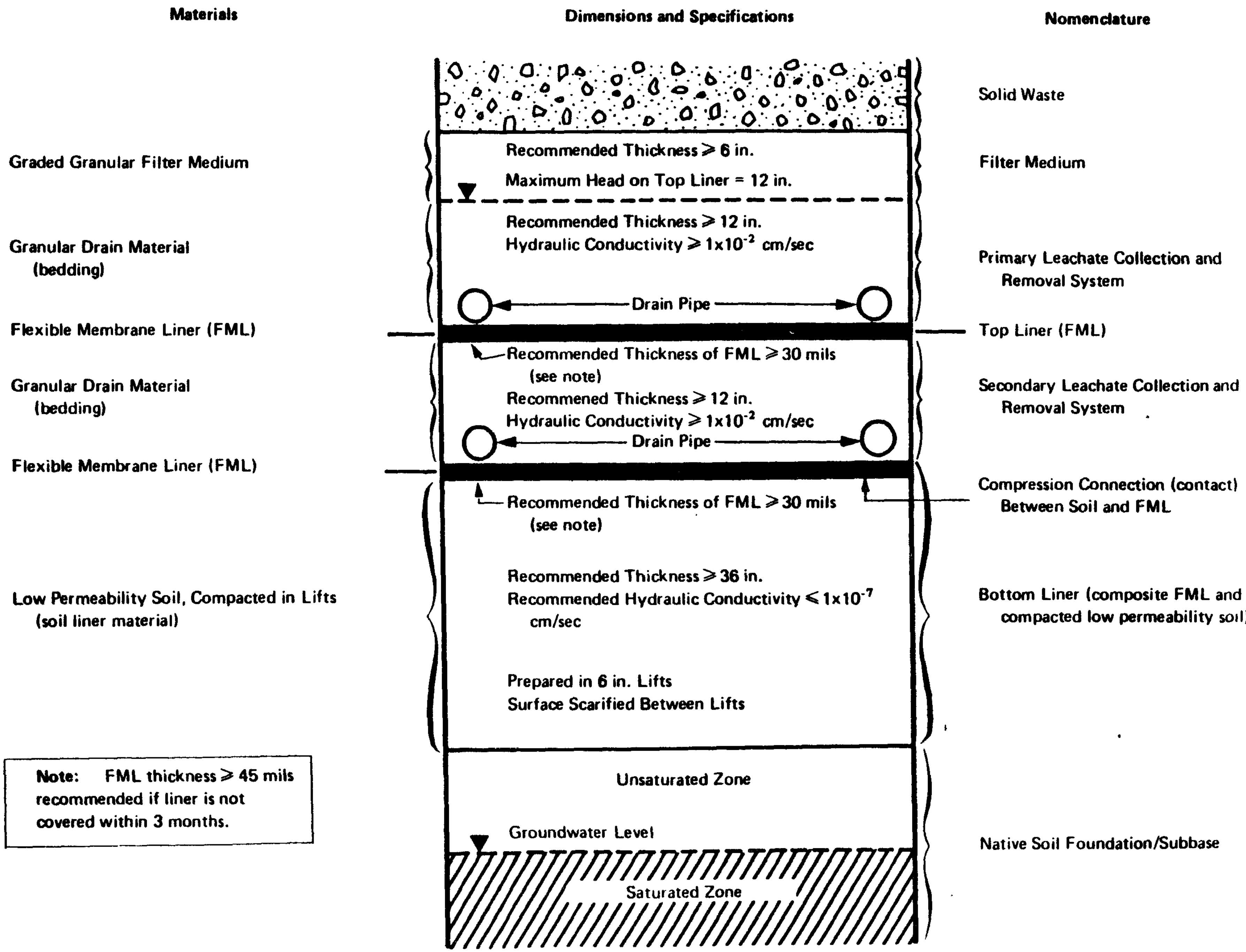
This guidance is intended to incorporate the current state-of-the-art regarding the design, construction, and operation of hazardous waste land disposal units. The attempt has been made to include an element of practicality in specifying how to construct a unit. However, this guidance does not address all components of facility design, construction, operation, and closure. For example, it does not address the final cover requirements for landfills and certain surface impoundments, nor does it discuss considerations for freeboard in impoundment design and operation. The Agency's previously issued guidance (July 1982) continues to be applicable in these areas. [NOTE: EPA does not believe §§264.228(a)(2)(iii)(E) or 264.310(a)(5) for permitted units require the installation of two FMLs in the final cover when two FMLs are used in the double liner system. A single FML in the final cover that is equivalent to the thicker FML used in the double liner system will be considered to have an equivalent permeability.]

This guidance is one step in the Agency's efforts to implement the minimum technology requirements of §§3004(o) and 3015 of the HSWA. We expect to formalize many of these guidelines in the future by incorporating them into the Agency's regulations.

FML/COMPOSITE DOUBLE LINER SYSTEM

The FML/composite double liner system consists, at a minimum, of a primary leachate collection and removal system (for landfills), a top FML liner, a secondary leachate collection system, and a bottom composite FML/low permeability soil liner. A detailed cross section of the basic components of the FML/composite double liner system for landfill and surface impoundment units is shown in Figure 5. The function of the primary leachate collection and removal system at landfills is to minimize the head (depth) of leachate on the top liner during operation and to remove liquids through the post-closure monitoring period. The leachate collection and removal system should be capable of maintaining a leachate head of less than 1-foot. The top liner should be designed, constructed, operated, and maintained to prevent migration of waste liquid constituents during operation (including the post-closure monitoring period) and should allow no more than de minimis infiltration of any constituent into the liner itself. The secondary leachate collection system between the two liners should be designed, constructed, operated, monitored, and maintained to rapidly detect, collect, and remove liquids entering the collection system for treatment through the post-closure monitoring period. The bottom liner consists of two components that are intended to function as one system, hence, the term "composite" liner. Like the top liner, the upper component of the bottom liner should be designed, operated, and constructed to prevent the migration of any constituent of the waste liquid into the upper component during the period of facility operation, including the post-closure monitoring period. For design purposes, the post-closure monitoring period should nominally be assumed to be 30 years. The lower component of the bottom liner should be designed, operated, and constructed to minimize the migration of any constituent of the waste liquid

FIGURE 5
SCHEMATIC PROFILE OF AN FML/COMPOSITE DOUBLE LINER SYSTEM FOR A LANDFILL



through the upper component if a breach in the upper component were to occur prior to the end of facility operation, including the post-closure monitoring period. Compacted low permeability soil is recommended for the lower component. EPA believes that this design is effective in protecting human health and the environment because the combination of the two components in the bottom liner system provides for virtually complete removal of waste or leachate by the leachate collection system if a leak were to occur in the top liner.

I. Primary Leachate Collection and Removal Systems for Landfills

Contents

A. Guidance

Overall Design, Construction, and Operation Objective

The primary leachate collection and removal system system should be designed to ensure that the leachate depth above the top liner does not exceed one foot; be constructed of materials that can withstand the chemical attack that results from waste liquids or leachates; be designed and constructed so as to withstand the stresses and disturbances from overlying wastes, waste cover materials, and equipment operation; be designed and operated to function without clogging through the post-closure monitoring period; and be operated to collect and remove leachate through the post-closure monitoring period. Components should be properly installed to assure that the specified performance of the leachate collection system is achieved.

Design

The primary leachate collection and removal system should have:

(a) At least a 30 centimeter (12 inch) thick granular drainage layer that is chemically resistant to the waste and leachate, with a hydraulic conductivity not less than 1×10^{-2} cm/sec and with a minimum bottom slope of 2 percent.

Innovative leachate collection systems incorporating synthetic drainage layers or nets may be used if they are shown to be equivalent to or more effective than the granular design, including chemical compatibility, flow under load, and protection of the FML (e.g., from puncture).

(b) A graded granular or synthetic fabric filter above the drainage layer to prevent clogging. Criteria for graded granular filters and for synthetic fabric filters are found in numerous publications such as the Geotextile Engineering Manual available from the Federal Highway Administration and others. The granular drainage material should be washed to remove fines before installation.

(c) A drainage system of appropriate pipe size and spacing on the bottom of the unit to efficiently collect leachate. These pipe materials should be chemically resistant to the waste and leachate. The piping system should be strong enough to withstand the weight of the waste materials and vehicular traffic placed on or operated on top of it.

(d) A primary leachate collection system that covers the bottom and sidewalls of the unit.

(e) A sump in each unit or cell should be capable of automatic and continuous functioning. The sump should contain a conveyance system for the removal of leachate from the unit such as either a sump pump and conveyance pipe or gravity drains.

(f) A written construction quality assurance (CQA) plan prepared by the owner/operator to be used during construction of the double liner system including the primary leachate collection and removal system. See Section IV, "Construction Quality Assurance", for specific details.

Construction

(a) The owner/operator should use the construction quality assurance plan to monitor and document the quality of materials used and the conditions and manner of their placement during construction of the primary leachate collection and removal system. See Section IV, "Construction Quality Assurance", for specific details.

(b) The documentation for the CQA program should be kept on-site in the facility operating record maintained for the landfill unit.

Operation

The following operational procedures should be followed:

(a) The leachate removal system should operate automatically whenever leachate is present in the sump and should remove accumulated leachate at the earliest practicable time to minimize the leachate head on the liner (not to exceed 12 inches);

(b) Inspect weekly and after major storm events for proper functioning of the leachate collection and removal system, and for the presence of leachate in the removal sump. The owner or operator should keep records on the system to provide sufficient information that the primary leachate collection system is functional and operated properly. We recommend the amount of leachate collected be recorded in the facility operating record for each unit on a weekly basis;

(c) Cleaning out of collection lines periodically; and

(d) A storage permit for collected leachate, if required. Collected leachate is subject to the prohibition on placement of liquids in landfills in RCRA §3004(c).

B. Discussion

The Agency believes that practical designs for leachate collection and removal systems can maintain a leachate depth of one foot or less, except perhaps temporarily (for a few days) after major storms. The specifications presented here, judiciously applied, are expected to accomplish that requirement.

The minimum thickness (30 centimeters or 12 inches) of the drainage layer allows sufficient cross sectional area for transport of drainage leachate. The two-percent minimum slope is also intended to promote drainage. In most cases, the Agency believes thicker drainage layers and greater slopes will be selected by owners and operators to maximize the efficiency of the leachate collection and removal system. The hydraulic conductivity of not less than 1×10^{-2} cm/sec was chosen because materials widely used as drainage media are coarse enough that their hydraulic conductivities are estimated to be 1×10^{-2} cm/sec or greater.

It is not clear if the statutory requirements of §3004(o)(1)(A)(i) require the primary leachate collection system to be on the sidewalls of a landfill. The current Part 264 requirements in §264.301(2) require a collection and removal system immediately above the liner to collect and remove leachate. The previous liner guidance dated July, 1982, did not specify whether the leachate collection system was only to cover the bottom or also the sidewalls of the unit. The Permit Writer's Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities, October 1983, indicates that the need for a leachate collection system of the sidewalls of a landfill should be based on site-specific conditions of expected leachate flow over the life of the facility. Generally, we encourage the installation of a primary leachate collection system on both the base and sidewalls of double liner systems under §3004(o)(1)(A)(i). The two designs in this guidance recommend leachate collection on the sidewalls because it allows leachate to drain to the sump faster and minimize ponding of leachate within the waste on the sidewalls of the top liner.

The following is a list of factors that affect liquid transmission in the leachate collection system drain layer:

- Impingement rate of liquid on the collection drain layer;
- Slope of the drain layer;
- Diameter and spacing between the drainage pipes;
- Coefficient of hydraulic conductivity of the saturated sand or gravel drain layer; and
- Cleanliness (lack of fines) of the sand or gravel.

A method for estimating quantity of liquids collected and liquid depth above the liner is presented in Landfill and Surface Impoundment Performance Evaluation, SW-869, April 1983 (EPA 83).

Drain pipe diameter and spacing are important because they affect the head that builds up on the top liner between pipes. The closer the pipes are together, the less the head. Also, the pipe diameter should be large enough to efficiently carry off the collected leachate. Since the philosophy for all aspects of liner design is to minimize liquid transmission through the liner system, the head on the liner should be minimized. But the spacing and size of the drainage piping system necessary to accomplish this depends on other characteristics of the drainage layer (e.g., hydraulic conductivity) and on the impingement rate of liquids, which is a function of precipitation and the effectiveness of the cover system. The Agency is, therefore, not specifying minimum spacing or pipe diameter in this guidance. However, EPA believes that designs incorporating 6-inch diameter perforated or slotted pipes spaced 50 to 200 feet (15 to 60 meters) apart will effectively minimize head on the liner system in most cases. Information on leachate collection is presented in Appendix V of Lining of Waste Impoundment and Disposal Facilities, SW-870, March 1983 (EPA 83A). The owner or operator should demonstrate through appropriate design calculations that the maximum recommended one-foot head will not be exceeded.

The leachate collection and removal system should be overlain by a graded granular filter or synthetic fabric filter. The purpose of this is to prevent clogging of the voids in the drain layer by infiltration of fines from the waste. If a granular filter is used, it is important that the relationship of grain sizes of the filter medium and the drainage layer be appropriate if the filter is to fulfill its function to prevent clogging of the drainage layer and not contribute to clogging. Criteria for graded granular filters and for synthetic fabric filters are found in numerous sources such as:

Graded granular filters:

- Earth Manual. 1984. Bureau of Reclamation, U.S. Department of the Interior. Government Printing Office, Washington, DC.

Geotextiles:

- Koerner, Robert M., and J.P. Welsh. 1980. Construction and Geotechnical Engineering Using Synthetic Fabrics. John Wiley and Sons, New York.

- Horz, R.C. 1984. Geotextiles for Drainage and Erosion Control at Hazardous Waste Landfills. EPA Interagency Agreement No. AD-96-F-1-400-1. U.S. EPA, Cincinnati, Ohio.

- Geotextile Engineering Manual, Training Manual, Federal Highway Administratio

Innovative leachate collection systems that are equivalent to, or more effective than, the granular system described above may be used. These innovative systems such as plastic nets can be very thin, on the order of one-inch thick, and have the drainage capacity of a sand layer one-foot thick. These systems should be capable of maintaining a leachate head of one foot or less. The following criteria should be addressed for determining equivalence:

° Design - hydraulic transmissivity (i.e., the amount of liquid that can be removed)

  - compressibility (i.e., ability to withstand expected overburden pressures while remaining functional)

- compatibility (chemical) with waste liquid
- compatibility (mechanical) with the FML (i.e., will not deform the FML under the expected overburden)
- slope stability

° Construction - Construction characteristics (i.e., ease of construction)

° Operation/performance characteristics

- drainage or flow characteristics (i.e. how fast liquids will flow and what volume will flow)
- time required to return the leachate head to one foot or less after a rainfall event
- material creep
- useful life of system
- ability to resist clogging
- ability to verify performance.

An owner or operator wishing to use a leachate collection system other than the recommended one should compare the properties of his design against the recommended design using the above criteria. If equivalent, or better he should proceed; if not, he should abandon the alternate design. If one or more of the factors is not equivalent, the collection system will probably not perform well, and will potentially become a source of constant trouble to its owner/operator.

II. Double Liner Specifications

Contents

A. Guidance

Overall Design, Construction, and Operation Objective

All new surface impoundments and landfills, new units, lateral expansions, and replacement units must have two liners. The two liners must be designed, constructed, and operated to protect human heal'h and the environment. The top liner should be designed, operated, and constructed of materials to prevent the migration of any waste liquid constituents into such liner during the period the unit remains in operation (including any post-closure monitoring period), and should allow no more than de minimis infiltration of waste constituents into the liner itself. The top liner discussed herein is a flexible membrane liner (FML). The secondary leachate collection system is between the two liners. The bottom liner consists of two components that are intended to function as one system, hence, the term "composite" liner.

Like the top liner, the upper component of the bottom liner should be designed, constructed, and operated to prevent the migration of any constituents into this component during the period of facility operation, including any post-closure monitoring period. The upper component of the bottom liner of this design is also an FML. The lower component of the bottom liner should be designed, constructed, and operated to minimize the migration of any constituent through the upper component if a breach in the upper component were to occur prior to the end of unit operation, including the post-closure monitoring period. The lower component of the bottom liner is a compacted low permeability soil material. All liner materials should be resistant to the waste liquid constituents the liner will encounter, and be of sufficient strength and thickness to withstand the forces it will encounter during construction and operation. Foundation preparation is recommended to ensure that the structural stability of the subgrade is sufficient to support the liners without damaging them and to prevent failure due to pressure gradients (including mechanical, gas, and liquid static and external hydrogeologic forces). The double liner system should cover all areas likely to be exposed to waste and leachate.

Design

° This liner system should be constructed completely above the seasonal high water table (i.e., in unsaturated soil).

° The two liners should consist of the following, as a minimum:

(a) An FML top liner;

(1) The FML top liner should be at least a 30 mils thick; however, if the liner is to be exposed to the weather for an extended period before it is covered by a protective soil layer or the waste, or if the liner is to be operated without a protective cover, it should be at least 45 mils in thickness.

Many units will require a thicker liner to prevent failure while the unit is operating, including any post-closure monitoring period. The adequacy of the selected thickness should be demonstrated by an evaluation considering the type of FML material and site-specific factors such as: expected operating period of the landfill or surface impoundment unit, pressure gradients, physical contact with the waste and leachate, climatic conditions (environmental factors), the stress of installation, and the stress of daily operation (e.g., placing wastes in the landfill or sludge removal in surface impoundments). Stresses tend to be higher for surface impoundment units than for landfill units. Several factors can increase liner stresses in surface impoundments such as: (1) cleaning or maintenance activities; (2) thermal stress; (3) hydrostatic pressure (head and wave action); (4) abrasion; (5) weather exposure (ultraviolet light, oxygen, ozone, heat, and wind); and (6) operating conditions (inlet and outlet flow, active life, exposure to animals, treatment processes). Because of these factors, uncovered surface impoundments generally require thicker liners than the 45-mil minimum. Thicknesses of 60-100 mils have been necessary in some applications. A protective layer covering the liner in surface impoundments can reduce the stresses on the liner. The Agency will consider appropriate historical data and actual test data regarding the performance of liner materials of the designed thickness as part of the evaluation of the permit application.

(2) Liners should be chemically resistant to the waste and leachate managed at the unit. The Agency strongly prefers test data because the demonstration of chemical resistance should be based on representative waste effects. The EPA Test Method 9090 (October 1, 1984, proposal or revised editions) or an Agency approved equivalent test method should be used to test chemical resistance of liners. Complete copies of the text of sampling

and analytical methodologies addressed in the October 1, 1984, proposed rules (including method 9090) are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161, (703) 487-4650. The document number is PB-85-103-026. In judging chemical compatibility of wastes and membranes, the Agency will consider appropriate historical data or actual test data if obtained under longer or more severe test conditions.

(3) The National Sanitation Foundation (NSF) presents liner material properties and factory seam requirements in their Standard Number 54 for Flexible Membrane Liners, November 1983. The Agency suggests that material and seam specifications such as those in the National Sanitation Foundation standard be used to assure material quality from the liner manufacturer. Liner materials listed by the National Sanitation Foundation for industrial service, or liner materials that are not listed but consistently meet the specifications of the NSF Standard 54, are acceptable for assuring quality from the manufacturer. Test methods used to establish these requirements should comply with applicable American Society of Testing and Materials (ASTM) procedures, recommended methods in EPA document SW-870 Lining of Waste Impoundment and Disposal Facilities (tables VIII-1 to 7) (EPA 1983A), or an equivalent method when available. The FMLs covered by NSF standard 54 include at least the following:

° Polyvinyl Chloride (PVC)
° Polyvinyl Chloride Oil Resistant (PVC-OR)
° Chlorinated Polyethylene (CPE)
° Butyl Rubber (IIR)
° Polychloroprene (CR)
° High Density Polyethylene (HDPE)
° Ethylene-Propylene Diene Terpolymer (EPDM)
° Epichlorohydrin Polymers (CO)
° Polyethylene Ethylene Propylene Alloy (PE-EP-A)

° High Density Polyethylene Elastomeric Alloy (HDPE-A)

° Chlorosulfonated Polyethylene (CSPE)
° Chlorosulfonated Polyethylene, Low Water Absorption (CSPE-LW)
° Thermoplastic Nitrile - PVC (TN-PVC)
° Thermoplastic EPDM (T-EPDM)
° Ethylene Interpolymer Alloy (EIA)
° Chlorinated Polyethylene Alloy (CPE-A)

The address for the National Sanitation Foundation is:

3475 Plymouth Road
P.O. Box 1468
Ann Arbor, Michigan 48106 USA

(4) FMLs should be free of pinholes, blisters, holes, and contaminants, which include, but are not limited to, wood, paper, metal, and nondispersed ingredients.

(5) The compounding ingredients used in producing FMLs should be first quality, virgin materials providing durable and effective formulations for liner applications. Clean rework materials containing encapsulated scrim or other fibrous materials should not be used in the manufacture of flexible membrane liners (FML) used for hazardous waste containment. Clean rework materials of the same virgin ingredients generated from the manufacturer's own production may be used by the same manufacturer, provided that the finished products meet the material specification requirements.

(6) FMLs in landfill units, and in units with the minimum recommended thickness, should be protected from damage from above and below the membrane by a least 30 centimeters (12 inches) nominal, 25 centimeters (10 inches) minimum, bedding material (no coarser than Unified Soil Classification System (USCS) sand (SP) with 100 percent of the washed, rounded sand passing the 1/4 inch sieve) that is free of rock, fractured stone, debris, cobbles, rubbish, and roots, unless it is known that the FML material is not physically impaired by the material under load. The surface of a completed substrate

should be properly compacted, smooth, uniform, and free from sudden changes in grade. The secondary leachate collection system or the low permeability soil may serve as bedding materials when in direct contact with FMLs if they meet the requirements specified herein. Polymeric materials such as geotextiles and synthetic drainage layers may also serve as bedding materials when in direct contact with either surface of the top FML or with the upper surface of the FML component of the bottom liner, if they provide equivalent protection. In determining equivalent protection given by geotextile or other specific materials, the Agency will consider historical data and actual test data that relate to site-specific conditions. To demonstrate that a synthetic drainage layer can serve as bedding material, it should be shown that the synthetic drainage layer does not exhibit brittle failure under overburden stresses and stresses caused by equipment used for construction or waste placement.

Note: In most cases an FML should not be in contact with native, in situ soil.

Note: Light geotextile bedding material may require an additional precaution if the slopes are exposed to high velocity winds.

(7) For surface impoundment and landfill units in which the sidewalls will be uncovered and exposed for extended periods before wastes are placed, the design of the bedding material used below the top liner should be highly permeable and include gas venting if the potential for gas generation under the bottom liner exists, or if the slopes of a surface impoundment will be exposed to high velocity winds.

(8) Penetration of a liner by any designed means should be avoided. Where structures are necessary, such as:

° Pipes (both horizontal and vertical),
° Vertical support columns,
° Inlets, outlets,
° Sumps, and
° Divider walls,

it is essential to obtain a secure, liquid-tight seal between the structure and the FML. An FML may be attached to a structure with a mechanical-type seal supplemented by chemically compatible caulking, adhesives, or heat fusion to effect a liquid-tight seal. Compaction of areas adjacent to the structure should be to the same density as the surrounding soil to minimize differential settlement. Sharp edges on the structure should not come in contact with an FML.

(9) Bridging or stressed conditions in the FML should be avoided with proper slack allowances for shrinkage of the FML during installation and before the placement of a protective soil layer or waste.

(b) A composite bottom liner;

(1) The composite bottom liner consists of two components, an upper FML component and a lower component of compacted low permeability soil.

(2) The upper FML component should be of at least a 30-mil membrane; some units will require a thicker liner to meet the site conditions without probable failure during construction and while the unit is operating, including any post-closure monitoring period. The adequacy of the selected thickness should be demonstrated by an assessment of the type of liner material and site-specific factors. The liner should be chemically resistant to the waste and leachate managed at the unit. The EPA test method 9090 or an equivalent test method should be used to test chemical resistance of liners. In judging chemical compatibility of the membrane with the waste to be managed, the Agency will consider appropriate historical data and actual test data obtained under longer or more severe test conditions.

(3) The upper FML component of the composite bottom liner should be protected from damage from above by at least 30 centimeters (12 inches) of bedding

material no coarser than Unified Soil Classification System (USGS) sand (SP) that is free of rock, fractured stone, debris, cobbles, rubbish, and roots, unless it is known that the liner material under load is not physically impaired by the material. The subgrade to the synthetic upper component will be the uppermost lift of the compacted lower component. This lift should be sufficiently smoothed to provide a good bed for the overlying synthetic material. The secondary leachate detection, collection, and removal system serves as the top bedding material and the low-permeable soil component of the bottom liner serves as the lower bedding material and should meet the requirements specified herein. Polymeric materials such as geotextiles may also be used as top bedding materials when in direct contact with the liner if they provide equivalent protection. They should not be used as the bedding below the FML, as they would increase the transmissity between the two components of the bottom liner. In determining equivalent protection for geotextile, the Agency will consider historical data and actual test data that relates to site-specific conditions.

(4) The FML upper component and the soil lower component interface must be in direct contact, and be designed and constructed to provide a compression connection (contact) between the two components to minimize flow between them. The two components are maintained in contact by the overburden load. The design and construction should minimize void space, channels, and other conditions promoting lateral flow of liquids at this interface. This requirement is not intended to preclude liner installers from purposely leaving designed folds in the synthetic liner material. No fabric or other high-permeability bedding material should be used between the upper and lower components that would have high transmissivity. Overburden pressure exerted on the secondary liner from overlying materials may be sufficient to adequately reduce the

potential for lateral flow. EPA recognizes that there may be procedures or materials which would further reduce the transmissivity of this interfacial zone and encourages demonstrations to that effect.

(5) The soil component of the composite liner should be at least 90 centimeters (36 inches) of compacted, emplaced, low permeability soil with an in-place saturated hydraulic conductivity of 1 X 10^{-7} cm/sec or less. The compacted material must be free of rock, fractured stone, debris, cobbles, rubbish, and roots that would increase hydraulic conductivity or serve to promote preferential leachate flow paths.

(6) The foundation subsoil that underlies the compacted low permeability soil component should be structurally immobile during construction and operation of the unit (including any post-closure monitoring period).

(c) The owner/operator should prepare a written construction quality assurance plan to be used during construction of the double liner system, including both the FML top liner and the composite bottom liner. See Section IV on Construction Quality Assurance for specific recommendations.

Construction

° The earth substrates and base materials should be maintained in a smooth, uniform, and compacted condition during installation of each liner and components.

° Surface impoundment and landfill units should be constructed with liners that meet the following, as a minimum:

(a) FML liners:

(1) The liner should be installed (seamed) at ambient temperatures within the range specified by the manufacturer of the particular liner. Temperature extremes may have an effect on transportation, storage, field handling and

placement, seaming, and backfilling (where required).

(2) When the field seaming of the FML is adversely affected by moisture, portable protective structures and/or other methods should be used to maintain a dry sealing surface.

(3) Liner installation should be suspended when wind conditions may adversely affect the ability of the installers to maintain alignment of seams and integrity of membranes and seams.

(4) Field seaming of FMLs should be performed when weather conditions are favorable. The contact surfaces of the FML should be free of dirt, dust, and moisture including films resulting from condensation in weather conditions of high humidity. Seams should be made and bonded in accordance with the supplier's recommended procedures. Both destructive and nondestructive testing methods should be used to evaluate seam integrity. All on-site seams should be inspected by nondestructive testing techniques to verify their integrity. Periodic samples should be removed from both factory and field seams and tested for seam integrity by destructive tests (tension and peel tests). On-site nondestructive seam samples should be made and evaluated with identical liner material, adhesive, and technique prior to actual field seaming each day, or when conditions change. Seam testing methods are described in more detail in an upcoming EPA report, Construction Quality Assurance for Land Disposal Facilities.

(5) Proper equipment should be selected in placing bedding material over FMLs to avoid undue stress.

(b) Low permeability soil:

(1) EPA is conducting studies to evaluate the construction criteria that most significantly influence the hydraulic conductivity of compacted

low permeability soil liners. Until specific research and/or demonstration data are available, the following are suggested as the best available procedures for optimizing construction of the compacted bottom component of the composite liner:

(i) Remove all lenses, cracks, channels, root holes, or other structural nonuniformities that can increase the nominal in-place saturated hydraulic conductivity of the liner above 1 X 10^{-7} cm/sec.

(ii) Construct the liner in lifts not exceeding 15 centimeters (6 inches) after compaction to maximize the effectiveness of compaction throughout the lift thickness. Each lift should be properly interfaced by scarification between lifts.

(iii) Scarify sufficiently between each lift so as not to create a zone of higher horizontal hydraulic conductivity at the interface of the lifts.

(iv) Break up clods and homogenize the liner material before compaction of each lift using mixing devices such as pug mills or rotary tillers. All oversized materials (such as trash, large roots, wood, or large clods) should be removed in order to facilitate moisture control operations, maximize compaction, reduce heterogenity, and minimize overall hydraulic conductivity of the compacted liner.

(v) Thoroughly mix in moisture needed to bring the liner to the desired water content using mixing devices such as pug mills, rotary tillers, or other effective methods.

(vi) Compact the liner after allowing a sufficient time for added water to penetrate to the center of the clods while not allowing so much time after water addition that the exterior of the larger clods becomes drier than optimum. The larger clods should be field checked for moisture distribution.

(vii) Take the necessary precautions to assure that the desired moisture content is maintained in the compacted liner to avoid desiccation cracking.

Precautions that are effective at preventing desiccation cracking should be taken both between the placement of lifts and after completion of the liner.

(viii) Construction should not take place using frozen or other indurated soil, and precautions should be taken to assure that the liner is not allowed to freeze after placement.

(ix) Sidewalls should be constructed so as to minimize flow between the lifts. EPA believes this can best be accomplished with lifts that are laid down parallel to the slope.

(x) A demonstration should be made that sidewalls can be effectively compacted at the maximum slope to be used in the design. The Agency suggests a maximum slope of 3 horizontal to 1 vertical.

(xi) Consideration should be made of the vector of compactive effort when calculating the number of passes necessary to obtain a certain degree of compaction on sidewalls.

(xii) The uppermost lift should be scraped and steel rolled to produce a smooth surface prior to placement of the FML upper component. This procedure is intended to minimize lateral flow between components of the composite bottom liner.

(2) EPA recommends that a representative test fill be constructed using the soil, equipment, and procedures to be used in construction of the compacted low permeability soil component to the composite liner in the full scale facility. The test fill should be used to verify that the specified density/moisture content/hydraulic conductivity values can be consistently achieved in the full scale facility. Test fills have been used to validate both design and construction procedures for critical earthen structures around dams and nuclear power plants. In order for the data collected from the test fill to be useful, however, construction control of the test fill must be strict and well documented.

Previously-developed data that describes the performance of an installed liner can be used, provided documentation is available on all the factors discussed above. EPA is not, however aware of any facility that currently has this data on hand.

All information gathered during construction and subsequent testing of the test fill should be documented. The CQA program to be followed during construction of the full scale facility should be strictly followed during construction of the test fill (Corps of Engineers, 1977). Recommended minimum test fill construction details are as follows:

(i) Construction using the same compactable materials, compaction equipment, and exact procedures as will be used to construct the full scale facility liner. All applicable parts of the quality assurance plan should be precisely followed to monitor and document construction of the test fill.

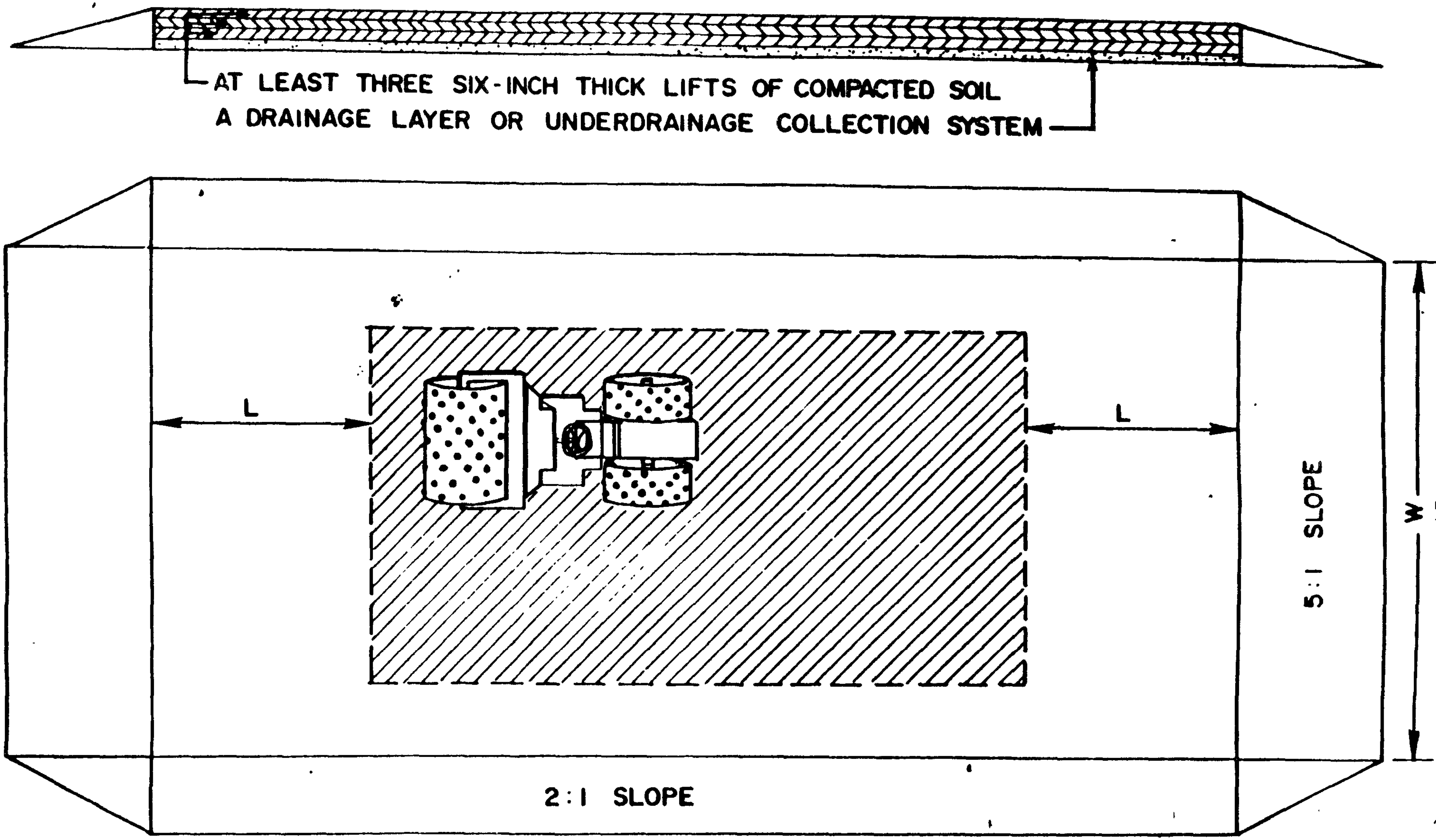
(ii) The test fill should be constructed at least four times wider than the widest piece of equipment to be used in construction of the full scale facility.

(iii) The test fill should be long enough to allow construction equipment to reach normal operating speed before entering the area to be used for testing (see Figure 6).

(iv) Construction so as to facilitate the use of field hydraulic conductivity tests and/or a complete quantification of all underdrainage. Field hydraulic conductivity tests should be conducted on the compacted test fill material as a verification of results of laboratory tests conducted on undisturbed samples taken from the compacted test fill material. The field hydraulic conductivity tests need only verify that the hydraulic conductivity is 1×10^{-7} cm/sec or less, not its actual value. These undisturbed samples can then be used for compacted liner/leachate compatibility testing.

(v) Construction so as to determine the relationship of the following to the moisture content/density/hydraulic conductivity values obtained in the field:

Figure 6



L = DISTANCE REQUIRED FOR CONSTRUCTION EQUIPMENT TO REACH NORMAL RUNNING SPEED

W = DISTANCE AT LEAST FOUR TIMES WIDER THAN THE WIDEST PIECE OF CONSTRUCTION EQUIPMENT

° Compaction method (detailed specifications of the compaction equipment);
° Number of passes of the compaction equipment;
° Mixing method (and resulting maximum clod size);
° Compaction equipment speed; and
° Uncompacted and compacted lift thickness.

(vi) A set of index properties should be selected that will be used to monitor and document the quality of construction obtained in the test fill. These index properties should include at least the following:

° Hydraulic conductivity (undisturbed samples);
° In-place density and water content;
° Maximum clod size;
° Particle size distribution; and
° Atterberg limits.

Data from these tests shall be used as standards for comparison with values obtained on samples from the full scale liner to indicate inplace field hydraulic conductivity.

(3) All lifts of the compacted low permeability soil liner that are part of the 3-ft minimum thickness should have a in-place hydraulic conductivity of $1X10^{-7}$ cm/sec or less. This hydraulic conductivity value should be verified both in the test fill liner and by the comparison of index property values between the test fill and each lift in the full scale liner. The values obtained should be numerous enough to fully document the degree of variability of all the index properties in both the test fill and each lift in the full scale liner.

(c) The owner/operator should implement a written quality assurance plan for monitoring and documenting the quality of liner materials used and the conditions and manner of their placement during construction of the top FML and composite bottom liners. See Section IV on "Construction Quality Assurance" for specific recommendations.

(d) The documentation for the CQA program for construction of the double liner should be kept on-site in the facility operating record.

Operation

The following operational criteria apply:

(a) The top (FML) liner should prevent migration of waste constituents into the liner through the closure period, except for de minimis leakage.

(b) The placement of removable coupons of the FML above the top liner is a technique for providing waste/liner chemical compatibility information during the operating period. Coupons are samples of the FML's used in the construction of the two liners that are placed in contact with wastes or leachate in the landfill or surface impoundment. The coupons are tested after various exposure periods in the unit to determine how the properties of the liner change over the operating period. This information, when compared to short-term compatibility data, can provide an early warning that the liner is degrading faster than anticipated and allow for corrective measures by the owner. The Agency recommends that landfill and surface impoundment owners consider removable coupon testing if wastes are likely to vary somewhat during operation.

(c) The owner should have on-site guidelines for operation and maintenance of the double liner system, which include recommendations on such subjects as:

- Frequency and documentation of inspection,
- Testing and repair of liner,
- Animal and plant control,
- Erosion control,
- Unacceptable practices,
- Placement of waste, and
- Coupon test schedule (optional).

B. Discussion

The EPA believes that an FML used in this double liner system, whether the top liner or the upper component of a composite liner, should meet the following criteria:

- A minimum thickness depending on the service;

    ° For buried FMLs the minimum thickness should be 30 mils when the membrane will be covered within three months by a protective layer against mechanical and weather conditions.

    ° For membranes that will be buried, but left unprotected for periods greater than 3 months, the minimum thickness should be 45 mils.

    ° For all liners used in impoundments that are left uncovered and exposed to the weather and experience light work on the surface, the minimum thickness should be 45 mils.

    ° The thickness of scrim layer, geotextile backing, or other reinforcing material should not be used in computing a minimum recommendation.

    ° For many units, particularly surface impoundments with exposed surfaces, FML's of 60-100 mils may be required to meet the mechanical stress requirements.

    ° The stresses on exposed liners are generally greater for surface impoundments because of exposure to more severe environmental conditions (climate), loading and unloading during daily operation, and sludge removal. Because of the more severe operation conditions, surface impoundments require substantially thicker liners. A protective layer covering the liner can reduce the stresses on the liner.

- Sufficient strength to prevent failure due to pressure gradients (including static head and external hydrologic forces, stresses of installation, and the stresses of daily operation);
- Compatibility with the waste to be managed in the unit;
- Low permeability; and
- Capable of being seamed to produce high strength, liquid-tight seams that retain their integrity during liner installation and on exposure to wastes for the duration of the operating life of the unit, including the postclosure monitoring period.

One of the primary reasons for failure of synthetic liners is damage (i.e., punctures, rips, and tears). Damage occurs during installation and/or during operation. The owner operator needs to demonstrate that the selected FML thickness is adequate for the site-specific conditions the liner will encounter while the unit is in operation (including any post-closure monitoring period).

EPA believes thickness and strength of the liner material are major factors in maximizing serviceability and durability. However, the lack of current technical data relating liner thickness for specific material types to successes and failures of liner systems prevents more specific guidance on thickness. The following is a list (EPA, 1983) of potential failure modes that should be considered in selecting the FML polymer type and thickness to maximize liner serviceability and durability:

Physical Modes of Failure

Abrasion
Creep
Differential settling
Hydrostatic pressure
Puncture
Stress-cracking (partly chemical)
Tear stress
Thermal stress

Chemical Modes of Failure

Extraction of plasticizer and soluble ingredients
High pH>10
Hydrolysis
Attack by ionic species
Low pH<2
Ozone-cracking
Attack by solvents and organic chemical species
Ultraviolent light attack

Biological Modes of Failure

Microbial attack (of plasticizers in FML compounds)

Liner failure mechanisms are addressed in a U.S. EPA Technical Resource Document, Lining of Waste Impoundment and Disposal Facilities, SW-870, March 1983. This document describes and discusses the categories and characteristics of liner failure in a service environment. The document is available from the U.S. Government Printing Office, publication number S/N 055-000-00231-2, $11.00, Superintendent of Documents, Washington, D.C. 20460. Kays (1977) also provides detailed discussion on liner failure mechanisms and methods to avoid failures for cut-and-fill reservoirs.

EPA believes that, for design purposes, the post-closure monitoring period can nominally be assumed to be 30 years. The double liner system should be designed so that no leakage out of the unit is expected through the operating period, including the 30-year post-closure monitoring period.

To help guard FMLs against damage, such as punctures, tears, and rips due to contact with sharp objects or other conditions, it is good practice to protect them from above and below by a minimum of 12 inches of bedding material. In landfills, the act of placing wastes sometimes causes damage (e.g., due to dropping of wastes or driving of vehicles on the liner); also, over extended time periods the wastes themselves may be capable of causing damage to the top FML and to the leachate drainage and collection system because they contain sharp objects or abrasives.

For landfill units, a leachate drainage and collection system must be placed above the top liner. This layer can be made of materials that meet both bedding and drainage material requirements. However, EPA suggests that for these units an additional layer of bedding material be installed above the top filter layer as well as below the top FML, unless it is known that the FML is not physically impaired by the materials, including pipes in the secondary leachate collection system. The drain pipes in both collection systems should be adequately protected against damage caused by waste placement and/or equipment operating on the working surface.

Bedding layers should consist of materials that are no coarser than sand (SP) as defined by the Uniform Soil Classification System (USCS). Use of a sand layer is common practice for protection of membranes and pipes from damage due to contact with grading equipment and materials, sharp materials in the soil, etc. As discussed above, the bedding layer need not be a separate layer, as the materials in the secondary leachate detection, collection, and removal system will often meet the necessary criteria.

For surface impoundments, a bedding layer above an FML also protects the FML from damage due to exposure to sunlight and wind while the unit is in operation. However, the bedding material is not always necessary above the top liner, since direct contact with the liquid wastes does not represent the same potential for puncture that is present in landfills. Nevertheless, the liner can be damaged during sludge removal or other dredging operations. Where mechanical equipment is used, EPA recommends a minimum of 45 centimeters (18 inches) of protective soil or the equivalent covering the top liner, unless it is known that the FML will not be damaged by the sludge removal practices. Some FML materials are known to be degraded by ultraviolet radiation and must be covered. Also, wind can get under the edge of exposed FMLs, causing flapping and whipping, which can lead to tears. These problems have occurred most commonly above the liquid level near the edge of the FML. As a result, it is common practice to cover FMLs with 6 to 12 inches of earthen material to prevent degradation due to sunlight and hold the liner down. The edges of FMLs are usually secured by anchor trenches at their perimeter. Of course, if the design is such that wind creates no difficulties, and if it is known that the FML is not subject to solar degradation, then these precautions are not necessary. The addition of a cover over the FML is expected to extend the service life of the liner. The bedding material need not be a separate layer, as the secondary leachate detection, collection, and removal system materials will often meet the necessary criteria for bedding.

Chemical testing of all construction material components is prudent because liners can be degraded by certain chemical species that may be present in the waste. Because wastes and liner chemical characteristics are almost infinitely variable, it is difficult to generalize concerning incompatibility or compatibility. The Agency, therefore, strongly suggests (and prefers) test data as the appropriate way to demonstrate the compatibility of the waste to be managed and the liner materials under consideration. Test results should demonstrate the acceptability of the selected liner materials. New test data may not be needed for units that have a well defined waste composition and for which previous test data showing that the proposed liner chemical characteristics are very predictable.

Waste liner material compatibility tests should be conducted using representative samples of wastes and leachates to which the liner is to be exposed. Several methods for obtaining samples of hazardous waste are discussed in Section one of Test Methods for Evaluating Solid Waste (SW-846).

An acceptable test method for assessing the compatibility of waste liquids and FML's is the "Immersion Test of Membrane Liner Materials for Chemical Compatibility with Wastes," found in EPA's Method 9090. In this test, samples of the candidate FML's are immersed at two temperatures in samples of the waste liquid to be managed and exposed for four months. After exposure for one-month intervals, an FML sample is tested for important strength characteristics (tensile, tear, and puncture) and weight loss or gain. The Agency considers any significant deterioration in any of the measured properties to be evidence of incompatibility unless a convincing demonstration can be made that the deterioration exhibited will not impair the liner integrity over the life of the facility. Even though the tests may show the amount of deterioration to be relatively small, the Agency is concerned about the cumulative effects of exposure over very much longer periods than those actually tested.

At present, no standard test method is available for assessing the compatibility of specific low permeability soils with a given waste liquid. Nevertheless, the compatibility of a soil with a waste liquid has been measured by comparing the permeability of the soil to water and to the waste liquid.

The Agency incorporated the National Sanitation Foundation's (NSF) standard specifications for flexible membrane liners into this guidance to provide suggested minimums values for physical properties. An NSF committee has been studying the subject for some time, and EPA believes that the specifications developed are reasonable and well thought out. Compliance with the NSF standard attests only to the basic quality of the liner itself and not to the advisability of its application under any given set of waste and unit-specific circumstances.

The top liner, an FML, is required to prevent migration of constituents of the waste liquid into the liner during the period the unit remains in operation (including any post-closure monitoring period) except for de minimis leakage. EPA recognizes that membranes will not always have zero leakage and that de minimis leakage may occur. De minimis leakage can occur as a result of vapor passing through the liner, very small imperfections in the liner that occur very rarely, or a seam that has a very small crack or hole. Although FML's are nonporous-homogeneous materials, vapor diffusion can transmit water and other liquids with dissolved constituents through synthetic liners. The transmission involves (1) sorption of the constituents of the waste liquid into the membrane, (2) diffusion through the FML, and (3) evaporation or dissolution of the constituents on the downstream side of the membrane. The principal driving force for permeation through an FML is the gradient across the liner in concentration, chemical potential, or vapor pressure of the individual constituents in the liquid or vapor. Permeability of an individual permeant depends upon its solubility and diffusion characteristics in a specific liner. De minimis leakage can also occur because of small and infrequent breaches in the liner that were not detectable during construction with current practical state-of-the-art construction quality assurance programs.

Detected leakage may be due to leakage through either the top or bottom liner.

EPA believes that current state-of-the-art technology for FML installation allows for hazardous waste management units to be built that will have very low leakage rates at installation. EPA does not have a specific maximum de minimis leakage rate that can be recommended. However, based on currently available preliminary field data, laboratory test results, and professional judgment, EPA believes that de minimis leakage should be approximately 1 gallon/acre/day or less. This rate should not be taken as a hard and fast rule because there are conditions where vapor transmission potentially could exceed this value. Also, this value does not apply to organic liquids, many of which can permeate an FML independently of the water in waste liquid. Some organic constituents can transmit at considerably higher rates than water, if the organic constituents are soluble in the membrane and organic concentration on the downstream side of the membrane is essentially zero. Dr. H. August et al, (1984), has shown laboratory permeation rates for concentrated hydrocarbons on 1 mm thick HDPE FML's were between 1 and 50g/m^2/day varying with the waste chemical structure and its affinity to the HDPE. Another finding of this study was that very dilute hydrocarbon solutions sometimes give high permeation rates of the hydrocarbons because of the relatively high solubility of the hydrocarbons compared to water in the HDPE. The concentration of organic waste in the liner surface can be higher by several orders of magnitude than the adjacent leachate or liquid waste containing hydrocarbons. Current laboratory tests cannot be related directly to estimate field rates of permeation because the tests do not simulate the ability of soil under the liner to transport the waste away from the liner. (See the suggested reading material list for additional information.) Review of information from recently constructed double synthetically lined surface impoundments shows that current state-of-the-art technology for installing synthetic liners is close to achieving 100% containment efficiency. The liner installations studied had extensive construction quality control to assure the seams did not leak.

A composite secondary liner including both FML and compacted soil components was selected as a result of various studies and analyses conducted by the Agency. A composite liner has several advantages. The FML component improves the efficiency of the secondary leachate collection system that must be installed between the top and bottom liners (see Section III). Any improvement in the collection efficiency of this system would allow earlier detection of liquids between the liners. Capillary forces present in an unsaturated low permeability soil liner may cause the initial leakage through the top liner to be absorbed before it is detected. FMLs on the other hand, can achieve virtually complete rejection of liquids and are, thus, more effective than compacted soils at detecting small amounts of leachate and overall removal efficiency. For this reason, a FML was selected for the upper component of the bottom liner.

While less efficient at detecting initial top liner leakage, compacted low permeability soil liners are not subject to the same types of installation and operational problems as FMLs. A problem that causes a puncture in a FML probably will not form a hole all the way through a compacted soil liner. In addition, a compacted soil liner has a potential to both minimize leakage through the FML and attenuate certain constituents in the leachate in the event of a leak. In the event of leakage through the FML component of the composite liner, the low hydraulic conductivity ($1X10^{-7}$ cm/sec or less) in the compacted soil liner would have the effect of both decreasing this leakage and increasing efficiency of the secondary leachate collection system. For these reasons, a compacted low permeability soil liner was selected as the lower component of the composite bottom liner. The compacted soil is a low permeability soil that has been compacted in 6-in. lifts, with an inplace hydraulic conductivity of 1 X 10^{-7} cm/sec or less. For purposes of this draft guidance, "compacted soil" is not meant to include materials such as soil cement, lime soil mixtures, or fly ash soil mixtures, and other soil amendments including natural or man made.

Objectives of the compacted low permeability soil component of the composite bottom liner include the following:

(1) to serve as a protective bedding material for the FML upper component;

(2) to serve as a long term structurally stable base for all overlying materials;

(3) to attenuate constituents in liquids that might leak through the FML upper component; and

(4) to minimize the rate of leakage through breaches in the FML upper component.

Objective number one can be met if the compacted soil is smoothed prior to the placement of the FML upper component. In most cases, three feet of compacted low permeability soil will be adequate to meet objective number two. However, the adequacy of a given compacted thickness will depend on the soil being compacted, the degree of compaction, the total expected load, and the geologic and hydrologic setting. Documentation should be provided that describes the capability for a given thickness to both serve as adequate bedding and provide sufficient structural support.

Objective three, attenuation of constituents, can best be met by assuring that the compacted soil is as homogeneous as possible. Preventing the formation of cracks (by preventing desiccation or freezing of the liner during or after placement) and reducing the number of large pores (by reducing clod size and optimizing compactive procedures) are two ways to enhance the attenuative capacity of the soil liner. If leachate has only relatively small pores through which to migrate, the waste constituents come in closer contact with the adsorptive surfaces of the compacted materials. One way to document the attenuative capacity of a given thickness of compacted soil is through the use of breakthrough curves (Griffen, 1978 and Anderson, 1982). To closely simulate actual field conditions, these breakthrough curves should be determined on undisturbed samples of the compacted soil collected from the test fill.

Objective four can be achieved by minimizing both the potential for lateral flow between the FML upper and compacted lower components of the bottom liner and by minimizing the flux of liquid through the compacted lower component. Lateral flow between the components of the bottom liner can be minimized by obtaining a good contact between the compacted lower component and the FML upper component. This contact is obtained by a combination of the following:

(1) smoothing the top of the uppermost lift of the compacted soil by use of smooth wheel steel rollers; and

(2) application of overburden pressure to the top of the FML upper component.

Overburden will be supplied by the weight of the overlying leachate collection layer, and waste (in the case of surface impoundments) and by the leachate collection layer, waste, and final cover (in the case of landfills). Additional procedures and materials are encouraged that may further reduce the lateral flow between the secondary liner components.

Minimizing the flux of liquid through the compacted soil can be accomplished as follows:

(1) minimizing the hydraulic gradient under which leachate will move; and

(2) minimizing hydraulic conductivity of the compacted soil.

There are two ways to minimize the hydraulic gradient: (1) reduce the depth of standing liquids in the leachate collection systems; and (2) construct a thicker compacted soil liner. Besides lowering the hydraulic gradient, constructing a thicker compacted liner should reduce the probability that a blemish of any kind would penetrate all the way through the compacted soil.

Whether referred to as blemishes, macrofeatures, or structural non-uniformities, construction imperfections may increase the overall saturated hydraulic conductivity by several orders of magnitude. Methods to reduce actual in-the-field hydraulic conductivity of a compacted soil should be included in the construction inspection program to both prevent and detect these imperfections. Details of the information that should be gathered before, during, and after construction of a compacted soil (which should serve to reduce the number of these imperfections) are given under "Construction Quality Assurance" (section IV).

Hydraulic conductivity testing on the in-place compacted low permeability soil is recommended because of concern that laboratory tests tend to underestimate the actual hydraulic conductivity in the field by a factor of 10 to 1000. The following recent references discuss the causes and magnitude of differences between field-measured and laboratory-measured hydraulic conductivity:

° Daniel, D. E., 1984. Predicting Hydraulic Conductivity of Clay liners. ASCE Journal of Geotechnical Engineering, 110(2):285-300.

° Griffin, R. A. et al. 1984. Migration of Industrial Chemicals and Soil-waste Interactions at Wilsonville, Illinois. In: Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste (EPA 600/9-84-007) USEPA Municipal Environmental Research Laboratory, Cincinnati, OH 45268.

° Herzog, B. L. and W. J. Morse. 1984. A Comparison of Laboratory and Field Determined Values of Hydraulic Conductivity at a Waste Disposal Site. In: Proceedings of the Seventh Annual Madison Waste Conference. University of Wisconsin-Extension, Madison, Wisconsin, p. 30-52.

° Boutwell, G.P. and V.R. Donald, 1982. Compacted Clay Liners for Industrial Waste Disposal, Presented ASCE National Meeting Las Vegas, April 26, 1982.

One reason why higher hydraulic conductivities are often obtained with field tests is that samples used in laboratory tests can be more readily prepared without the defects that can greatly affect actual hydraulic conductivity. Methods that are used to prepare soil liners in the field are difficult to simulate in the laboratory. One example is the method of compaction. Soil liners are often compacted in the field with a kneading action through the use of sheepsfoot rollers. In contrast, soil liner samples are usually prepared in the laboratory using impact compaction. Even though identical densities may be obtained with different methods of compaction, the soil samples compacted by different methods may have very different hydraulic conductivities (Mitchell, 1976).

There are a variety of other reasons for the large discrepancies reported between laboratory and field tests. Samples prepared in a laboratory are not subject to the climatic variables (such as cracking due to either freezing or desiccation) (EPA 1984A). There may also be a tendency to run laboratory tests on samples of selected finer textured soil materials (Olson and Daniel 1981). It is often suggested, however, that the most important reason for observed differences is that field tests can evaluate much larger and, hence, more representative samples than is practical in laboratory tests.

EPA believes that field hydraulic conductivity tests are essential to verify the requirement to have an in-place hydraulic conductivity of $1X10^{-7}$ cm/sec or less. Currently available field hydraulic conductivity tests, if conducted on the actual compacted soil liner may, however, cause substantial delays in construction and result in other problems due to prolonged exposure of the liner. In addition, it would be extremely costly if it were determined from field tests on the actual liner that it did not meet or exceed performance standards. Much time and effort can be saved if, prior to construction of the actual liner, a test section of the liner is prepared and tested. These tests can be used to document the capability of the proposed materials and construction procedures that result in a compacted soil liner that meets the desired performance standards. Therefore, the EPA recommends that a test fill be constructed using the same borrow soil, compaction equipment, and construction procedures as proposed for the full scale facility. The test fill is also recommended for use in demonstrating the actual in-place hydraulic conductivity of the compacted soil liner.

Field hydraulic conductivity tests of the compacted soil in the test fill are necessary to assure that the materials and procedures used in the field will result in a compacted soil liner with a hydraulic conductivity of $1X10^{-7}$ cm/sec or lower. Field testing is not intended to preclude the use of laboratory testing in the design or construction phase or as a means of evaluating liner-leachate compatibility. It is expected that the overall design and construction quality assurance (CQA) program will include a mixture of both field and laboratory hydraulic conductivity tests.

As appropriate methods are developed and verified, the EPA intends to require field hydraulic conductivity tests be conducted on the full scale facility. Field hydraulic conductivity tests can be performed in the test fill without causing delays during construction of the full scale facility. The field test used should be capable of verifying that the hydraulic conductivity of the compacted soil liner is $1X10^{-7}$ cm/sec or less.

Field infiltrometers capable of measuring very low hydraulic conductivities in compacted soil liners have been developed and reported by Anderson et al (1984), Day (1984), and Day et al (1985). An alternative to the use of field infiltrometers is the use of a system for capturing and collecting all under-drainage from the test fill. Day (1984) used such an underdrain to evaluate the accuracy of results obtained from field infiltrometers. While the field infiltrometers were found to accurately measure hydraulic conductivity, the underdrain was considered even more accurate.

Both infiltration and underdrainage tests should be conducted until stable flow and/or drainage rates are obtained. Where infiltrometers are used, there should be enough replicate tests to document areal variability in the hydraulic conductivity of the liner to the test fill. A sufficient number of index property tests (listed earlier in this section) should be conducted to accomplish the following:

(1) verification of the aspects of the CQA plan related to compacted soil liners; and

(2) document the degree of variability in each of the properties tested in the compacted soil liner for both the test fill and full scale facility.

In addition to being used as a site for field hydraulic conductivity tests, the test fill should be used to verify all elements of the design and construction of the soil liner. These elements should include at least the following:

(1) verification that the proposed soil material is uniformly suitable to be compacted into a liner (i.e., no cobbles, sand lenses, or indurated materials).

(2) verification that the equipment and procedures for breaking up clods, mixing in water, and compacting the soil are suitable for consistently achieving the required hydraulic conductivity specification.

(3) verification that the CQA plan is sound in all respects. The proposed CQA plan for construction of the full scale facility should be followed exactly as applied to construction of the test fill. If methods to improve the CQA plan are documented during construction and testing of the test fill, these improvements should be incorporated into the CQA program implemented during full scale facility construction.

Technical personnel who will be in charge of day to day implementation of the CQA plan on the full scale facility should also monitor and thoroughly document construction and testing of the test fill. This documentation should include at least the following:

(1) a detailed description of the type of equipment used during the borrow and construction operations,

(2) location of work, including borrow and construction sites;

(3) size, location, number, and identification of test samples collected and results of all tests performed;

(4) a diary of all relevant climatic and working conditions that may affect construction of the full scale liner;

(5) index of all tests and results that will be used to compare the liner constructed in the test fill to the full scale liner; and

(6) test fill report that compiles all documentation on the construction of the test fill and includes all raw data and test results.

Laboratory hydraulic conductivity tests should be conducted on undisturbed samples collected from the soil liner in the test fill. Care should be taken to avoid conditions that bias test results. Examples of these conditions include excessive effective confining pressure (Boynton and Daniel, 1985; Anderson, 1982) and sidewall flow (Daniel et al 1985). Methods for collecting undisturbed samples of soil liners have been suggested by Anderson et al (1984) and Day (1984). The undisturbed samples may not provide hydraulic conductivity values that precisely reflect field values. However, comparison of values obtained from the test fill and full scale liners should provide an indicator of gross changes in either the materials or procedures used in construction.

EPA believes that additional testing is warranted to evaluate the hydraulic conductivity of landfill and surface impoundment sidewalls. Especially in surface impoundments, the sidewalls may be the predominant pathway by which leachate can migrate beyond the liner systems. At this time however, the Agency is not aware of a suitable method for evaluating hydraulic conductivity of the sidewalls other than by construction of a costly scale impoundment. There would need to be separate underdrains for the sidewalls and bottom portions of the liner or it would be difficult to determine how much each portion was contributing to the total underdrainage. EPA is temporarily deferring the recommendation for sidewall testing to allow interested parties to develop economical and effective test methods. Comments are requested on the following:

(1) Are tests of the hydraulic conductivity of landfill and surface impoundment sidewalls necessary?

(2) Are there methods available for evaluating the hydraulic conductivity of sidewalls?

(3) Are there additional methods that should be developed to facilitate this testing?

In construction of FMLs, consideration should be given to the effects from humidity in the air. Seaming of FMLs with some solvent cements at high levels of relative humidity can result in moisture condensation on the adhesive surface during the seaming process and may result in poor adhesion. A relative humidity requirement may not be necessary for seaming techniques that rely on heat to bond the liner sheets, as the heat could prevent moisture from condensing on warm surfaces of the FML.

III. Secondary Leachate Collection System Between The Liners

Contents

A. Guidance

Overall Design, Construction and Operation Objective

The system should be capable of rapidly detecting, collecting, and removing liquid entering the collection system; be constructed of materials that can withstand the chemical attack that results from wastes or leachates, and the stresses and disturbances from overlying wastes, waste cover materials, and equipment operation; be designed and operated to function without clogging; and be operated to detect, collect, and remove liquid through the post-closure care period. This guidance also sets out methods for proper installation of components to assure that the specified performance of the leachate collection system is achieved.

Design

The secondary leachate collection system should have:

(a) A drainage layer that will permit rapid detection, collection, and removal of any migration of liquid into the space between the liners. The drainage layer should also be designed to collect and remove liquids rapidly and to produce little or no head of liquid on the bottom liner.

(b) Materials that are chemically resistant to the waste and leachate, a minimum bottom slope of 2 percent, and a minimum hydraulic conductivity of $1X10^{-2}$ cm/sec.

(c) A system of drainage pipes of appropriate size and spacing on the bottom of the unit to efficiently remove leachate.

An innovative leachate collection system such as a synthetic drainage layer will be considered by the Agency if it can be demonstrated to be equivalent to a conventional granular system with pipes and meets (a) and (b). These materials must be chemically resistant to the waste and leachate; they must be compatible with and non detrimental to the FML and not collapse under the designed load.

(d) Direct contact with the FML component of the bottom liner.

(e) A sump of appropriate size to efficiently collect leachate and be positioned at least 30 centimeters (12 inches) below the drainage layer grade. Each landfill or surface impoundment unit should have its own sump. For landfills, the sump for the secondary leachate collection system must be separate from the primary leachate collection sump.

(f) A collection system that cover all areas between the double liners likely to be exposed to waste and leachate.

(g) Methods of measuring and recording fluid volumes in the collection system sump.

(h) The owner/operator should implement a written construction quality assurance plan during construction of the double liner system, including the secondary leachate collection system. See Section IV on Construction Quality Assurance for specific details.

<u>Construction</u>

(a) The owner or operator should use the construction quality assurance plan to monitor and document the quality of materials used and the conditions and manner of their placement during construction of the collection system of the unit.

(b) The documentation of the CQA program should be kept on-site in the facility operating record,

(c) The secondary collection system, including sump, should be free of liquids and hazardous constituents when the waste management unit begins operation.

<u>Operation</u>

The following operational measures should be followed;

(a) Removal of liquids, if any, on a daily basis, minimizing the head on the composite liner;

(b) The owner or operator should establish an inspection schedule that will allow him to determine that the system is functional and operated properly. EPA recommends that the removal sump be inspected for the presence of liquids and proper operation of the system on each operating day or, at a minimum, weekly during the active life depending upon site-specific conditions, and at least <u>quarterly</u> during closure and post-closure. The owner or operator should keep records on the system to provide sufficient information that the secondary leachate collection system is functional and operated properly. Documentation may include the amount of leachate present in the detection, collection, and removal system of the unit. This information should be recorded in the facility operating record;

(c) Repair of damaged leachate collection system components as soon as practicable during the operating period;

(d) As a general matter EPA will include in draft permits a requirement that the owner or operator notify the Regional Administrator, in writing, of the presence of liquids in the secondary leachate collection system in a timely manner. Such notification may include, if necessary:

(i) leakage rate (quantity);

(ii) the concentrations of hazardous constituents [indicator parameters specified by 264.98(a)].

EPA may, on a case-by-case basis, consider requiring owners and operators of permitted units to respond to leaks in the top liner, if this requirement is necessary to protect human health and the environment.

(e) A storage permit for collected leachate, if required.

If the unit is not yet permitted (i.e., it is an interim status unit), the owner/operator should modify the Part B application indicating the unit has liquids in the secondary leachate collection system. The Agency will consider this information at permitting to determine if the liner is leaking.

B. Discussion

The Agency believes that it is practical to design and operate a secondary leachate collection system to rapidly detect liquids in the space between the liners, minimize the head on the bottom composite liner, and remove leachate for treatment. The specifications presented here, judiciously applied, are expected to accomplish these requirements.

The following is a list of factors that affect liquid transmission in the drain layer of the leachate collection system:

° Impingement rate of liquid on the collection drain layer;

° Slope of the drain layer;

° Size and spacing of the drainage pipe; and

° Hydraulic conductivity of the saturated sand or gravel drain layer.

Drainage pipe diameter and spacing are important because they affect the time to liquid detection, rate of removal, and the head that builds up on the bottom composite liner between pipes. The pipe diameter should be large enough to efficiently carry off the collected leachate rapidly. Since the philosophy for all aspects of liner design is to minimize the transmission of waste constituents through the liner system, the head on the bottom liner should be minimized. The closer the pipes are together, the more quickly liquids are likely to be detected. However, the spacing and size of the piping system necessary to accomplish this depends on other characteristics of the drain layer (e.g., hydraulic conductivity) and on the impingement rate of liquids from the leak. Unlike the primary leachate collection system for landfills and piles, the secondary leachate collection system detects liquids as well as collecting and removing them. Thus, pipe size and spacing need be sufficient for rapid transmission of liquids and need not be designed to remove some predetermined volume rate of flow. EPA is, therefore, not specifying minimum spacing or size in this guidance. Nevertheless, a reasonably sized drainage system, coupled with an efficient sump system for removing collected liquids, will result in the capacity to remove leaking liquids, except in the case of severe breaches of the top liner.

Innovative secondary leachate collection systems that are equivalent to or more efficient than conventional granular systems may be used. The following criteria should be used to determine equivalence:

- Design
  - hydraulic transmissivity (i.e., the amount of liquid that can be removed);
  - compressibility (i.e., ability to withstand overburden pressure while remaining functional);
  - compatibility (mechanical) with the liners (i.e. thin, low-modulus FML's in contact with some drainage materials may distort under pressure);

- ability to collect leachate;
- compatibility with leachate and waste;

° Construction method

° Operation/performance characteristics

- drainage or flow characteristics (i.e., how fast liquid will flow and what volume will flow)
- sensitivity to leakage/small leaks;
- time required for detection of leachate;
- ability to verify performance ;
- reusability of the system once a leak is detected; and
- useful life of the system.

An owner/operator wishing to use an innovative collection system should compare the properties of his design against a conventional granular design that uses the recommended design specification [see Design (a),(b) and (c)]. If the alternative drain layer is equivalent, he may proceed; if not, the alternative design should be abandoned. If one or more of the factors are not equivalent, the collection system would probably not perform as well as a conventional granular system and would be a source of constant trouble to its owner/operator.

If the owner or operator wishes to determine the source of liquids found in the secondary collection system, the following records on the design, operation, and closure of landfill and surface impoundment units may provide useful information:

° Subsurface drilling logs including seasonal ground-water elevations;

° "As-built" drawings, certified by a professional engineer, for the double liners and collection system(s);

° Analytical data indicating the waste characteristics over time and the leachability of these constituents under site-specific conditions as included in the waste analysis plan;

° Accurate tables and plots of measured primary (for landfills) and secondary leachate collection system fluid volumes;

- Tables and plots of monthly averages of data from primary and secondary leachate analyses (consistent parameters should be used);
- Construction quality assurance documentation report;
- Other supporting data; e.g., rainfall, temperature, etc.; and
- An explanation prepared during design to explain why observed leachate may not be due to a leak in the top liner.

Additionally, EPA suggests that the owner/operator may determine that simple statistical analyses (such as comparing the quality of liquids in the leachate collection system to the quality in the leak detection system), may be helpful in developing assessments of top liner integrity. The use of tracers to determine the extent of migration could also be used.

The Agency believes that it is practical to operate a collection system between two liners. Sites are currently using these systems to monitor the performance of the top liner. The collection system allows the owner/operator to detect, collect, and remove liquids in the secondary leachate collection system.

IV. Construction Quality Assurance

Contents

A. Guidance

Overall Design, Construction, and Operation Objective

All new surface impoundments and landfills, new units, lateral expansions, and replacement units must have at least two liners with a leachate collection system between the liners (and above for landfills). The double liners and collection system(s) must be designed, constructed, and operated to protect human health and the environment. To assure that a completed double-liner system meets or exceeds all projected design criteria, plans, and specifications, a construction quality assurance (CQA) program is necessary. In addition, the regulations for permitted units (§§264.226 and 264.303) specifically require liners to be inspected during construction for uniformity, damage, and imperfections (e.g., holes, cracks, thin spots, or foreign materials); immediately after construction FML's must be inspected to ensure tight seams and joints, and the absence of tears, punctures, or blisters.

As part of the CQA program for compacted soil liners, a test fill should be constructed using the same material procedures and equipment that will be used in the full scale facility. The CQA plan to be followed during the full scale facility construction should be exactly followed during construction of the test fill.

Design and Construction

(a) The owner/operator should submit and implement a written construction quality assurance plan to be used during construction of the primary leachate collection system (for landfills), secondary leachate collection, and top and composite bottom liners. The plan should be used in monitoring and documenting the quality of materials used and the conditions and manner of their placement. The plan should be developed, administered, and documented by a registered professional civil or geotechnical engineer with experience in hazardous waste disposal facility construction and construction site inspections. While the specific content of the construction quality assurance plan will depend on site-specific factors, the following specific components should be included, at a minimum:

° Areas of responsibility and lines of authority in executing the CQA plan;

° Qualifications of CQA personnel;

° Specific observations, and tests - preconstruction, construction, and post-construction tests to verify that materials and equipment will perform to specifications, and that the performance of the individual parts of the double-liner system conform to design specifications. As completed, the individual parts of the double-liner installation should be tested for functional integrity. The FML joints, seams, and mechanical seals should be checked both during and after installation. A variety of testing methods can be used such as:

- hydrostatic
- vacuum
- ultrasonic
- air jet
- spark testing.

In addition to hydraulic conductivity tests on undisturbed samples taken from the compacted soil layer during construction, the low-permeable soil layer should be tested for functional integrity through the use of field hydraulic conductivity testing on the completed soil layer when practical. The collection layer(s) should be tested to assure the components are functioning as designed.

° Sampling program design; the frequency and scale of observations and tests, acceptance-rejection criteria, corrective measures, and statistical evaluation.

° Documentation of CQA should include daily recordkeeping (observation and test data sheets, problem reporting and corrective measures data sheets), block evaluation reports for large projects, design engineer acceptance reports (for errors, inconsistencies, and other problems), and final documentation. After completion of the double-liner system, a final documentation report should be prepared. This report should include summaries of all construction activities, observations, test data sheets, problem reports and corrective measures data sheets, deviations from design and material specifications, and as-built drawings.

(b) The documentation for the CQA program for the construction of the unit should be kept on-site in the facility operating record.

B. Discussion

Construction quality assurance (CQA) during construction of the double-liner system is essential to assure, with a reasonable degree of certainty, that the system meets the design specifications. This involves inspecting and documenting the quality of materials used and the construction practices employed in their placement. CQA serves to detect deviation from the design caused by error or negligence on the part of the construction contractor, and to allow for suitable corrective measures before wastes are disposed. Without proper construction quality assurance, problems with the leachate collection system(s), and FML top and composite bottom liners due to construction may not be discovered until the system fails during operation.

A recent survey of hazardous waste surface impoundment technology has found that rigorous quality assurance is necessary to achieve good unit performance (Ghassemi, et al 1984). Liner failures at several impoundments were attributed to various factors including "failure to execute proper quality assurance and control." The success of surveyed facilities that have performed well is attributed to many factors including "the use of competent design, construction, and inspection contractors, close scrutiny of all phases of design, construction, and QA inspection by the owner/operator, excellent QA/QC and recordkeeping during all phases of the project, and good communications between all parties involved in constructing the units."

Specific problems that can cause failure of the double-liner system and that can be avoided with careful construction quality assurance include:

Collection System(s)

° The use of materials other than those specified in the approved design;

° Foreign objects (e.g., soil) left in drain pipes, which plug or restrict flow and may not be removable using currently available maintenance procedures;

° Neglecting to install materials at locations specified in the design;

° Neglecting to follow installation procedures specified in the design;

° Siltation of drainage material resulting from improper upgradient drainage during construction and/or careless construction techniques;

° Improper use of construction equipment causing crushing or misalignment of pipes;

° Improper layout of the system, including misalignment of pipe joints or improper slopes and elevation of pipes; and

° Use of unwashed gravel or sand in drain layers.

FML's Used as the Top Liner and as the Upper Component of the Composite Bottom Liner

- The use of materials other than those specified in the approved design;
- Improper preparation of the supporting surface (usually soil subgrade) to receive the liner;
- The use of improper installation techniques and procedures by the contractor;
- The improper use of construction tools and equipment;
- Inadequate sealing and anchoring of the liner to structures, pipes, and other penetrations through the liner;
- Installation of the liner during inclement weather; and
- Improper repair of defects in the installed liner resulting from manufacturing processes and installation methods.

Low Permeability Soil Layer in Composite Bottom Liner

- The use of materials other than those specified in the approved design;
- Improper compaction equipment;
- Inadequate compactive effort;
- Improper compaction procedures;
- Inadequate scarification between lifts;
- Excessive lift thickness;
- Inadequate liner thickness;
- Excessive field hydraulic conductivity;
- Inadequate method of water addition;
- Inadequate time allowed for even distribution of moisture;
- Inadequate method used to maintain the optimum moisture content in the liner between construction of each lift and after completion of the liner; and
- The use of an inadequate quantity of added fine-grained materials (important with bentonite/soil liners).

The ability of the hazardous waste disposal unit to meet its designed regulatory performance goals depends on adherence to approved design plans and specifications during construction. Confidence in the ability of the installed liners to perform properly is attained through a well-developed, well-implemented, and well-documented CQA program. The program should be developed by the design engineer, who can focus the emphasis of quality assurance on those elements of the design that are critical to FML and low-permeable soil liner performance. Implementation of the CQA program should include participation by the design engineer in resolving construction or design problems that may be identified during construction. Timely identification of such problems during construction allows corrective measures to be taken before construction is completed and wastes are deposited. Confidence in the liner is established through:

° Careful documentation of:

- Construction scheduling, conditions, and progress;
- Site inspections;
- Material/equipment testing results and data verification; and
- As-built conditions.

° The owner/operator providing the opportunity for review, inspection, and approval by appropriate regulatory and permitting agencies.

Each of the elements identified as components of the written construction quality assurance plan will be described in detail in an upcoming document on the subject of construction quality assurance for hazardous waste land disposal units entitled, Construction Quality Assurance for Hazardous Waste Land Disposal Facilities. The document will address the components listed below:

° Low permeability soil liners;

° Flexible membrane liners (FML's) or synthetic membrane liners;

° Dikes;

° Low permeability soil caps and cover systems; and

° Leachate collection systems.

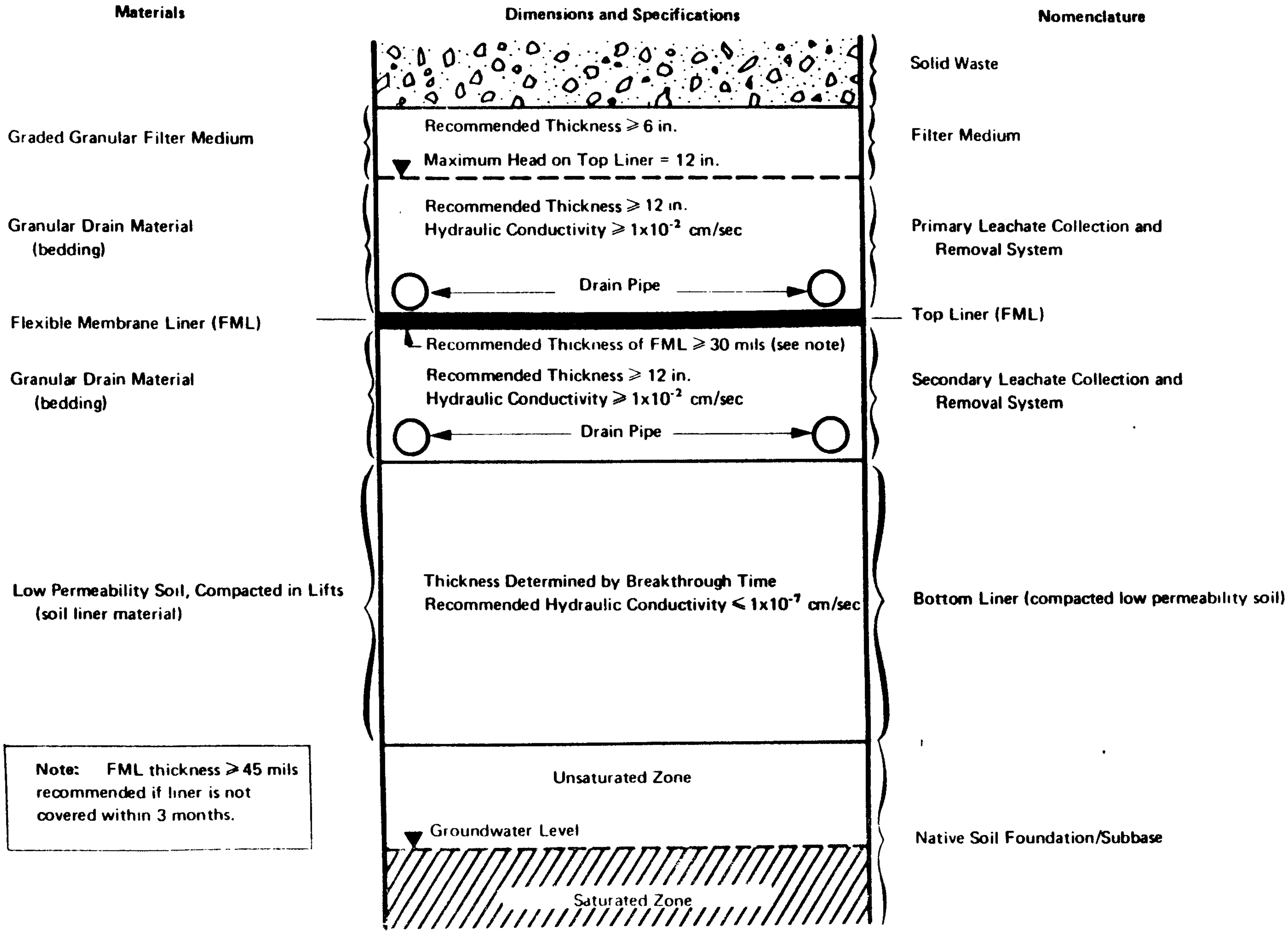
FML/LOW-PERMEABILITY SOIL DOUBLE LINER SYSTEM

The FML/compacted low permeability soil double liner design consists, at a minimum, of a primary leachate collection and removal system (for landfills), an FML top liner designed, operated, and constructed of materials to prevent the migration of any constituent into such liner during the period the unit remains in operation (including any post-closure monitoring period), a secondary leachate collection system, and a bottom liner designed, operated, and constructed to prevent the migration of any constituent through the liner during this period (See Figure 7). The bottom liner should consist of compacted soil with a hydraulic conductivity of 1×10^{-7}. The liner should be of compacted low permeability soil materials rather than in-situ soil materials. The liner thickness should be calculated using the formulas and assumptions set out in this section of the guidance and should be three feet thick at a minimum.

EPA believes that this design will protect human health and the environment because if liquid appears between the liner, the compacted soil clay bottom liner provides for removal of some leachate by the leachate collection system and infiltration of the remaining leachate into the liner. The liner is designed to be of sufficient thickness to prevent migration during the period of facility operation, including the post-closure monitoring period.

Section 3004(o)(5)(B) provides that, until the effective date of EPA regulations implementing Section 3004(o)(1)(A), the statutory requirement for two liners may be satisfied by the installation of a top liner designed, operated, and constructed of materials to prevent the migration of any constituent into such liner during the period the facility remains in operation (including any post-closure monitoring period) and a lower liner designed, operated, and constructed to prevent the migration of any constituent through

FIGURE 7
SCHEMATIC PROFILE OF AN FML/COMPACTED SOIL DOUBLE LINER SYSTEM FOR A LANDFILL



such liner during this period. Section 3004(o)(5)(B) also provides that a lower liner shall be deemed to satisfy this requirement if it is constructed of at least a 3-foot thick layer of compacted clay or other natural material with a permeability of no more than 1 x 10^{-7}.

The Agency's FML/compacted soil double liner design contains the performance standards set out in the statute. The important difference between the Agency's design and the statutory interim standard is that three feet of recompacted clay will satisfy the statutory requirement, while three feet is the minimum recommended thickness in the Agency's design. Until EPA issues regulations implementing the statute, EPA will accept a bottom liner design of three feet of compacted clay or other natural material with a permeability of no more than 1 x 10^{-7}. However, the Agency believes that this bottom liner will not in practice meet the requirement to prevent migration of any constituent through the liner during the operational period. EPA believes that owners and operators who wish to install a clay lower liner should consider three feet as a minimum thickness and use this guidance to determine the recommended thickness.

In order to meet this performance standard, both the top and bottom liner should be chemically resistant to the waste and leachate managed at the unit. In addition, these liners should be constructed of materials that have appropriate properties and sufficient strength and thickness to prevent both structural and chemical failure caused by factors which include material aging and the stresses of construction and operation.

The top liner must be a FML material that meets the requirement that constituents not migrate <u>into</u> the liner. EPA's recommended bottom liner design is:

(1) That it consist of a minimum three feet of compacted soil with a hydraulic conductivity of 1 X 10^{-7} cm/sec or less; and

(2) That it be sufficiently thick so as to prevent any constituent from migrating through the bottom of the compacted soil liner prior to the end of the post-closure monitoring period.

Until the effective date of regulations implementing section 3004(o)(1)(A), EPA will accept a three foot bottom liner. However, EPA believes that in practice a bottom liner consisting of three feet of compacted soil with a hydraulic conductivity of $1X10^{-7}$ cm/sec will not meet the second standard listed above. In the case of a saturated soil, low effective porosity values may allow the early release of constituents. In the case of an unsaturated soil, capillary forces may draw constituents through the liner prior to the end of the post-closure monitoring period. Therefore, EPA recommends that an owner or operator who wishes to install a bottom compacted low permeability soil liner use this guidance to determine the thickness of the bottom liner.

Methods that have been suggested for modifying a compacted soil liner to meet the recommended standard are as follows:

(1) Decrease its permeability; and/or

(2) Increase its thickness.

Either of these ways of modifying the liner could theoretically result in a liner that would prevent migration for the combined active life and 30 year post-closure monitoring period of a facility (usually a total of 40-50 years). The Agency does not discourage rigorous demonstrations of compacted low permeability soil liner designs that would meet the recommended standard. The Agency has, however, strong reservations concerning the likelihood that such a design is either economically or technically feasible. Some of the issues underlying these reservations are as follow:

(1) There are no clear criteria or techniques available for making breakthrough determinations. While several methodologies have been suggested,

the Agency is not aware of any methods which have undergone rigorous field-verification testing.

(2) It is not clear whether it would be economically feasible to construct a low permeability soil liner thick enough to prevent breakthrough for over 40 years assuming adequate flow from the overlying landfill or surface impoundment to maintain continuous unsaturated (capillary) flow through the soil liner during that period. Recent computer models of unsaturated flow through compacted liners suggest that assuming continuous flow through the liner, a liner may need to be much greater than 10 feet thick even at hydraulic conductivities substantially less than 1 X 10^{-7} cm/sec.

(3) Hydraulic conductivities of 1 X 10^{-7} cm/sec or less have not been routinely and consistently obtained in the past on an overall in-field scale liner system. A number of studies have suggested that actual field scale hydraulic conductivities may be in the range of 10 to 1000 times higher than the 1 X 10^{-7} to 1 X 10^{-8} cm/sec values that are routinely obtainable in laboratory tests. The Agency believes that if a testfill (described in the section on construction of low permeability soil) is used, a hydraulic conductivity of 1X10^{-7} can be achieved in the liner.

(4) The capability of current testing methods to verify with a high degree of confidence the actual field performance of a compacted low permeability soil liner has not been demonstrated. Consequently, the Agency currently believes that the best method would include construction of a test fill and the collection of field hydraulic conductivity data.

Test fills have been used by the geotechnical engineering community to evaluate the design of soil liners used in cooling ponds for the nuclear power industry. Test fills have also been used during the design stage of dams to obtain information on engineering properties of the compacted soil such as density, strength, and hydraulic conductivity (Barron, 1977). Construction control of test fills must be very strict and well documented or the data obtained will be of questionable value (Corps of Engineers, 1977).

Field hydraulic conductivity tests have been found to give a much more accurate assessment of the hydraulic conductivity of compacted soil liners (Daniel, 1984; Day 1984). Field tests conducted in a test fill should be an effective and accurate method to predict the overall saturated hydraulic conductivity of a compacted soil liner. Both test fills and field hydraulic conductivity tests are discussed in greater detail in Section II of this guidance document.

The time required for liquid to breakthrough a compacted soil liner will, in most cases, be initially governed by unsaturated liquid flow through the liner. During the early stages of wetting of a compacted liner, capillary attraction forces predominate over gravitational forces. As a compacted liner becomes wetter, the capillary forces would decrease in importance. In a saturated liner, capillary forces are negligible in comparison to gravitational forces.

To accurately and reliably estimate the time to breakthrough for a given liner thickness, a field verified equation is required that accounts for effective porosity, water content, capillary forces, and unsaturated hydraulic conductivity at various depths in the liner over time. Unsaturated hydraulic conductivity measurements are both difficult and not routinely performed by soil engineering laboratories. The task of documenting unsaturated hydraulic conductivity values for a compacted low permeability soil liner at several water contents would indeed be difficult on even a small laboratory scale. In addition, the Agency is not aware of any field scale studies to verify laboratory-derived unsaturated hydraulic conductivity values.

The Agency is studying the breakthrough of constituents through compacted low permeability soil liners. There is currently however, no field verified method for determining either breakthrough or the associated liner thickness requirements. Using the draft computer model which is currently in development and as yet not field tested (SOILINER), the interim design (i.e., a three foot thick compacted liner with a saturated hydraulic conductivity of $1X10^{-7}$ cm/sec) representing a landfill scenario with a one foot head above the liner results in a breakthrough time of approximately three years (Johnson and Wood, 1984). Assuming adequate flow from the overlying landfill or surface impoundment to maintain continuous unsaturated (capillary) flow through the soil liner during the operating and post-closure period, a compacted liner would need to be at least several times this thickness or be of a lower order of permeability in order to prevent breakthrough of mobile waste constituents during the 40 to 50 years most surface impoundments and landfills will be operated, including the post-closure monitoring period.

The draft computer model discussed above has been published by the EPA (1984B). The Agency plans to update this model and evaluate further the appropriateness of it for use in estimating the thickness requirements or breakthrough time for compacted liners.

Conservative assumptions should be used in estimating the compacted low permeability soil liner thickness because of the lack of precision with which such estimates can be made. There are several difficult to estimate variables that affect the thickness needed to prevent migration of hazardous constituents over the operational life of the soil liner. Examples of the conservative assumptions that should be used to estimate soil liner thickness are as follows:

1. Breaches develop in the top FML during the first year of operation.

Even with a rigorously implemented construction quality assurance plan, it is not possible to be 100% certain that all defects initially present in the FML have been detected. In addition, weak seams may open up shortly after installation due to operational stresses (e.g., overburden pressures that occur during the initial placement of wastes). Equipment is more likely to damage the FML shortly after installation because there may only be a leachate collection layer between the equipment and the liner.

2. The leakage/impingement rate of leachate to the soil liner should be based on an estimate of active life and post-closure (for disposal units) conditions.

For landfills during the active life the leakage into the compacted soil liner should be based on the rate of moisture/liquid infiltration into the landfill considering (1) leachate collection and removal by the primary leachate collection system under proposed removal conditions, (2) leachate leakage through potential top liner failure conditions, (3) leachate collection and removal by the secondary leachate collection system, and (4) the compacted soil liner surface conditions. Failure conditions for the top liner should consider data from existing similar units currently in operation when available. The failure conditions should consider all liner breaches that may be expected to occur during construction, active life, and the post-closure monitoring period of the unit. Even small leaks in the FML could allow a steady supply of leachate to a portion of the compacted soil liner. The type of failures that should be considered (i.e., seam failures, punctures, rips, tears, chemical compatability) are addressed in the U.S. EPA Technical Resource Document Lining of Waste Impoundments and Disposal Facilities, SW-870, March 1983.

If the owner or operator agrees to repair breaches in the liner during operation or other time periods then repair can be included as part of the calculation. The repair assumptions in the calculation should be representative of actual repair operating practices.

Unless data is available to demonstrate that the top liner will have zero leakage throughout the operating life of the unit (including the post-closure monitoring period) a very small leakage rate should be assumed to occur when leachate is in the primary leachate collection system.

For surface impoundments during the active life the leakage rate into the compacted soil liner should be based on (1) the maximum designed operating head for the impoundment, (2) leakage through potential top liner failure conditions, (3) leachate collection and removal by the secondary leachate collection system, and (4) the compacted soil liner surface conditions. The top liner failure conditions that should be considered are discussed above under landfills.

During the post-closure monitoring period the leachate impinging on the primary leachate collection system for a landfill or top liner in a surface impoundment should represent 1) the effectivness of the final cover in minimizing precipitation infiltration during the post-closure monitoring period and 2) drainage from the waste resulting from precipitation that was intercepted by the waste during the active life, and leachate that is generated from decomposit of the organic waste constituents.

3. The post-closure monitoring period should be at least 30 years.

Current Subpart G requirements are for post-clsoure care to "continue for 30 years after the date of completing closure". This time frame is considered by EPA to be a minimum estimate of how long the waste will remain hazardous.

4. Leakage from potential top liner failure conditons would occur throughout the operation period unless the owner or operator agrees to repair the breaches.

As discussed in assumption Number 2, there are several ways leachate can form during the operational period of the unit.

5. Nature and quantity of the waste should be considered.

Volume of leachate released by the waste as decomposition by-products will depend on the total organic content of the waste. The higher the organic content of a waste, the greater would be the fraction of the waste which could be liquify during its decomposition. The total quantity of organic materials in the facility would affect the total volume of leachate that could eventually be generated from decomposition of the waste.

Composition of a waste will affect the composition of the leachate. High concentrations of certain leachate components may increase the rate at which a soil liner transmits leachate (Anderson, 1982). If the leachate has a flow rate through the compact soil liner faster than water this should also be considered in the evaluation of required liner thickness.

6. Any allowance for attenuation of the waste constituents by the soil liner should take into account the nature of the waste and any factors that may reduce attenuation.

Some waste constituents (such as cations) can be strongly attenuated by soils under ideal conditions (EPA, 1983C). The effect is difficult to quantify but may be considered in limited cases such as some monofills. The demonstration of acceptability should be based on data from field tests. The extent to which many of these are attenuated can, however, be greatly decreased in the acidic and anaerobic conditions that are often present near soil liners. Other waste constituents (such as anions) may not be appreciably attenuated by soil. Movement of waste constituents will also be affected by the effective porosity of the soil liner. There are a number of other conditions under which attenuation can be greatly reduced. In addition, the conditions that optimize attenuation of one constituent may promote leaching of another (Lindsey, 1979).

7. The effective porosity would be 0.05.

Total porosity of a compacted soil will usually be less than 0.5 (Anderson et al., 1984; and Brown and Anderson, 1983). Effective porosity can be much less than total porosity in fine-grained soils (Gibb et al., 1985). Green et al, (1985) found that in some compacted samples only 10% of the total porosity was effective in transmitting liquids. Ten percent of even the highest total porosity likely in a compacted specimen would result in an effective porosity of no greater than 0.05.

8. The compacted low permeability soil liner and adjacent soil strata would be initially unsaturated.

Design criteria given elsewhere in this document state that the liner system for the two designs should be constructed completely above the seasonal high water table (i.e., in unsaturated soil). Under these conditions, the soil strata immediately adjacent to the liner would probably also be unsaturated.

The owner/operator should fully document methods used to evaluate the necessary liner thickness. These evaluations should also address at least the following:

(1) Horizontal hydraulic conductivity within and between the individual lifts (Brown et al, 1983 Boynton, 1983);

(2) Variability in the hydraulic conductivity of the compacted soil liner in the field (Daniel, 1984);

(3) The potential for long term changes in hydraulic conductivity resulting from loss of moisture by the liner due to climatic conditions

or the equilibrium moisture content in the adjacent soil deposits; and

(4) The effect of liner aging on the long-term equilibrium hydraulic conductivity of the liner (Mitchell et al, 1965; Dunn and Mitchell (1984); Boynton, 1983).

Under this approach to bottom liner design, the leachate collection and removal system between the two liners must be: (1) capable of detecting, collecting, and removing liquids in case leaks develop in the primary liner, (2) constructed of materials that can withstand the chemical attack that results from wastes or leachates, (3) capable of withstanding the stresses and disturbances from overlying wastes and operating practices, and (4) operated to collect and remove liquids through the operating period, including the post-closure monitoring period.

The collection system between the two liners should comply with the guidance contained in Section III of the Synthetic/Composite Double Liner System. For landfills, the leachate collection and removal system above the top liner should comply with the guidance contained in Section I of the Synthetic/Composite Double Liner System. The top liner should comply with the guidance contained in section II. The bottom liner should comply with the relevant portions of section II dealing with the compacted lower component of the composite liner. Section IV, on Construction Quality Assurance, should be used to assure that the completed double liner system meets the design criteria and specifications.

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