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BACKGROUND DOCUMENT ON BOTTOM LINER PERFORMANCE IN DOUBLE-LINED LANDFILLS AND SURFACE IMPOUNDMENTS

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BACKGROUND DOCUMENT ON BOTTOM LINER PERFORMANCE IN DOUBLE-LINED LANDFILLS AND SURFACE IMPOUNDMENTS

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CHAPTER 1

INTRODUCTION

1.1 LEGISLATIVE HISTORY AND CURRENT REQUIREMENTS

1.1.1 Legislative and Regulatory History

Under Section 3004 of the Resource Conservation and Recovery Act (RCRA), owners and operators of treatment, storage, and disposal facilities (TSDFs) are required to comply with standards "necessary to protect human health and the environment". Regulations that established the major components of these standards were issued on May 19, 1980 (45 FR 33221); these were the first national standards that defined acceptable management practices for hazardous waste. They established EPA's first phase of requirements under Section 3004 of RCRA for owners and operators of facilities that treat, store, or dispose of hazardous wastes. These standards included Part 265 requirements applicable during the interim status period and Part 264 requirements applicable to permits.

On July 26, 1982 (47 FR 32274), EPA promulgated technical and permitting standards under Part 264 for landfill, waste pile, surface impoundment, and land treatment units. These regulations consisted of a set of design and operating standards separately tailored for each type of unit. The design and operating standards required units (other than land treatment units) to have a liner and leachate collection system to prevent migration of wastes to the subsurface soil or to ground water or surface water during the active life of the unit.

The Hazardous and Solid Waste Amendments (HSWA) to RCRA became law November 8, 1984. Under Section 3004(o) and 3015 of these amendments, certain surface impoundments and landfills must have "two or more liners and a leachate collection system above (in the case of a landfill) and between such liners." This is the minimum technological requirement for new units, replacement units, and lateral expansions of existing units which are not subject to statutory variances.

1.1.2 Legislative Requirements

The double liner system requirements developed under HSWA are intended to satisfy the policy objective stated in RCRA 3001(a)(4) to "assure that hazardous waste management practices are conducted in a manner which protects human health and the environment". An interim minimum double liner requirement was included in HSWA (RCRA 3004(o)(5)(B)) to provide time (30 months) for EPA to develop regulations and guidance documents on double liner systems. The interim double liner system requires:

> "a top liner designed , operated, and constructed of materials to prevent the migration of any constituent into such liner during the period such 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 such liner during such period. For the purpose of the preceding sentence, a lower liner shall be deemed to satisfy such requirement if it is constructed of at least a 3-foot thick layer of recompacted clay or other natural material with a permeability of no more than 1×10^{-7} centimeter per second."

The current regulations on double liner systems codified in the Code of Federal Regulations(CFR) promulgated July 15, 1985 (50 FR 28747, 28748) reflects the interim minimum technology standards stated in RCRA 3004 (o)(5)(B). In language that almost identically tracks the statute, the regulations (Parts 264 and 265) require new and replacement units and lateral expansions of units at surface impoundments and landfills to have a double liner system with a leachate collection and removal system that protects human health and the environment.

1.1.2.1 Current Requirements for Top Liner

The top liner of a double liner system required by the current regulations must be "designed, operated, and constructed of materials to prevent the migration of any constituent into such liner during the period such facility remains in operation (including any post-closure monitoring period).

1.1.2.2 Current Requirements for Bottom Liner

The bottom liner of a double liner system required by the current regulations must be "designed, operated, and constructed to prevent the migration of any constituent through such liner during such period" (the active life and post-closure care period).

The regulations state that the bottom liner requirement can be satisfied by a bottom liner that is at least a 3-foot thick layer of recompacted clay or other natural material with a permeability (hydraulic conductivity) of no more than 1×10^{-7} centimeter per second (cm/s).

1.1.3 Proposed Double Liner Rule of March 28, 1986

On March 28, 1986, EPA proposed double liner and leachate collection system requirements for landfills and surface impoundments (51 FR 10706-10723). These proposed regulations are intended to codify the minimum technology double liner requirements mandated by the HSWA for landfills and surface impoundments. The March 28, 1986, proposed rule requires new units, lateral expansions, and replacements of existing units at landfills and surface impoundments to have two or more liners and a leachate collection and removal system above (for landfills) and between the liners. The liner system proposed in the March 28, 1986 Federal Register consists of:

- A top liner, designed, constructed and operated to prevent migration of liquids into it; and

- One of two possible bottom liners;

  --A bottom liner designed, constructed and operated so that liquids do not migrate through it. The minimum standard is a 1-m (3.0-ft.) layer of compacted soil with a maximum hydraulic conductivity of 1×10^{-9} m/s (1×10^{-7} cm/s);

OR

--A composite bottom liner made of two components. The upper component would be designed, operated, and constructed to prevent migration of hazardous constituents into it and a lower component designed, operated, and constructed to minimize migration of hazardous constituents through it if the upper component were breached before the post-closure care period ends. At a minimum, this lower bottom liner component must be a compacted soil with a maximum hydraulic conductivity of 1 x 10^{-9} m/s (1 x 10^{-7} cm/s).

While the rule proposed for codification on March 28, 1986, does not provide minimum specifications for the geomembrane (FML) components of the top and bottom liners, EPA has developed guidance on minimum specifications for these materials. According to the Draft Minimum Technology Guidance on Double Liner Systems of May 24, 1985 (EPA 530-SW-85-012):

- The geomembrane top liner should be at least 0.75 mm (30 mil) thick, if it is protected in a timely manner after placement; if it is not protected in a timely manner, the top FML should be at least 1.12 mm (45 mil) thick.

- The upper geomembrane component of a bottom liner should be at least 0.75 mm (30 mil) thick.

Examples of double liner systems in hazardous waste management units are given in Chapter 2.

1.1.4 Proposed Liner/Leak Detection Rule (Pending)

EPA is currently developing proposed regulations for leak detection systems intended to satisfy the HSWA statutory requirements for leak detection systems at landfill, surface impoundment, waste pile and land treatment units. EPA is planning to require minimum system performance criteria for leak detection systems as well as minimum specifications for components of the leak detection system in the proposal on leak detection. In addition to the leak detection regulations, EPA is also planning to extend the minimum technology double liner requirements to waste piles. It also will establish construction quality assurance (CQA) requirements for owners or operators of hazardous waste management units.

1.2 PURPOSE AND SCOPE OF THE BACKGROUND DOCUMENT

1.2.1 Purpose of the Background Document

In its development of the Proposed Double Liner Rule and the pending Proposed Liner/Leak Detection Rule, and through its ongoing research and development efforts, EPA has gathered data that indicates that compacted low-permeability soil bottom liners provide a lower level of performance capability in double liner systems than composite bottom liners comprised of a geomembrane upper component and a compacted low-permeability soil lower component. To announce this data to the public, EPA plans to issue a Notice of Data Availability on Bottom Liners in April 1987. In addition to announcing the data, the Notice will provide a summary of the data and a discussion of their significance. The purpose of this technical background document is to fully document all relevant data relating to the comparative performance of compacted soil and composite bottom liners.

The purpose of this document is to: (1) present data relating to the comparative performance of compacted low-permeability soil and composite bottom liners; (2) compare the capabilities of compacted low-permeability soil and composite bottom liners to satisfy the statutory goal of RCRA to prevent the migration of hazardous constituents from the hazardous waste management unit and detect leakage through the top liner at the earliest practicable time; and, (3) quantify performance differences between double liner systems with compacted low-permeability soil and composite bottom liners. To the extent possible, comparisons will be presented in relation to the following three criteria that EPA believes relate to protection of human health and the environment for land disposal units:

- leak detection capability;

- leachate collection system efficiency; and

- leakage volume into and out of the bottom liner.

1.2.2 Sources of Available Data

Several sources of data have been reviewed and used during preparation of this technical background document. These include:

- case study information on observed leakage rates through compacted soil liners;

- case study information on the integrity (number of holes) of installed geomembrane liners;

- case study information on leakage rates through large-scale model composite liners;

- analytical and numerical studies of flow into, through, and out of compacted low-permeability soil and composite bottom liners;

- analytical and numerical studies of differences in the performance of leak detection systems due to different (compacted low-permeability soil or composite) bottom liners; and

- responses to an EPA questionnaire on current bottom liner construction practices at hazardous waste management facilities.

1.2.3 Scope of the Background Document

This technical background document is divided into seven chapters, each of which is summarized below. Note that in the remainder of this document, compacted low-permeability soil liners are referred to simply as compacted soil liners.

Chapter 1 presents an introduction to the technical background document. This introduction includes a description of the Legislative History leading to the Notice of Data Availability on Bottom Liners. This introductory chapter also describes the purpose and scope of the background document.

Chapter 2 provides a brief description of key concepts which are used in this document. They include such introductory materials as definitions of lining system, double liner, single liner, and composite liner; leachate collection and removal systems; functions of lining system components; and, important characteristics of lining system components. Chapter 2 also discusses EPA's "liquids management strategy" and describes the lining system performance criteria (detection capability, leachate collection system efficiency, and leakage volume out of the unit) useful in evaluating to what degree bottom liners meet EPA's goal of preventing migration through the lining system and out of the unit. This chapter is included as background to ensure that all readers are familiar with the basic concepts that are fundamental to understanding the significance of the data presented herein, as well as to ensure that all readers have a source of basic information to assist them in interpretation of the data.

Chapter 3 presents a discussion of the performance of compacted soil liners. This chapter reviews case studies of leakage through compacted soil liners. This data can be used to estimate achievable soil hydraulic conductivities in the field and to estimate the breakthrough times and flows out of the unit associated with compacted soil liners. Chapter 3 also presents the results of analytical and numerical studies of the performance of compacted soil bottom liners. The analytical investigation is based on the application of Darcy's law. The numerical investigations make use of the SOILINER and UNSAT2D computer models. The UNSAT2D model is also used to investigate overall LDCRS/bottom liner system performance.

Chapter 4 is concerned with the performance of composite bottom liners. Case study data is presented and then used to draw conclusions regarding the number and types of holes in properly constructed FML (geomembrane) liners. Small-scale laboratory test results of seepage through composite liners are also reviewed. The analytical and numerical methods presented in Chapter 3 are also used in Chapter 4 to investigate the performance of composite bottom liners. The UNSAT2D model is also used here to investigate overall LDCRS/bottom liner system performance.

Chapter 5 summarizes the comparative performance of compacted soil and composite bottom liners. Comparisons are made by excerpting data from Chapters 3 and 4, respectively, and then comparing it in terms of LDCRS detection sensitivity and collection efficiency, as well as the the cumulative leakage through the bottom liner and time for leakage to break through the bottom liner.

Chapter 6 summarizes current practices in double liner system design at hazardous waste management units. This summary is based on the results of an EPA survey conducted in January and February 1987.

Chapter 7 provides a concise summary of the findings presented in background document.

CHAPTER 2

DEFINITIONS AND CONCEPTS RELATED TO DOUBLE LINER SYSTEMS

2.1 INTRODUCTION

2.1.1 Purpose of this Chapter

The purpose of this chapter is to ensure that all readers are familiar with the important basic concepts of hazardous waste management units, waste containment, lining systems, leachate collection and removal systems, and leak detection systems as well as the materials used to construct lining systems, leachate collection and removal systems, and leak detection systems.

The concepts presented in this chapter provide many of the foundations for EPA's "liquids management strategy" and "systems approach" to waste containment. This strategy is discussed herein, and the lining system performance criteria which are influenced by the bottom liner and which are relevant to the strategy are defined.

2.1.2 Organization of this Chapter

This chapter is comprised of four sections devoted respectively to hazardous waste management units, lining systems, leakage, and EPA's liquids management strategy. A brief outline of each section is as follows:

- Section 2.2 gives a general description of the various hazardous waste management units such as landfills, surface impoundments, and waste piles, and discusses ground pollution mechanisms which may be associated with leakage from these units.

- Section 2.3 presents the various types of lining systems used in hazardous waste management units and the materials used to construct these lining systems. Also, Section 2.3 defines basic lining system elements such as double liners, composite liners, leachate collection and removal systems, and leak detection systems.

- Section 2.4 discusses the concept of leakage (what is leakage? what is a leak?), the purpose of leak detection systems (why is it important to detect leakage? complementarity of leak detection and leachate collection), and performance characteristics of leak detection systems.

- Section 2.5 discusses EPA's goal for bottom liners and defines lining system performance criteria that are relevant to achieving this goal.

2.2 WASTE MANAGEMENT UNITS

2.2.1 Introduction

2.2.1.1 Definition

"Waste management unit" is a generic term which is used in this report to describe land disposal units used to treat, store or dispose of hazardous waste. These units include: landfills, surface impoundments, and waste piles.

2.2.1.2 Purpose of this Section

It is not possible to discuss leakage without a knowledge of:

- the containment facilities from which leakage is taking place; and

- the lining systems through which leakage is taking place.

The purpose of Section 2.2 is to briefly describe surface impoundment, landfill and waste pile units, and to discuss pollution mechanisms that may be associated with leakage from these units. The next section (2.3) will be devoted to lining systems used in those units.

2.2.2 Description

2.2.2.1 Types of Waste Management Units

Three types of waste management units are considered: landfills, surface impoundments, and waste piles. These three types of units are illustrated in Figure 2-1 and their usage is as follows:

- landfills are used for permanent disposal of solid waste (hazardous waste in "hazardous waste landfills" or municipal waste in "sanitary landfills");

- surface impoundments are used to store liquids (with, possibly, particles in suspension, which settle progressively) or sludges (which consolidate progressively); and

- waste piles are used for temporary storage of solid waste.

2.2.2.2 Geometry of Waste Management Units

2.2.2.2.1 Surface Impoundments

The overall shape of surface impoundments is roughly that of an inverted truncated pyramid with "side slopes" and a "bottom". The side slopes can be as steep as permitted by geotechnical considerations and they typically range between 2H/1V and 4H/1V, while the bottom is nearly horizontal with just the slope (e.g., 2%) required for the drainage layer if there is a double liner.

2.2.2.2.2 Landfills

The lower part of a landfill has roughly the shape of an inverted truncated pyramid, like a surface impoundment. This is the part of a landfill which is lined prior to waste placement. The side slopes of the bottom part of a landfill can be as steep as permitted by geotechnical considerations and they typically range between 2H/1V and 4H/1V, while the bottom is nearly horizontal with just the slope (e.g., 2%) required for the drainage layer(s) that is (are) incorporated into the lining system.

The upper part of a landfill includes a cap which is placed on top of the waste to close the landfill after completion of waste placement operations. The cap is a lining system used to prevent (or, at least, minimize) penetration of rain water into the landfill.

Large landfills may be divided into cells which are operated sequentially.

2.2.2.2.3 Waste Piles

A waste pile can have any shape compatible with waste stability. The lining system placed under the waste pile is nearly horizontal, with just the slope (e.g., 2%) required for the drainage layer(s) that is (are) incorporated into the lining system.

2.2.3 Ground Pollution Mechanism

2.2.3.1 Surface Impoundments

A surface impoundment can cause pollution of soil and ground water if the hazardous liquid contained in the impoundment leaks through the lining system and into the ground.

In rare occasions, waves of liquids stored in surface impoundments have overtopped the crests of the impoundments thereby causing ground-water pollution.

2.2.3.2 Landfills

The mechanism by which a landfill can cause soil and ground-water pollution includes two steps:

- first, leachate is generated in the landfill; and
- then, pollution occurs if some leachate migrates through the lining system into the ground.

Leachate can be produced by two mechanisms, intrusion of water into the waste and generation of leachate within the waste:

- Intrusion of Water in the Waste. The main cause of leachate production is infiltration of rain water into the waste. The rain water seeping through the waste becomes progressively polluted and the resulting polluted liquid is called "leachate". In exceptional cases, leachate can be produced by intrusion of ground water into the waste (if the ground water table rises), or, even more exceptionally, by intrusion of flood water into the waste.

- Generation of Leachate within the Waste. Leachate can originate in the waste if liquid is entrapped in the waste during waste placement. Drums containing liquids are not allowed in hazardous waste landfills, and the only possibility for entrapping liquids is through moisture in the waste or in the earth used for the daily covers (i.e., the layers of compacted earth, placed every day on the waste). Part of the moisture included in the waste or the daily covers can be expelled by consolidation (i.e., decrease in volume of the waste and the daily covers due to compression caused by the own weight of the waste and the daily covers).

To prevent pollution of soil and ground water by landfills, all efforts should be made to prevent production of leachate:

- A low-permeability cap must be placed on the landfill immediately after completion of waste placement operations to prevent intrusion of rain water.

- Selection of landfill location and appropriate design should prevent intrusion of ground water and flood water.
- Waste and daily cover material should not contain excess liquids.

Since leachate production cannot be totally prevented, especially during landfill operation (i.e., during waste placement) when rain can fall freely on the landfill, a lining system is necessary at the bottom and on the side slopes of the landfill.

2.2.3.3 Waste Piles

The two-step mechanism by which waste piles can cause soil and ground-water pollution is similar to the mechanisms related to landfills which were described in Section 2.2.3.2. Waste piles are temporary storage units and the waste is normally removed after some time.

2.3 LINING SYSTEMS USED IN WASTE MANAGEMENT UNITS

2.3.1 Introduction

2.3.1.1 Importance of Lining Systems

From the above discussion it is clear that the lining system placed on the bottom and the side slopes of a waste management unit has a critical role: the ground is polluted as soon as liquid leaks through the lining system. Therefore it is essential to have a good knowledge of lining systems prior to discussing leakage.

2.3.1.2 Scope of this Section

The purpose of this section is to provide basic information on the types of lining systems used in hazardous waste management units, and on the materials used to construct these lining systems. This section should familiarize the reader with the vocabulary used to describe lining systems.

This section will address the following: definition of lining systems, materials used in lining systems, double liners, and composite liners. (Experience shows that it is not practical to discuss double liners and composite liners without a knowledge of materials used to construct lining systems.)

2.3.1.3 Definition of Lining Systems

The terms "liner" and "lining system" are not synonymous.

A liner is a low-permeability barrier used to impede liquid or gas flow. Note that "low permeability" is used, and not "impermeable". If there was such a thing as an impermeable barrier, it would be possible to prevent leakage, and many of the discussions and considerations presented in this background document would be pointless. Although it may be possible that a glass is impermeable to water, in modern technology there is no material that is impermeable at the scale of a waste management unit where the area to be lined can be as large as tens of hectares (dozens of acres).

Since no liner is impermeable, pollution control can only result from a combination of liners and drainage layers, performing complementary functions:

- Liners (which are low-permeability barriers) impede the flow of undesirable (polluted) liquids toward the ground.

- Drainage layers (which have a high permeability) convey the undesirable flow away from the ground.

Such combination of liners and drainage layers is called a "lining system".

2.3.2 Materials Used in Lining Systems

2.3.2.1 Introduction

Materials used in lining systems include:

- low-permeability materials to construct the liners;

- high-permeability materials to construct the drainage layers;

- transition materials (or interface materials) acting as filters or protective layers (i.e., providing filtration or protection) between various layers of a lining system; and

- reinforcement materials which increase the strength of a lining system (if required).

These materials are briefly discussed below.

2.3.2.2 Liner Materials

2.3.2.2.1 Introduction

Low-permeability materials used in civil engineering to construct liners include: compacted low-permeability soils, geomembranes, concrete, and asphaltic concrete. Concrete and asphaltic concrete are not used in hazardous waste units for the following reasons:

- Concrete liners tend to undergo much cracking and therefore tend to leak significantly.

- Asphaltic concrete cannot be used because asphalt has a poor resistance to attack by many chemicals typically found in waste management units.

Therefore, only low-permeability soils and geomembranes are discussed in this document.

2.3.2.2.2 Compacted Soils

Compacted low-permeability soils used to construct liners include: clay, silty clay, clayey sands, and silty sands. If such soils are not available at the site, it is possible to make a low-permeability soil by mixing bentonite with sand. Bentonite is composed of extremely small particles of sodium montmorillonite. When it is dry, it becomes a powder which can be put in bags, and is purchased and transported like cement.

2.3.2.2.3 Geomembranes

- Definition

Geomembranes are low-permeability membranes used in civil engineering as fluid barriers. By definition, a membrane is a material that is thin and flexible.

- Examples

All geomembranes presently used in hazardous waste management units are synthetic geomembranes. (Asphaltic geomembranes, which are used for lining water storage facilities, are not used in hazardous waste units because they do not have adequate resistance to chemical attack.) Typical examples of geomembranes used in hazardous waste units include: high density polyethylene (HDPE) geomembranes; linear low density polyethylene (LLDPE) geomembranes; polyvinyl chloride (PVC) geomembranes; and chlorosulfonated polyethylene (CSPE) geomembranes.

- Terminology

The term geomembrane is often used by the engineering community in place of the term "flexible membrane liner" (FML). EPA is using the term "flexible membrane liner" or FML to be consistent with the terminology used in the past in documents discussing waste management units. Therefore, for consistency with previous EPA documentation "flexible membrane liner" or "FML" will be used in the remainder of this document to describe synthetic membranes used as low-permeability liners.

2.3.2.3 Drainage Materials

2.3.2.3.1 Introduction

High-permeability materials used to construct drainage layers include: high-permeability soils, synthetic drainage materials, and pipes. High-permeability soils and synthetic drainage materials are discussed below.

2.3.2.3.2 High-Permeability Soils

High-permeability soils include a wide variety of sands and gravels ranging from fine to coarse in size and well-graded to uniform in gradation. Selection of a high-permeability soil for specific conditions must consider the following:

- the drainage layer should be able to collect and rapidly remove liquids entering the leak detection, collection and removal system as a result of leakage through the top liner;

- the high-permeability soils should not damage FMLs when the FMLs are directly in contact with the soils; and

- the drainage layer should be physically compatible with transition materials to prevent any potential migration of the transition materials into the drainage layer which could lead to clogging.

2.3.2.3.3 Synthetic Drainage Materials

Synthetic drainage materials are made of planar structures which are thick enough to convey fluids in their plane. Synthetic drainage materials are usually made from polymers. Typical polymers include polypropylene, polyester, polyethylene. These polymers are highly inert to biological and chemical degradation.

Four types of synthetic drainage materials are currently available. These are thick needlepunched nonwoven geotextiles, geonets, geomats and corrugated or waffled plates. With the exception of needlepunched nonwoven geotextiles, these materials can be combined with geotextile filters to form drainage geocomposites.

2.3.2.4 Transition Materials

Transition materials include filters or protective layérs.

2.3.2.4.1 Filters

Filters are located between the drainage layer and the soil to be protected. They usually consist of a granular layer or a combination of granular layers, or a geotextile. Their function is to allow free flow into the drainage layer and at the same time prevent the migration of particles of the protected soil into the drainage layer.

2.3.2.4.2 Protective Layers

Protective (cushion) layers are located between the drainage layer and the FML. Their function is to protect the FML from damage by the drainage material. Cushion layers usually consist of a sand layer or a thick needlepunched nonwoven geotextile.

2.3.2.5 Reinforcement Materials

Reinforcement materials are typically placed in a soil layer. Typical functions include reinforcing the lining system on steep slopes to prevent sliding along the slope, reinforcing slopes to prevent slope failure, or bridging over cavities, depressions or soft spots. The materials most frequently used in reinforcement applications at waste management units are geogrids and geotextiles.

2.3.3 Double Liners

2.3.3.1 Introduction

2.3.3.1.1 Definitions

- Double Liner

A "double liner lining system" simply called a "double liner system" or a "double liner" is a lining system which includes two liners with a leachate collection and removal system between the two liners.

Clearly, two liners in contact (i.e., without a leachate collection and removal system between the two liners) do not constitute a double liner (they constitute a single liner, as discussed below).

- Single Liner

A lining system which includes only one liner is called a "single liner".

- Composite Liner

A composite liner is a liner comprised of two or more low-permeability components of different materials in contact with each other. For example, a FML and a clay layer placed in contact with each other constitute a composite liner (a FML composite liner). Composite liners do not constitute a double liner because there is no leachate collection and removal system between the two low-permeability components.

The purpose of a FML-compacted soil composite liner is to combine advantages of FMLs and compacted soils. FMLs have a much lower permeability than compacted soils, but they may have holes through which large leakage can occur if the FML is placed on a pervious medium and then subjected to a hydraulic head on its top surface. The leakage rate through a FML hole is reduced if there is compacted low-permeability soil under the FML.

2.3.3.1.2 Terminology Related to Double Liners

- Terminology Related to the Liners

In this document, the upper liner of a double liner is called "top liner" and the lower liner is called "bottom liner". We recognize that this terminology may be confusing since the term "bottom liner" may be mistaken for "bottom lining system", i.e., the lining system located at the bottom of a waste management unit.

"Top liner" is synonymous with "upper liner" or "primary liner".

"Bottom liner" is synonymous with "lower liner" or "secondary liner".

- Terminology Related to the Leachate Collection and Removal Systems

In all waste management units lined with a double liner there is a pervious layer between the two liners. This layer is called the "leachate collection and removal system (LCRS) between the liners". If this system is also used as a leak detection system (LDS), its name becomes "leak detection, collection, and removal system" (LDCRS).

While in surface impoundments there is only one pervious layer (i.e., the LDCRS mentioned above), there are two pervious layers in landfills: the LDCRS and the layer located above the top liner and called the "leachate collection and removal system (LCRS) above the top liner".

2.3.3.2 Use of Double Liners in Waste Management Units

2.3.3.2.1 Current Regulations

Current EPA regulations (40 CFR Parts 264 and 265) require a double liner system in all new hazardous waste landfill and surface impoundment units. Furthermore, as discussed in Chapter 1, the two liners comprising the double liner system should meet the following requirements:

- "A top liner designed, operated, and constructed of materials to prevent the migration of any constituent into such liner during the period such facility remains in operation (including any post-closure monitoring period)".

- "A bottom liner designed, operated and constructed to prevent the migration of any constituent through such liner during such period. For the purpose of the preceding sentence, a lower liner shall be deemed to satisfy such requirement if it is constructed of at least a 3-foot thick layer of recompacted clay or other natural material with a permeability of no more than 1 x 10^{-7} centimeter per second".

According to the Draft Minimum Technology Guidance on Double Liner Systems of May 24, 1985 [USEPA, 1985]:

- The top liner FML should be at least 0.75 mm (30 mil) thick, if it is protected in a timely manner after placement; if it is not protected in a timely manner the top liner FML should be at least 1.15 mm (45 mil) thick.

- The upper FML component of a bottom composite liner should be at least 0.75 mm (30 mil) thick.

2.3.3.2.2 Examples of Uses of Double Liners in Waste Management Units

- Types of Double Liners Used in Waste Management Units

From the above discussion, it appears that four types of double liners are currently permitted by existing EPA regulations (Figure 2-2). Such double liners can be used for landfills, surface impoundments, and waste piles. The double liner using two composite liners (Figure 2-2(b)), called "double composite liner", is increasingly used in order to minimize the amount of leakage through the top liner while maximizing the collection efficiency of the LDCRS.

- Caution on the Use of Top Composite Liners in Surface Impoundments

The use of a top composite liner in a surface impoundment requires special caution. If the FML (which is the upper component of the top composite liner) is not covered with a heavy material (such as a layer of earth, or concrete slabs), and if there is leakage through the FML, liquids tend to accumulate between the low-permeability soil (which is the lower component of the top composite liner) and the FML since the submerged portion of the FML (whose specific gravity is close to 1) is easily uplifted. Then, if the impoundment is rapidly emptied, the FML is subjected to severe tensile stresses because the pressure of the entrapped liquids is no longer balanced by the pressure of the impounded liquid. Therefore, a top composite liner should always be loaded, which is automatically the case in a landfill or in a waste pile, and which must be taken into account in the design of a liquid impoundment.

2.3.3.2.3 Influence of Liner on Leak Detection

The LDCRS between the top and bottom liner is also used as a leak detection system to form a leak detection, collection, and removal system (LDCRS). The leakage that is collected has migrated through the top liner and flows, in the LDCRS, over the top surface of the bottom liner. It appears that the two liners have the following influence:

- The top liner governs the amount of leakage entering the LDCRS. Many hazardous waste management units include a top composite liner in order to minimize leakage through the top liner.

- The bottom liner has a major influence on the performance of the LDCRS. As will be shown in Chapter 5, a compacted soil liner allows greater leakage into and through the bottom liner than does a composite. For this reason, a composite (Figure 2-3 (a)) is preferable to compacted soil (Figure 2-3 (b)).

As will be shown in Chapter 6, owners and operators of hazardous waste management units rarely use compacted soil bottom liners (Figure 2-3 (a)) because of the performance deficiencies associated with them in comparison to composite bottom liners (Figure 2.3 (b)).

2.4 LEAKAGE DEFINITION AND DETECTION

2.4.1 Definitions

2.4.1.1 Leak and Leakage

According to Webster:

- A leak is "a crack or opening that permits something to escape from or enter a container or conduit".

- Leakage is "something that escapes by leaking" or "an amount lost as the result of leaking".

From these definitions, it clearly appears that what is monitored between the top and the bottom liners is the leakage, not the leaks. Therefore, the monitoring system should be called "leakage detection system". While "leakage detection system" is grammatically correct, the phrase "leak detection system" has been codified by RCRA. For the sake of consistency with the law, the phrase "leak detection system" will be used in this document.

On the other hand, systems used in quality assurance of FML installation, such as the vacuum box, are clearly intended to find leaks.

2.4.1.2 Leak Size and Leakage Rate

According to the above definitions, the term "leak size" designates the size of a hole, expressed as a surface area or dimensions such as a diameter (e.g., a 1 cm^2 leak, a 1 $in.^2$ leak, a 2 mm diameter leak, a 1/4-in. diameter leak). The term "leak size" is sometimes mistakenly used for "leakage rate" which is the flow rate through a leak or a group of leaks, which is expressed as a volume per unit of time (m^3/s, liters/day, gallons/day). The term "leakage rate" will often be used in this document as an abbreviation for "leakage rate per unit area", which is expressed as a volume per unit of time per unit of area ($m^3/s/m^2$ (which is equivalent to m/s), liters/hectare/day, liters/1000m^2/day (Ltd), gallons/acre/day (gpad)).

(Note: 1 hectare = 100 m x 100 m = 10 000 m^2.)

The following conversions apply:

1 gallon/acre/day	=	1.08×10^{-11} m/s
	=	9.35 liters/hectare/day
	=	0.935 liters/1000 m^2/day
1 liter/hectare/day	=	1.16×10^{-12} m/s
	=	0.11 gallons/acre/day
	=	0.1 liters/1000 m^2/day
1 liter/1000m^2/day	=	1.16×10^{-11} m/s
	=	1.1 gallon/acre/day
	=	10 liters/hectare/day
1 m/s	=	8.64×10^{10} liters/1000m^2/day
	=	8.64×10^{11} liters/hectare/day
	=	9.24×10^{10} gallons/acre/day

From a practical standpoint, the approximate conversion can be used:

1 liter/1000m^2/day	=	1 gallon/acre/day
1 Ltd	=	1 gpad

2.4.1.3 Leakage Collected and Leakage Out of the Unit

The possible fates of liquids entering a double liner system are shown in Figure 2-4.

The leakage discussed in the previous sections is the leakage that the LDCRS system is intended to collect and detect. This is the leakage through the top liner (C in Figure 2-4).

The leakage out of the unit, which is the leakage through the bottom liner (J in Figure 2-4), is only a fraction of the leakage through the top liner. Other fractions include:

- leakage entrapped in the LDCRS by absorption, capillarity, ponding, etc. (F in Figure 2-4);

- leakage collected at the LDCRS sump (G in Figure 2-4); and

- leakage absorbed in the bottom liner (I in Figure 2-4).

If the LDCRS is properly designed, the liquid head on the bottom liner is very small, and leakage through the bottom liner (which is governed by head on the bottom liner) is very small. This is consistent with the EPA's goal of protecting human health and environment through system impermeability and not liner impermeability. No liner is perfectly impermeable but proper design can almost achieve system impermeability.

2.4.2 Leak Detection System

2.4.2.1 Definition

In the context of this background document, leak detection refers to leakage through the top liner and, therefore, a leak detection system is a system which is placed between the two liners of a double liner system to monitor the leakage through the top liner.

2.4.2.2 Purpose of Leak Detection

As indicated in the definition given in Section 2.4.2.1, the purpose of a leak detection system is to monitor leakage through the top liner. Monitoring leakage through the top liner is an important component of EPA's systems approach to the containment of hazardous constituents using double liner systems.

2.4.2.3 Performance Characteristics of Leak Detection Systems

The important performance characteristics of leak detection systems include:

- the leak detection sensitivity, which is the smallest leakage rate that can be detected by the considered leak detection system;

- the detection time (i.e., the time necessary to detect a leak), which is a function of the leakage rate;

- the leachate collection efficiency, which is the ratio between the leakage that is collected at the sump of the LDCRS and the leakage that actually passes through the top liner into the LDCRS.

2.5 EPA LIQUIDS MANAGEMENT STRATEGY

2.5.1 Introduction

The previous sections of this chapter have described waste management units, lining systems, and leakage through lining systems. This section of Chapter 2 discusses EPA's "liquids management strategy" for land disposal units. From an understanding of this strategy, key lining systems performance criteria are identified which will be used in subsequent sections to compare the performance of compacted soil and composite bottom liners and establish the best demonstrated available technology (BDAT) for double liner systems.

2.5.2 EPA Liquids Management Strategy

The fundamental goal of EPA's hazardous waste management regulations is the protection of human health and the environment. To fully understand the relationship of this document to the hazardous waste land disposal regulatory program promulgated on July 26, 1982, the "liquids management strategy" must be considered.

Since the onset of the hazardous waste land disposal program, EPA's strategy for protecting human health and the environment has been to set a "no migration" lining system goal for land disposal units. Congress perpetuated this performance goal in Section 3004(o)(5)(6) of the 1984 RCRA amendments by providing an interim design that uses a top liner "designed, operated and constructed to prevent migration of any constituent into it "and a bottom liner" designed, operated and constructed to prevent the migration of any constituent through such liner." EPA's Proposed Double Liner Rule of March 28, 1986, maintains EPA's goal of preventing migration of constituents out of the hazardous waste management unit.

While the EPA's position has been and continues to be to prevent hazardous constituent migration out of the unit, it recognizes that the "no migration" goal is not always achievable. However, through the EPA's "liquids management strategy" and through the use of BDAT for double liner systems, it is believed that waste management units with double liner systems can come very close to the "no migration" goal (see discussion in Section 2.4.1.3 on leakage out of the unit).

EPA's liquids management strategy has two main objectives: (i) minimize leachate generation in the waste management unit (which was discussed in Section 2.2.3.2); and (ii) maximize leachate removal from the waste management unit at the earliest practical time. It is through these two operational objectives that EPA will achieve the Congressional goal of preventing migration of hazardous constituents out of the unit.

This background document applies to the second part of the "liquids management strategy", namely, maximizing leachate removal from the waste management unit. The double liner <u>system</u> is the mechanism by which leachate collection and removal can be maximized. The top and bottom liner together with the LCRS above the top liner (in the case of landfills) and the LDCRS between the liners function in an integrated, interdependent manner to prevent leachate migration out of the unit by maximizing its collection and removal. Each of the system elements reinforces and supports the other: the liners serve as a barrier to leachate migration and facilitate its collection and removal; the leachate collection and removal system (LCRS) above the top liner in landfills enables collection and removal of leachate and minimizes the buildup of the liquid pressure on the top liner; the leachate collection and removal system between the liners serves to minimize the buildup of head on the bottom liner; and the leak detection system provides the owner or operator and EPA with notification of leakage through the top liner, which enables the review of existing conditions and may lead to the taking of certain response activities.

In this integrated system, the bottom liner serves several functions. These include:

- maximizing the detection capability of the leak detection system to enable leak detection at the earliest practicable time (RCRA 3004(o)(4)(A)); detection sensitivity, defined subsequently, is a key detection capability performance criterion;

- maximizing leachate collection and removal in the LDCRS; this is achieved by having a LDRCR/bottom liner system with as high a collection efficiency as possible; the key performance criterion here is leachate collection system efficiency; and

- minimizing the migration of leakage into and through the bottom liner; this is achieved by minimizing hydraulic head on the bottom liner (which is accounted for by having an LDCRS with a sufficiently permeable drainage media) and, for a given hydraulic head, by choosing a bottom liner which prevents to the extent technically feasible migration of hazardous constituents out of the unit.

2.5.3 Performance Criteria for Evaluation of Bottom Liners

In Section 2.5.2 several performance criteria for evaluation of the comparative performance of bottom liners were identified based on EPA's liquids management strategy. These criteria are defined below.

For clarity an illustration of a compacted soil bottom liner with some typical dimensions is given in Figure 2-3 (a). An illustration of a composite bottom liner with some typical dimensions is given in Figure 2-3(b).

2.5.3.1 Leak Detection Sensitivity

The detection sensitivity is the smallest leakage rate through the top liner (E in Figure 2-4) that can be detected in the LDCRS sump within a reasonable amount of time. The hydraulic conductivity of the bottom liner (or top component of a composite bottom liner) is the variable which most influences detection sensitivity. The smaller the hydraulic conductivity, the better the leak detection sensitivity.

2.5.3.2 Leachate Collection Efficiency

The leachate collection efficiency is the ratio of the leakage collected at the LDCRS sump (G in Figure 2-4) divided by the leakage entering the LDCRS (E in Figure 2-4). There are two measures of collection efficiency: (i) cumulative collection efficiency measured from the time of unit start-up to any other point in time; and (ii) steady-state collection efficiency at any point in time after the LDCRS has "wetted up". The two factors that most influence collection efficiency are the hydraulic conductivity of the bottom liner and the capillary tension in the LDCRS drainage media (the latter factor affects the cumulative collection efficiency only).

2.5.3.3 Leakage Out of the Unit

Leakage out of the unit refers to leakage that passes through the bottom liner into the ground (J in Figure 2-4). The factor which most influences leakage out of the unit is the hydraulic conductivity of the bottom liner.

2.5.3.4 Breakthrough Time

While breakthrough times are not considered to be critical performance criteria within the context of EPA's "liquids management strategy", they do provide useful information on compacted soil liner behavior and are included herein for completeness. Breakthrough time refers to the time from when leakage first enters the LDCRS (E in Figure 2-4) until the time it first passes through the bottom liner and enters the ground (J in Figure 2-4). The two factors which most influence breakthrough time are the hydraulic conductivity and thickness of the compacted soil bottom liner.

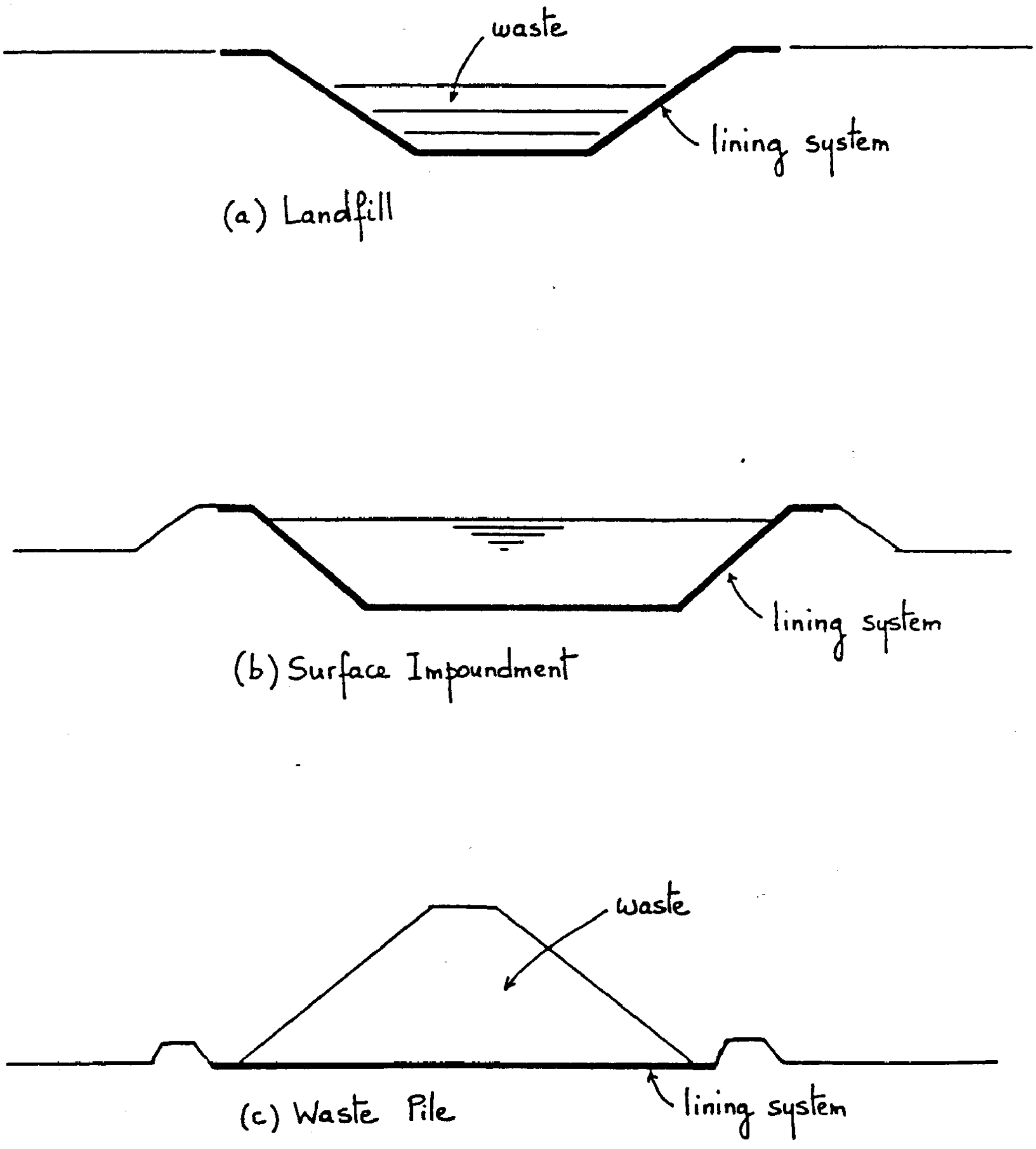


Figure 2-1. Waste management units.

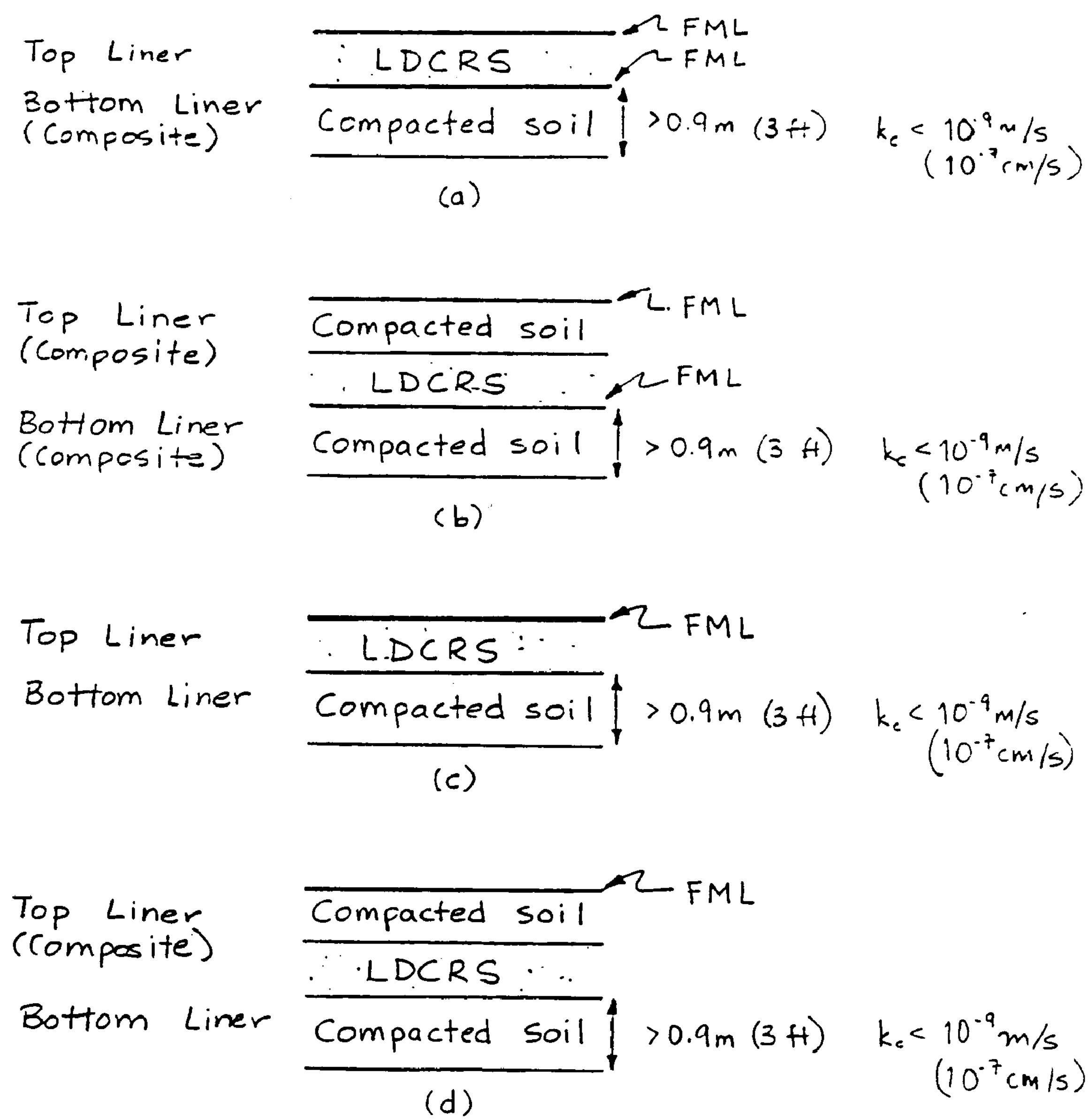


Figure 2-2. Four types of double liner systems used in hazardous waste management units.

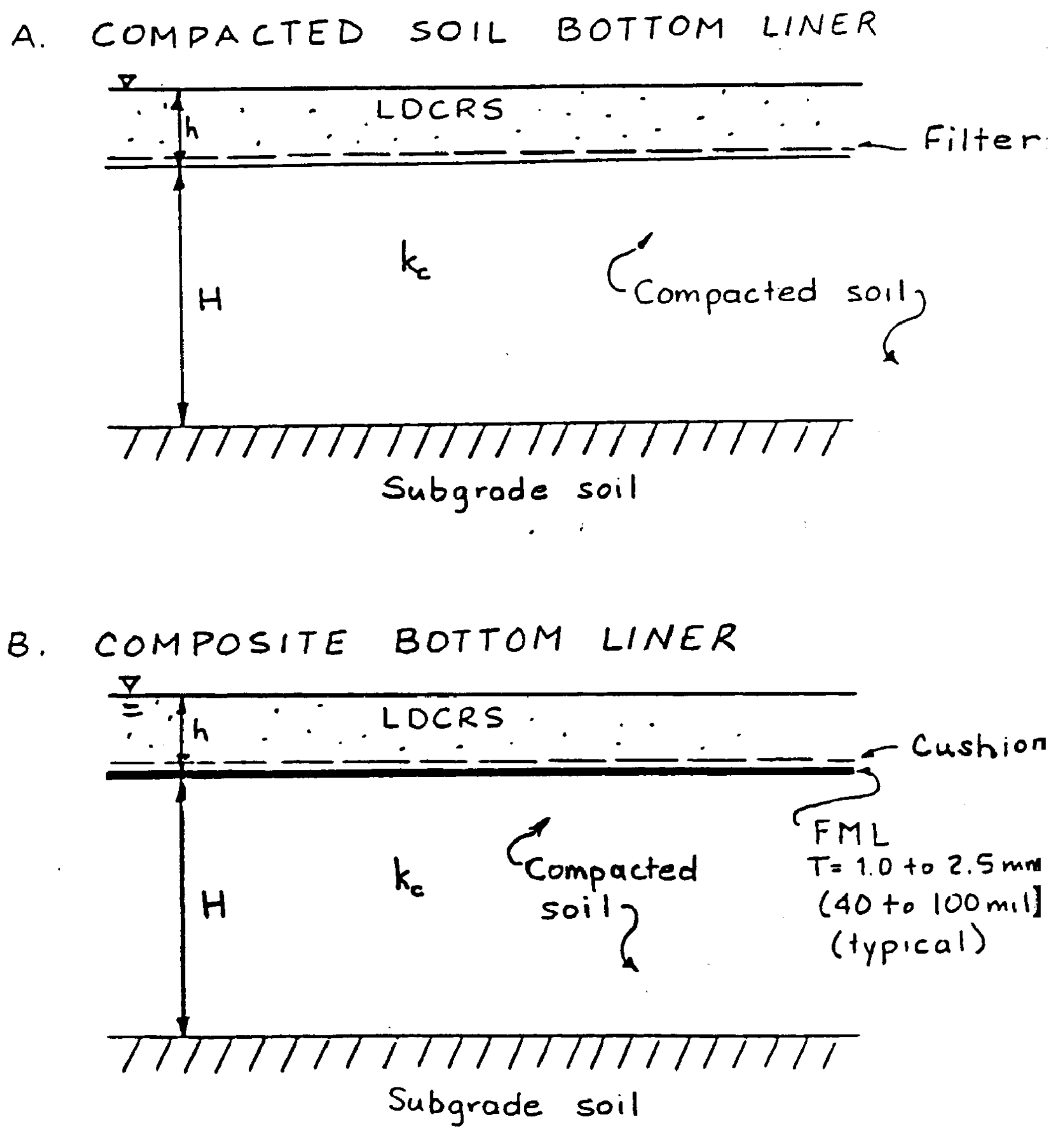


Figure 2-3. Illustrations and typical properties of bottom liners: (a) compacted soil; and (b) composite.

	A = leachate collected in the LCRS sump →
Leachate Collection and Removal System (LCRS)	B = leachate stored* in LCRS
	C = leachate from the LCRS into top liner
Top Liner	D = leachate stored* in top liner
	E = leakage from the top liner into the LDCRS
	G = leakage collected in the LDCRS sump →
Leak Detection Collection and Removal System (LDCRS)	F = leakage stored* in LDCRS
	H = leakage from the LDCRS into the bottom liner
Bottom Liner	I = leakage stored* in the bottom liner
Ground	J = leakage from the bottom liner into the ground

* Stored liquids due to capillarity, absorption, etc.

Figure 2-4. Fate of liquids entering a double liner system at a landfill unit.

CHAPTER 3

PERFORMANCE OF COMPACTED SOIL LINERS

3.1 INTRODUCTION

This chapter addresses the performance of compacted low-permeability soil liners. The performance of composite liners will be addressed in Chapter 4.

The performance of compacted soil liners can be affected by a variety of parameters. The purpose of this section is to review these parameters and study how they affect soil liner performance. In Section 3.2, the factors affecting compacted soil liner performance are described. In Section 3.3, a literature review of case histories documenting compacted soil liner performance is summarized. A summary of each case history is presented in Appendix A. In Section 3.4, a one-dimensional saturated flow analysis is made. In Section 3.5, a one-dimensional partially saturated flow analysis is presented. In Section 3.6, a two-dimensional partially saturated flow analysis is presented. In Section 3.7, a comparison of these three analyses is made. In Section 3.8, the information presented in the chapter is summarized and conclusions are drawn.

Compacted soil lining system performance can be evaluated in terms of four criteria:

- leak detection capability (defined by leak detection sensitivity);
- leachate collection system efficiency;
- leakage into the bottom liner and out of the unit; and
- breakthrough time.

The analyses presented in Sections 3.4, 3.5, and 3.6 evaluate the effect of compacted soil bottom liner properties on lining system performance, using the above four criteria.

3.2 FACTORS AFFECTING COMPACTED SOIL LINER PERFORMANCE

3.2.1 Nature of Compacted Soils

In order to discuss the factors affecting compacted soil liners it is first necessary to understand the nature of compacted soil. Compaction is the densification of soil through the application of mechanical energy. The strength, ductility, permeability, and structure of a compacted soil will be affected by the method of compaction, level of compactive effort, and water content at which the soil is compacted. The dry density and water content of a soil are used to evaluate the degree to which the soil has been compacted. The typical variation of dry density as a function of water content is shown in Figure 3-1. It can also be observed that, for a given level of compactive effort, the dry density of the soil will first increase with increasing water content, and then decrease. The water content corresponding to the apex of the curve is called the optimum water content, while the dry density corresponding to the apex is called the maximum dry density. Not shown in Figure 1 is the fact that, at a given water content, the dry density of the soil increases with increasing compactive effort.

Compaction curves, such as the one shown in Figure 3-1, are usually obtained by performing Standard Proctor or Modified Proctor laboratory tests [ASTM D698 and ASTM D1557, respectively]. These tests are used to determine the maximum dry density attainable, for a given level of compactive effort, in a standard laboratory mold. The standard and modified test are carried out in essentially the same manner, except that in the modified test the soil is compacted into the mold in thinner lifts (i.e., 5 lifts instead of 3) and higher compaction energy is used. The test results are used to develop specifications for the compaction water content and compactive effort in the field. They are also used as part of the Construction Quality Assurance (CQA) program to determine if an adequate degree of field compaction has been achieved. This is the same procedure used to verify the construction procedure of earthen fills. The only difference between a traditional earthen fill and a compacted soil liner is that different water contents and compactive efforts may be specified so as to minimize permeability (liners) rather than maximize strength (earthen fills). Compacted soil liners will usually be compacted at higher water contents (at water contents wet of optimum) than earthen fills.

3.2.2 Hydraulic Conductivity

Permeability is a critical parameter which describes the rate and volume of flow through a compacted soil liner. The degree of permeability of a soil is often expressed in terms of its hydraulic conductivity (or coefficient of permeability), k (m/s):

$$k = V/(Ait) \qquad \text{(Equation 3-1)}$$

which is the volume, V (m^3), of fluid passing per unit area, A (m^2), per unit hydraulic gradient, i (m/m), per unit period of time, t (s). The hydraulic conductivities of natural soils vary over many orders of magnitude. The hydraulic conductivity of a soil compacted to a given water content and dry density is highly dependent upon its post-compaction degree of saturation (S_r). The higher the S_r, the higher the hydraulic conductivity. Typical saturated (S_r = 100%) hydraulic conductivities for a range of soil types are summarized in Table 3-1. The degree of saturation of a compacted soil liner is high (e.g., above 90% or more). Therefore, the saturated hydraulic conductivity is usually conservatively used in the design of soil liners.

The saturated hydraulic conductivity of a soil is affected by a variety of factors such as: compaction water content and compactive effort; natural, construction-related, or environmentally-related secondary structures; and interactions between the soil and permeating liquid. The effect of each of these factors will be reviewed below, separately, even though they can be interrelated.

3.2.2.1 Compaction Effort and Water Content

The hydraulic conductivity of a compacted soil will depend on the compaction effort and the water content at which it is compacted. At a given water content, the hydraulic conductivity of a soil will decrease with increasing compactive effort. At a given dry density, the hydraulic conductivity of a soil will be one to two orders of magnitude higher if compacted dry of optimum, than if compacted wet of optimum, as can be seen in Figure 3-1. It is important that dry density and water content be controlled when trying to achieve a low-permeability soil, because just a small decrease in compaction water content (from wet of optimum to dry of optimum) may result in an order of magnitude decrease in hydraulic conductivity.

3.2.2.2 Secondary Structures

3.2.2.2.1 Definition of Secondary Structures

A secondary structure [Terzaghi and Peck, 1967] is a random or repeating feature which disrupts the continuity of a soil mass and thereby affects the performance of the soil mass (e.g., permeability, strength, compressibility, etc.). The discussion here is limited to the effect of secondary structures on permeability. Examples of secondary structures are root holes, unremolded soil clods, desiccation cracks, and construction related secondary structures such as zones of variable density or water content which result in preferential fluid pathways through the compacted soil mass. Secondary structures can result from natural, construction-related, or environmental factors; each type of secondary structure is discussed below.

3.2.2.2.2 Natural Secondary Structures

Examples of natural secondary structures are root holes, fissures resulting from large ground deformations, or slickensided surfaces. In general, these structures are formed over time and are commonly found in natural soil formations. They are not expected to exist in recently compacted soil liners. However, it should be realized that they can exist in the natural soil subgrade upon which the compacted soil liner is placed.

3.2.2.2.3 Construction Related Secondary Structures

The hydraulic conductivity of a compacted soil mass can be affected by the presence of secondary structures generated during construction. Typically, soil is compacted in 150 mm (6 in) thick lifts and nonhomogeneity can occur within a given lift and along the interfaces between lifts. These zones of nonhomogeneity, or secondary structure, may be reflected in either zones of higher hydraulic conductivity within the compacted soil mass, or as a soil mass with a higher hydraulic conductivity in the horizontal direction than in the vertical direction.

The hydraulic conductivity within a given soil lift can vary by several orders of magnitude because of such factors as inadequate compactive effort, variation in soil water content, and variations in the soil structure. If a good bond is not developed between adjacent soil lifts, the interface between lifts can act as a preferred horizontal flow path, with a hydraulic conductivity higher than that in the vertical direction. If the zones of high hydraulic conductivity of a compacted soil mass become connected, seepage can occur at rates well in excess of the rates predicted from laboratory hydraulic conductivity tests.

Secondary structures in soil liners can also result from soil clods which are present in the soil prior to its placement. These clods are not always remolded during the compaction process. As a result, the compacted soil can have a structure composed of soil clods surrounded by reworked soil. The structure of the clods will be the same as the natural soil deposit from which the soil was taken. The structure of the natural soil clods which have not been remolded by the compaction process will present a discontinuity to uniform hydraulic flow through the liner. The presence of clods (and stones or cobbles with dimensions that are a large fraction of the lift thickness) are one of the primary causes of nonhomogeneous compacted soil masses. It should be realized that clods are broken down in the laboratory and stones and cobbles are screened from the sample and therefore the effects of both are not accounted for in permeability tests on laboratory compacted samples.

3.2.2.2.4 Environmentally Related Secondary Structure

As reported in the case studies in Appendix A, a primary cause of secondary structures in compacted soil liners is excessive drying after placement. A compacted soil can be placed at the correct moisture content and compacted to the specified dry density. If, however, it is not properly maintained between the time of compaction and placement of the next lining system component, drying can occur by moisture evaporation from the soil surface. Drying of the soil will result in desiccation cracks opening up in the soil. This is especially true in soils with very low hydraulic conductivities because the clay minerals which impart this low hydraulic conductivity usually have the property of undergoing shrinkage upon drying. It has been reported that cracks up to 150 to 200 mm deep (6 to 8 in) can occur within one day of placement if the surface is not properly protected [Ghassemi et al., 1983]. The presence of cracks or fissures will act as channels for the passage of liquids, and as a result, the effective hydraulic conductivity of the soil mass may be several orders of magnitude higher than the hydraulic conductivity of intact soil samples of typical laboratory size.

3.2.2.3 Interactions between Compacted Soil and Leachate

Hydraulic conductivity tests performed in the laboratory normally use distilled or tap water as the permeating liquid. A number of studies have evaluated the hydraulic conductivities of soils using permeants other than water. These permeants are intended to simulate the leachate generated in waste disposal units [Bowders et al., 1986; Brown et al., 1983; Fernandez and Quigley, 1985; Gordon and Forrest, 1981; Pierce and Peel, 1985]. The studies have indicated that some permeants generate higher hydraulic conductivities in some soils than those obtained using distilled water. These differences in hydraulic conductivities may be due to any one of several factors including chemically induced soil structural changes and solution or precipitation of solids. The chemical composition of the permeating fluid should be considered when designing a waste disposal unit.

3.2.3 Capillary Stresses

In partially saturated fine grained soils the existing water is held at the soil particle contacts. A tension force exists on the surface of this held water, resulting in the soil being hygroscopic. The degree to which the soil is able to take on water is often expressed in terms of the negative pore water stresses which exists in the soil, which are called capillary stresses (or suction stresses). The existence of capillary stresses will alter the hydraulic conductivity of the soil. Capillary stress is inversely proportional to the degree of saturation, S_r. The larger S_r, the smaller the capillary stress. The smaller the capillary stress, the higher the hydraulic conductivity. An example of the variation of hydraulic conductivity as a function of capillary stress (suction) is shown in Figure 3-2.

3.2.4 Settlement

All subgrades will undergo settlement when loaded. The magnitude of settlement will depend upon the subgrade soil properties and the magnitude of the applied load. The performance of both compacted soil liners and leachate collection and removal systems can be affected by settlements in the supporting subgrade.

3.2.5 Conclusions

A number of factors can influence the performance of compacted soil liners, as described in this section. These factors affect performance primarily through their effect on hydraulic conductivity. For the purpose of this study, which is to compare compacted soil and composite bottom liners, the most important factors affecting the hydraulic conductivity of a compacted soil liner constructed using a specific soil are:

- compactive effort
- compaction water content; and

• secondary structures.

These factors must be considered when determining the expected hydraulic conductivity of a compacted soil liner. For the purposes of this background document, it is important to understand that various factors can affect the hydraulic conductivity of a compacted soil liner, so that the variation can be accounted for in subsequent analyses. The degree to which the hydraulic conductivity may vary in the field can be estimated from a review of case histories of compacted soil liner performance.

3.3 CASE HISTORIES OF CLAY LINING SYSTEM PERFORMANCE

3.3.1 Overview of Case Histories

Appendix A summarizes the documented performance of compacted soil lining systems for both landfills and surface impoundments. The landfill facilities reviewed were primarily for the containment of sanitary waste, however, one case history described the performance of a clay lining system at a hazardous waste landfill. Another case history reports the results from a large scale field test. The surface impoundment case histories describe facilities which were constructed to hold fresh water, salt water (brine), or contaminated liquid. The landfill case histories are summarized in Section A.2 of Appendix A and the surface impoundments are summarized in Section A.3.

3.3.2 Summary of Case Histories

In all cases when field and laboratory data were available, it was found that the field measured hydraulic conductivity was as much as an order of magnitude or more higher than the laboratory measured hydraulic conductivity. The range of values obtained and the probable cause of the difference between the laboratory and field measured values are summarized in Table 3-2. Only the more conclusive case histories have been summarized in Table 3-2. It can be observed that several factors can have an effect on the performance of a compacted soil liner. Most of these factors relate to secondary structures (nonuniformities) in the compacted soil liner caused by:

- desiccation cracks;
- soil clods;
- spatial variation in compactive effort and compaction water content; and
- quality assurance of construction operation.

It should be realized that the above variables, which affect field performance, are seldom reproduced in standard laboratory tests. Therefore, achieving the desired hydraulic conductivity in the laboratory does not guarantee the same value will be obtained in the field. However, it is possible to achieve a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) in the field and this is the design objective of the EPA. Achieving this goal requires the proper soils, compaction procedures, and construction conditions. Recognizing the number of factors which can affect the hydraulic conductivity, and that the design goal is not always achieved, the subsequent analyses will consider both a standard hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) and a lower bound hydraulic conductivity of 10^{-8} m/s (10^{-6} cm/s). This lower value of conductivity might be representative of a compacted soil liner with some degree of secondary structure resulting from nonuniform compaction conditions, soil clods, drying or other factors. These conductivities will be used in the investigation of leak detection system sensitivity, leachate collection efficiency, leakage out of the unit, and breakthrough time for compacted soil liners.

3.4 ANALYSIS OF PERFORMANCE - STEADY STATE SATURATED FLOW (1D)

3.4.1 Introduction

In this section, analyses of compacted soil bottom liner performance are presented. These analyses are based on steady-state saturated flow in one dimension. The analysis of lining system performance can utilize analytical or numerical models having various degrees of complexity, as indicated in Figure 3-3. The analyses presented in this section use the simplest of the three models presented in Figure 3-3, that of one-dimensional steady-state saturated flow. This simple model readily permits the evaluation of a wide variety of scenarios. The model will be used to evaluate the effect of several parameters on the leak detection systems sensitivity, leachate collection efficiency, leakage out of the unit, and breakthrough time. In Section 3.7, the results obtained here will be compared with those from the one-dimensional (Section 3.5) and two-dimensional (Section 3.6) partially saturated flow analyses.

In the following calculations it will be assumed that the compacted soil liner is in a saturated state and that its permeability does not change with time. It is also assumed that the compacted soil is homogeneous (i.e., it does not possess secondary structures such as root holes or desiccation cracks).

3.4.2 Overview of Analysis

Flow through a homogeneous saturated soil can be modeled using Darcy's equation:

$$v = ki \qquad \text{(Equation 3-2)}$$

where v = apparent fluid velocity (m/s); and k = hydraulic conductivity (also called coefficient of permeability (m/s)).

The apparent velocity is the quantity of water that flows in a unit period of time across a unit area, perpendicular to the direction of flow. It should be noted that water actually flows through the voids at a higher rate than that given by the apparent velocity. The actual velocity or seepage velocity, v_s, is equal to:

$$v_s = v/n \qquad \text{(Equation 3-3)}$$

where v = apparent velocity and n is the porosity of the soil. The apparent velocity should be used when calculating the quantity of flow through a section, while the seepage velocity should be used to calculate the time it takes a unit of liquid to flow a given distance.

Therefore, the seepage velocity is used to calculate breakthrough time.

If the surface area, A, of the compacted soil liner is known, then the volume of flow per unit time can be established from the following relationship:

$$Q = vA = kiA \qquad \text{(Equation 3-4)}$$

The application of Equations 3-2 and 3-4 can be applied to a compacted soil liner, such as that shown in Figure 3-4. For the case shown in Figure 3-4, Darcy's equation can be rewritten as:

$$v = k \frac{(h+H)}{H} \qquad \text{(Equation 3-5)}$$

where h = hydraulic head acting on the bottom liner, and H = thickness of the compacted soil liner. For a given cross-sectional area, A, the volume of flow per unit time, Q (m^3/s), is:

$$Q = k \frac{(h+H)}{H} A \qquad \text{(Equation 3-6)}$$

where all of the units have been defined above.

From Equations 3-4 and 3-5 it can be observed that for a given area, A, the performance of the compacted soil liner will be dependent upon three variables:

- h - hydraulic head;
- H - compacted soil liner thickness;
- k_c - hydraulic conductivity of the compacted soil liner;

The remainder of Section 3.4 investigates the effect of hydraulic head, compacted soil liner thickness, and compacted soil hydraulic conductivity on leak detection system sensitivity, leachate collection efficiency, leakage out of the unit, and breakthrough time.

3.4.3 Leak Detection Systems Sensitivity

In general, the leak detection system sensitivity is dependent upon the properties of both the LDCRS and the bottom liner. In the event of a concentrated leak through the top liner, a two-dimensional analysis (and ideally, a three-dimensional analysis) is required to evaluate detection sensitivity. However, if uniform leakage through the top liner is considered, it is possible to establish a lower bound for detection sensitivity using a one-dimensional analysis.

The minimum top liner leakage rate that can be detected must be greater than the rate at which liquid will flow, due to gravity, into the bottom liner, with the hydraulic head, h, just equal to zero. Under this condition, the minimum leakage rate will be independent of the hydraulic head on the liner (it is zero) or the thickness of the liner (the hydraulic gradient is one). Therefore, the minimum detectable leakage rates for hydraulic conductivities of 10^{-8} and 10^{-9} m/s (10^{-6} and 10^{-7} cm/s) are:

Hydraulic Conductivity m/s	Hydraulic Conductivity (cm/s)	Leakage Rate liters/1000m^2/day or (gpad)
10^{-8}	(10^{-6})	860
10^{-9}	(10^{-7})	86

It should be noted that these rates are the theoretical minimum detectable leakage rates for uniform top liner leakage throughout the waste management unit. The actual minimum detectable leakage rate is site-specific and will depend on many factors (e.g., type of leak, location of leak, effective hydraulic conductivity of bottom liner, and design of the LDCRS).

3.4.4 Leachate Collection Efficiency

In general, the steady-state leachate collection efficiency is dependent upon the properties of both the LDCRS and the bottom liner. However, it is possible to evaluate the collection efficiency using one-dimensional saturated flow by making two simplifying assumptions. The first assumption is that leakage through the top liner is uniform. The second assumption is that a head of 0.03 m (0.1 ft) acts on the bottom liner, irrespective of the rate of leakage through the top liner. This is believed to be a conservative assumption because the hydraulic head on the bottom liner should normally be small.

The calculated steady-state collection efficiencies (%) for a range of top liner leakage rates and bottom liner hydraulic conductivities of 10^{-9} m/s (10^{-7} cm/s) and 10^{-8} m/s (10^{-6} cm/s) are:

Leakage Rate Through Top FML liters/1000m^2/day or gpad	Collection Efficiency %	
	$k_c=10^{-9}$ m/s (10^{-7} cm/s)	10^{-8} m/s (10^{-6} cm/s)
10	0	0
100	11%	0
1000	91%	11%

The above results indicate that the leakage rate through the top liner must be approximately 1000 Ltd (gpad) for a collection efficiency greater than 90%, if the bottom liner hydraulic conductivity is 10^{-9} m/s (10^{-7} cm/s). The leakage rate must be even larger to get a comparable efficiency when the hydraulic conductivity is 10^{-8} m/s (10^{-6} cm/s).

3.4.5 Leakage Out of the Unit

3.4.5.1 Hydraulic Head on Bottom Liner

The variation of leakage out of the unit as a function of the hydraulic head acting on the liner is studied for the case of a 1 m (3 ft) thick compacted soil liner with a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s). For these calculations, a range of hydraulic heads from 0.03 to 3.0 m (0.1 to 10 ft) was conservatively assumed. For this range of hydraulic heads the calculated leakage out of the unit is:

Hydraulic Head m	(ft)	Leakage Out of Unit liters/1000m²/day or (gpad)
0.03	(0.1)	89
0.06	(0.2)	92
0.3	(1.0)	112
3.0	(10)	344

From these results it can be seen that the steady-state leakage out of the unit is not greatly influenced by the hydraulic heads acting on the bottom liner as long as the hydraulic head is about 0.3 m (1 ft) or less. Further for these hydraulic heads, it is observed that in terms of orders of magnitude, the steady-state seepage through a bottom liner is approximately equal to the detection sensitivity associated with the bottom liner. The result for a hydraulic head of 3.0 m (10 ft) shows about 3 times more steady-state leakage out of the unit than for the smaller hydraulic heads. This case represents the "upper bound" of hydraulic head on a bottom liner for a surface impoundment that has undergone catastrophic failure of the top liner and LDCRS.

3.4.5.2 Liner Thickness

The effect of liner thickness on leakage out of the unit was investigated for a compacted soil bottom liner with a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) subjected to 0.03 m (0.1 ft) of head. The leakage out of the unit was calculated for liner thicknesses varying from 1 to 3 m (3 to 10 ft). The leakages out of the unit for this range of thicknesses are:

Liner Thickness m (ft)	Leakage Out of the Unit liters/1000m^2/day or (gpad)
1 (3)	89
2 (6)	87
3 (10)	87

It can be seen that increasing the bottom liner thickness will not significantly reduce the leakage out of the unit.

3.4.5.3 Liner Hydraulic Conductivity

The influence of compacted soil liner hydraulic conductivity on steady-state leakage out of the unit was investigated for the case of a 1 m (3 ft) thick soil liner subjected to a 0.03 m (0.1 ft) hydraulic head, and hydraulic conductivities of 10^{-9} and 10^{-8} m/s (10^{-7} and 10^{-6} cm/s). The calculated leakages for these hydraulic conductivities are 89 Ltd (gpad) and 890 Ltd (gpad), respectively. It can be observed (as expected) that the leakage out of the unit is directly proportional to the hydraulic conductivity.

3.4.6 Breakthrough Time

3.4.6.1 Hydraulic Head on Bottom Liner

The effect of hydraulic head on breakthrough time for a 1 m (3 ft.) thick compacted soil liner with a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) is analyzed. Since breakthrough time is a transient phenomenon, it will be interesting to compare the results of this calculation with subsequent calculations which assume partially saturated flow. For these calculations, the compacted soil bottom liner is assumed to have a porosity of 0.5. Hydraulic heads ranging from 0.01 m (0.03 ft) to 0.3 m (1.0 ft) are considered. The breakthrough times for the assumed range of hydraulic heads are:

Hydraulic Head m	(ft)	Breakthrough Time (years)
0.01	(0.03)	16
0.06	(0.2)	15
0.3	(1)	12

The breakthrough time is not greatly influenced by the hydraulic head acting on the bottom lining system, as long as the head remains within the assumed range.

A hydraulic head of 0.3 m (1 ft.) is conservatively used in the subsequent discussions on the effect of liner thickness and liner hydraulic conductivity.

3.4.6.2 Liner Thickness

The influence of compacted soil liner thickness on the theoretical breakthrough time is illustrated in Figure 3-5, which shows the variation of breakthrough time as a function of thickness, for three different soil hydraulic conductivities. These breakthrough times were calculated considering a soil porosity, n, equal to 0.5. The discussion here will be limited to only one hydraulic conductivity, k= 10^{-9} m/s (10^{-7} cm/s). For the curve indicated in Figure 3-5, it can be observed that, for a compacted soil liner less than 1 m (3 ft.) thick, the breakthrough time is very sensitive to liner thickness. The calculated breakthrough time for a range of thicknesses (and k = 10^{-9} m/s (10^{-7} cm/s)) are summarized as follows:

Liner Thickness m	(ft)	Breakthrough Time (years)
0.5	(1.5)	5
1	(3)	13
2	(6)	28

If the desired design goal is considered to be no breakthrough during at least the active life and post-closure care period (about 30 years) of the unit, then, from the above results (based on one-dimensional steady state saturated flow) it is likely that a 1 m (3 ft.) compacted soil liner with an average hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) will not meet the design goal based on saturated flow. For such a design goal, a compacted soil liner will be required with a thickness greater than 2 m (6 ft.), and with $k_c = 1 \times 10^{-9}$ m/s (1×10^{-7} cm/s) or better in all areas to be lined (i.e., minimal secondary structures).

3.4.6.3 Liner Hydraulic Conductivity

The influence of compacted soil liner hydraulic conductivity on breakthrough time is illustrated in Figure 3-5, which shows the variation of breakthrough time as a function of thickness, for three different soil hydraulic conductivities. It can be observed that the three curves have the same shape and that, for a given liner thickness, changing the hydraulic conductivity by an order of magnitude will change the breakthrough time by about an order of magnitude.

It was shown in Section 3.3 that the hydraulic conductivity of a compacted soil liner can vary by up to several orders of magnitude and that the field value depends on many factors. Thus, the expected value of hydraulic conductivity must be carefully evaluated if a reasonable evaluation of breakthrough time (as well as other performance criteria) is to be made.

3.4.7 Summary

The effect of hydraulic head, liner thickness, and hydraulic conductivity on compacted soil bottom liner performance was evaluated using a model based on one-dimensional steady-state saturated flow. The results presented in this section, along with additional results, are summarized in Table 3-3. It can be observed from the results that the hydraulic head does not significantly affect detection sensitivity, leakage out of the unit, or breakthrough time.

Increasing the liner thickness will increase the breakthrough time, but will not influence the detection sensitivity or leakage out of the unit. The hydraulic conductivity has the most effect on bottom liner performance. An order of magnitude decrease in the hydraulic conductivity will decrease the breakthrough time and increase the leakage out of the unit proportionally. Possibly the most significant observation is that with compacted soil bottom liners leakage out of the unit will be large (if there is leakage through the top liner), and collection efficiencies will be low, even in units meeting current EPA design requirements ($k_c = 1 \times 10^{-9}$ m/s (1×10^{-7} cm/s) and H = 1 m (3 ft)).

3.5 ANALYSIS OF PERFORMANCE - PARTIALLY SATURATED FLOW (1D)

3.5.1 Introduction

In Section 3.4 the performance of a saturated compacted soil liner was analyzed. However, under most field conditions, compacted soil liners will be in a partially saturated state. As was discussed in Section 3.2.3, capillary stresses exist in a partially saturated soil which will influence the liner performance. In Section 3.5 the effect of partial saturation on one-dimensional flow through a compacted soil liner will be investigated.

3.5.2 Overview of Analysis

3.5.2.1 Description of Model

The analysis of one-dimensional flow through a partially saturated soil mass is performed using the SOILINER computer model [GCA, 1986]. The program uses the finite difference technique to solve nonlinear equations describing unsaturated one-dimensional flow. The SOILINER program is capable of simulating multilayered systems, variable initial moisture content, and changing boundary conditions. The program user can specify an initial suction stress distribution in the compacted soil liner and natural soil, corresponding to the desired partially saturated state. The computer program will then incrementally alter the suction stress distribution to correspond to the change in soil moisture content that will occur as fluid flows through the soil liner. The relationship between moisture content and soil suction stress is based on characteristic moisture curves, included in the computer program. Curves for 12 different soil types are available. The computer program also incrementally changes the hydraulic conductivity to correspond to the moisture content distribution which exists at a given point in time. A complete description of the mathematical model and soil characteristic curves can be found in the user's manual [GCA, 1986] and will not be repeated here.

3.5.2.2 Summary of Analysis Performed

The primary purpose of the analyses performed was to study the effect of soil suction in conjunction with the three parameters studied in Section 3.4 (hydraulic head, hydraulic conductivity, and compacted soil liner thickness) on compacted soil bottom liner performance (FMLs cannot be adequately modeled using SOILINER). The simple lining system shown in Figure 3-6 was analyzed, in order to simplify interpretation of the results, and to allow a comparison with the data presented in Section 3.4. The comparison of the results are presented in Section 3.7. The parameters, which were varied, included initial soil suction stress, ψ; hydraulic head acting on the bottom liner, h; soil liner thickness, H; and hydraulic conductivity of the compacted soil liner, k_c. The effects of varying the above parameters on detection sensitivity, leakage out of the unit, and breakthrough time are presented below. It is noted that the effect of the natural soil hydraulic conductivity, k_n, and depth of the water table, h_1, were also investigated. It was found that variations in these parameters had only a minor effect on leakage out of the unit and breakthrough time.

3.5.3 Leak Detection Sensitivity

In general, leak detection sensitivity is dependent upon the properties of both the LDCRS and the bottom liner. For concentrated leakage, a two-dimensional analysis is required to evaluate detection sensitivity. However, if uniform leakage through the top liner is considered, it is possible to use a one-dimensional analysis to establish a lower bound for the detection sensitivity.

The minimum leakage rate which can be detected must be greater than the rate at which liquid can flow, due to gravity, into the bottom liner. In the case of partially saturated flow, leakage into the bottom liner will occur due to capillary suction which acts in addition to gravity. The capillary stresses will be in effect until saturated conditions are reached, after which point only gravity forces will drive the flow. As flow occurs through the bottom liner, the degree of saturation of the bottom liner will increase with time and, in turn, the magnitude of the capillary stresses will decrease. Therefore, the influence of the capillary stresses will decrease with time. This effect can be observed in the following results, which show the variation of leakage into the bottom liner as a function of time until steady-state conditions are reached (initial suction stress ψ = -274 kN/m² (-40 psi)):

Time (years)	Leakage into Bottom Liner (liters/1000m²/day or gpad)
0.5	200
1.0	156
2.5	120
4.5	105
5.9 (steady state)	97

It should be noted that the above numbers are for a 0.08 m (0.25 ft) head acting on the bottom liner and are considered to overestimate the minimum detectable uniform leak by approximately 10%. From the above, it can be observed that the detection sensitivity will change with time until steady-state conditions are achieved within the bottom liner.

3.5.4 Leakage Out of Unit

3.5.4.1 Effect of Soil Suction Stress

The effect of soil suction stress, ψ, on leakage out of the unit was analyzed by varying the initial suction stress in the soil and holding other variables constant, for the soil liner shown in Figure 3-6. The variables held constant and their respective values are:

hydraulic head on liner, h = 0.08 m (0.25 ft)
soil liner thickness, H = 1 m (3 ft)
soil liner hydraulic conductivity, k_C = $1x10^{-9}$ m/s ($1x10^{-7}$ cm/s)
natural soil hydraulic conductivity, k_n = $1x10^{-4}$ m/s ($1x10^{-2}$ cm/s)
depth to water table, h_1 = 1 m (3 ft)

The soil suction stresses ranged from -1 kN/m² (-0.14 psi) to -550 kN/m² (80 psi). A value of -1 kN/m² (-0.14 psi) is representative of an almost completely saturated soil liner, while a value of -549 kN/m² (-80 psi) is representative of the suction stresses in a soil liner constructed with a plastic clay with a water content close to the plastic limit. Obviously, this later value represents an extreme condition. In all cases, the steady-state leakage out of the unit was 97 Ltd (gpad). The only role of the soil suction stresses are to change the rate at which this steady-state condition is achieved. It is useful to note that the calculated values for steady-state leakage out of the unit are very consistent with those calculated using Darcy's law in Section 3.4.5.2.

3.5.4.2 Effect of Hydraulic Head

The effect of hydraulic head, h, on the steady-state rate of leakage out of the unit was analyzed by varying the hydraulic head acting on the bottom liner over a range from 0.03 m (0.1 ft) to 0.3 m (1.0 ft). Other variables were held constant as follows:

initial suction stress = -274 kN/m^2 (-40 psi)
soil liner thickness, H = 1 m (3 ft)
soil liner hydraulic conductivity, k_c = 1x10^{-9} m/s (1x10^{-7} cm/s)
natural soil hydraulic conductivity, k_n = 1x10^{-4} m/s (1x10^{-2} cm/s)
depth to water table, h_1 = 1 m (3 ft)

The calculated steady-state rate of leakage out of unit for the following hydraulic heads are:

Hydraulic Head m	(ft)	Steady-State Rate of Leakage Out of Unit liters/1000m^2/day or gpad
0.03	(0.1)	91
0.08	(0.3)	97
0.15	(0.5)	105
0.30	(1.0)	118

It can be observed that for the considered range of hydraulic heads, the head acting on the bottom liner has little effect on the steady-state rate of leakage out of the bottom liner.

3.5.4.3 Effect of Liner Thickness

The effect of compacted soil liner thickness on the steady-state rate of leakage out of the unit was analyzed by varying the liner thickness and holding other variables constant for the soil liner shown in Figure 3-6. Other variables were held constant as follows:

initial suction stress, ψ = -274 kN/m^2 (-40 psi)
hydraulic head, h = 0.08 m (0.25 ft)
soil liner hydraulic conductivity, k_c = 1x10^{-9} m/s (1x10^{-7} cm/s)
natural soil hydraulic conductivity, k_n = 1x10^{-4} m/s (1x10^{-2} cm/s)
depth to water table, h_1 = 1 m (3 ft)

The calculated steady-state rate of leakage out of the unit for the following liner thicknesses are:

Soil Liner Thickness m	(ft)	Steady-State Rate of Leakage Out of Unit liters/1000m²/day or gpad
0.3	(1)	147
1.0	(3)	97
2.0	(6)	90
3.0	(10)	87

It can be observed that the steady-state rate of leakage out of the unit is not greatly influenced by the compacted soil liner thickness as long as the liner is at least 1.0 m (3 ft) thick.

3.5.4.4 Effect of Liner Hydraulic Conductivity

The effect of compacted soil liner hydraulic conductivity on the steady-state rate of leakage out of the unit was analyzed by varying the liner hydraulic conductivity and holding other variables constant for the soil liner shown in Figure 3-6. The variables held constant and their respective values are:

initial suction stress, $\psi = -274$ kN/m² (-40 psi)
hydraulic head, h = 0.08 m (0.25 ft)
soil liner thickness, H = 1 m (3 ft)
natural soil hydraulic conductivity, $k_n = 1x10^{-4}$ m/s ($1x10^{-2}$ cm/s)
depth to water table, $h_1 = 1$ m (3 ft)

Liner hydraulic conductivities of 10^{-10}, 10^{-9}, and 10^{-8} m/s (10^{-8}, 10^{-7}, and 10^{-6} cm/s) were investigated. The calculated steady-state rates of leakage out of the unit are:

Liner Hydraulic Conductivity m/s	(cm/s)	Steady-State Rate of Leakage Out of Unit liters/1000m²/day or gpad
10^{-10}	10^{-8}	10
10^{-9}	10^{-7}	97
10^{-8}	10^{-6}	970

It can be observed that the steady-state rate of leakage out of the unit is highly dependent upon the liner hydraulic conductivity. The calculated leakage rates are very consistent with those obtained in Section 3.4.5.3 using Darcy's law.

3.5.5 Breakthrough Time

3.5.5.1 Effect of Soil Suction Stress

The effect of the initial soil suction stress, ψ, on breakthrough time was analyzed by varying the initial suction stress in the soil and holding other variables constant, for the soil liner shown in Figure 3-6. The variables held constant and their respective values are:

hydraulic head on liner, $h = 0.08$ m (0.25 ft)
soil liner thickness, $H = 1$ m (3 ft)
soil liner hydraulic conductivity, $k_c = 1 \times 10^{-9}$ m/s (1×10^{-7} cm/s)
natural soil hydraulic conductivity, $k_n = 1 \times 10^{-4}$ m/s (1×10^{-2} cm/s)
depth to water table, $h_1 = 1$ m (3 ft)

Soil suction stresses ranging from -1 kN/m² (-0.14 psi) to -550 kN/m² (-80 psi) were investigated. The soil suction stress in the compacted soil liner is taken to be constant with depth, and in the natural soil it is assumed to have a minimum (maximum suction) at the liner interface and vary linearly with depth to zero at the ground water table, as shown in Figure 3-6.

The calculated breakthrough time for the stated range of soil suction stresses are:

Initial Suction Stress kN/m²	(psi)	Breakthrough Time (years)
- 1	(- 0.1)	13.2
- 10	(- 1.4)	12.2
- 69	(-10.0)	11.3
-137	(-20.0)	11.1
-274	(-40.0)	10.9
-549	(-80.0)	10.8

It can be observed from the above results that breakthrough time decreases with increasing suction stress. However, the reduction is not large and the breakthrough time is almost constant for suction stresses less than approximately -100 kN/m² (-14 psi).

3.5.5.2 Effect of Hydraulic Head

The effect of hydraulic head, h, on breakthrough time was analyzed by varying the hydraulic head on the bottom liner from 0.03 m (0.1 ft) to 0.3 m (1 ft). Other variables were held constant as follows:

initial suction stress = -274 kN/m² (-40 psi)
soil liner thickness, H = 1 m (3 ft)
soil liner hydraulic conductivity, k_c = $1x10^{-9}$ m/s ($1x10^{-7}$ cm/s)
natural soil hydraulic conductivity, k_n = $1x10^{-4}$ m/s ($1x10^{-2}$ cm/s)
depth to water table, h_1 = 1 m (3 ft)

The calculated breakthrough times for the following hydraulic heads are:

Hydraulic Head m	(ft)	Breakthrough Time (years)
0.03	(0.1)	12.0
0.08	(0.3)	10.9
0.15	(0.5)	9.9
0.30	(1.0)	8.5

It can be observed that if the hydraulic head acting on the bottom liner is decreased from 0.3 m (1 ft) to 0.03 m (0.1 ft), then the breakthrough time is decreased by approximately 30 percent.

3.5.5.3 Effect of Liner Thickness

The effect of liner thickness on breakthrough time was analyzed by varying the liner thickness and holding other variables constant, for the soil liner shown in Figure 3-6. The variables held constant and their respective values are:

initial suction stress, ψ = -274 kN/m^2 (-40 psi)
hydraulic head, h = 0.08 m (0.25 ft)
soil liner hydraulic conductivity, k_c = 1x10^{-9} m/s (1x10^{-7} cm/s)
natural soil hydraulic conductivity, k_n = 1x10^{-4} m/s (1x10^{-2} cm/s)
depth to water table, h_1 = 1 m (3 ft)

The calculated breakthrough times for the following liner thicknesses are:

Soil Liner Thickness m	(ft)	Breakthrough Time (years)
0.3	(1)	2
1.0	(3)	11
2.0	(6)	25
3.0	(10)	42

It can be observed that breakthrough time is greatly influenced by the liner thickness.

3.5.5.4 Effect of Liner Hydraulic Conductivity

The effect of liner hydraulic conductivity on breakthrough time was analyzed by varying the liner hydraulic conductivity and holding other variables constant, for the soil liner shown in Figure 3-6. The variables held constant and their respective values are:

initial suction stress, $\psi = -274$ kN/m^2 (-40 psi)
hydraulic head, $h = 0.08$ m (0.25 ft)
soil liner thickness, $H = 1$ m (3 ft)
natural soil hydraulic conductivity, $k_n = 1 \times 10^{-4}$ m/s (1×10^{-2} cm/s)
depth to water table, $h_1 = 1$ m (3 ft)

Liner hydraulic conductivities of 10^{-10}, 10^{-9}, and 10^{-8} m/s (10^{-8}, 10^{-7}, and 10^{-6} cm/s) were studied and the calculated breakthrough times are shown below:

Liner Hydraulic Conductivity m/s	(cm/s)	Breakthrough Time (years)
10^{-10}	10^{-8}	109
10^{-9}	10^{-7}	11
10^{-8}	10^{-6}	1

It can be observed that the breakthrough time is highly dependent upon the liner hydraulic conductivity.

3.5.6 Summary

The effect of hydraulic head, liner thickness, and hydraulic conductivity on compacted soil bottom liner performance was evaluated using a one-dimensional partially saturated flow model. The study showed that partial saturation had only a small effect on the performance of compacted soil liners. This effect is largest when the degree of saturation is smallest and reduces as conditions approach steady state. The results presented in this section are summarized in Table 3-4. It can be observed from the results that the hydraulic head does not greatly affect leak detection sensitivity, leakage out of the unit, or breakthrough time. Increasing the liner thickness will increase the breakthrough time; liner thickness has little influence, however, on detection sensitivity and leakage out of the unit. Hydraulic conductivity is the variable that most influences bottom liner performance. An order of magnitude decrease in the hydraulic conductivity will decrease the detection sensitivity and breakthrough time proportionally and will increase leakage out of the unit by an order of magnitude. In summary, the results obtained using SOILINER and $k_c = 1 \times 10^{-7}$ cm/s indicate detection sensitivities in the range of 100 Ltd (gpad), collection efficiencies that are zero below the detection sensitivity and remain low until very large leakage rates are encountered, and the potential for large amounts of leakage out of the unit (approximately 100 Ltd (gpad)) prior to leak detection and any possibility of response actions.

3.6 ANALYSIS OF PERFORMANCE - PARTIALLY SATURATED-2D

3.6.1 Introduction

The UNSAT2D computer program [Radian, 1987] was used to implement a two-dimensional study of compacted soil bottom liner performance. This program employs a numerical methodology founded in the finite element method and is described in Section 3.6.2. Also presented in Section 3.6.2 is an overview of the results obtained. In Section 3.6.3, the performance of LDCRS with compacted soil bottom liners are evaluated in terms of leak detection sensitivity. In Section 3.6.4 the performance of LDCRS with compacted soil bottom liners are evaluated in terms of leachate collection efficiency. In Section 3.6.5, leakage out of units with compacted soil bottom liners is investigated. In Section 3.6.6, the breakthrough times which can be expected with compacted soil bottom liners are presented.

3.6.2 Overview of Analysis

3.6.2.1 Description of UNSAT2D Program

UNSAT2D is a two-dimensional finite element computer program prepared by S.S. Papadopulos & Associates, Inc. to simulate soil moisture movement within waste disposal units including landfills, surface impoundments, and waste piles. Input parameters to the program include water movement across model boundaries and/or hydraulic head on model boundaries, unit geometry and materials, material properties and initial moisture conditions in the unit and surrounding soils. The program simulates the transient-state distribution of hydraulic head and soil moisture within the unit for each defined time step.

The program simulates a two-dimensional section through a waste management unit. In formulation of the program it has been assumed that adjacent parallel sections are identical in their physical and hydrological characteristics. As a result, the program can only model linear tears in the FML (holes cannot be modeled).

The program models FMLs and geotextiles as one-dimensional (linear) elements which have zero moisture storage. Leakage across the element is proportional to the head difference across the element. Soil and waste are modeled by two-dimensional, triangular elements which have moisture storage capacity.

3.6.2.2 Summary of Study

The UNSAT2D program is capable of modeling a complete waste management unit including lining system, waste, and cover systems. In this investigation only the performance of the LDCRS and compacted soil bottom liner are analyzed because the intent of this study is the influence of the bottom liner on lining system performance. The lining system modeled in UNSAT2D is shown in Figure 3-7.

In contrast to the analyses in Section 3.4 and 3.5 where hydraulic head on the bottom liner was a constant, UNSAT2D holds the leakage rate through the top liner constant and the hydraulic head on the bottom liner is allowed to vary. The leakage rate through the top liner was controlled by varying the hydraulic head on the top liner and the properties of the top liner material. Three types of top liner leaks were considered in the UNSAT2D numerical simulations (Figure 3-7):

- uniform leakage through the entire top liner (uniform leak);
- leakage through a portion of the top liner on facility side slope (sidewall leak); and
- leakage through a portion of the top liner on the bottom of the unit (bottom leak).

A limitation of the program is that the smallest top liner sidewall and bottom leak which could be analyzed is 3 m (10 ft) wide. In reality, FML top liner field defects are more likely to be small tears or punctures, typically only a few millimeters (fraction of an inch) in diameter. Thus, the UNSAT2D top liner leak probably better represents leakage through a composite top liner than through a top liner consisting of an FML alone.

In addition to varying top liner leakage rate and type of leak, the bottom liner hydraulic conductivity and thickness were also varied in the UNSAT2D simulations. The above four parameters were varied and seven different combinations were analyzed. The seven combinations are summarized in Table 3-5.

For the seven cases presented in Table 3-5 the following evaluations are presented in subsequent sections:

- initial leak detection time;
- leachate collection efficiency;
- leakage out of the unit; and
- breakthrough time.

Additional information on each of the UNSAT2D numerical simulations can be found in Appendix C.

3.6.3 Initial Leak Detection Time

Leak detection sensitivity was previously defined as the minimum rate of top liner leakage that can be detected in the LDCRS sump. Detection sensitivity is calculated based on saturated, steady-state conditions. Associated with detection sensitivity is "leak detection time", which is the time between when leakage enters the LDCRS (when it has just passed through the top liner) to the time it appears in the LDCRS sump. Leak detection time can also be calculated assuming saturated steady-state conditions. When calculated on this basis, it is referred to as the steady-state leak detection time. Another parameter related to LDCRS performance is the initial leak detection time. This parameter corresponds to the time required to detect leakage after a leak first occurs. It is different than steady-state leak detection time because it accounts for the delay in leak detection due to the requirement to "wet up" the LDCRS drainage media prior to the initiation of drain flow (this is due to capillary suction in the LDCRS) and because it accounts for the loss of liquid into the bottom liner due to bottom liner permeability. Both of these factors are ignored in steady-state leak detection time calculations. The initial leak detection time represents the behavior of a relatively dry LDCRS during the early active life of a waste management unit.

For a given top liner leakage rate and unit geometry, the factors that most influence the initial leak detection time are the capillary suction in the LDCRS and the hydraulic conductivity of the bottom liner. In this section, the effect of bottom liner hydraulic conductivity on the initial leak detection time is investigated using the UNSAT2D computer model.

The variation in initial leak detection time with leakage rate is summarized in Table 3-6 for different lining systems. Three different leakage rates are presented for the case of a 1 m (3 ft) thick compacted soil liner with a hydraulic conductivity of 10^{-9} m/s (10^{-7}

cm/s). It can be observed that at a leakage rate of approximately 1000 Ltd (gpad) the initial leak detection time is a few months. However, if the rate of leakage is an order of magnitude less, 100 Ltd (gpad), the leak is not detected within a 10-year period. The long time required to initiate drain flow for these cases are due to two causes: (i) the $k_C = 1 \times 10^{-7}$ cm/s compacted soil liner permits leakage out of the unit at a rate in the range of 100 Ltd (gpad); and (ii) the numerical simulations with UNSAT2D used an LDCRS drainage media with $k = 1 \times 10^{-3}$ cm/s, which corresponds to a fine sand with capillary suction of about 1.0 m (3 ft). Therefore, a large volume of leakage through the top liner will be held by capillary suction in the LDCRS which will significantly delay the initiation of drain flow.

The results presented in Table 3-6 show leakage rates of approximately 1000 Ltd (gpad) will go undetected for longer than 10 years if the hydraulic conductivity of a 1 m (3 ft) thick compacted soil liner is only 10^{-8} m/s (10^{-6} cm/s). This indicates that the initial leak detection time is very dependent upon the hydraulic conductivity of the compacted soil bottom liner.

One procedure for improving the overall performance of a compacted soil liner is to increase its thickness. The leakage rate for a 2 m (6 ft) thick compacted soil bottom liner ($k = 10^{-7}$ cm/s) is also summarized in Table 3-6. It can be observed that at a leakage rate of approximately 1000 Ltd (gpad) increasing the thickness has little effect on the initial leak detection time.

3.6.4 Leachate Collection Efficiency

Leachate collection efficiency was defined in Section 2.5.3.2 as the ratio of the liquid collected in the LDCRS sump divided by the leakage through the top liner.

This section reviews the effect of compacted soil bottom liner hydraulic conductivity and thickness on the collection efficiency of the LDCRS assuming uniform leakage through the top liner. Figure 3-8 shows collection efficiencies as a function of time for three scenarios with roughly equivalent top liner leakage rates (Q):

- 1 m (3 ft) thick compacted soil liner, $k_c = 10^{-9}$ m/s (10^{-7} cm/s), Q = 801 Ltd (gpad);

- 1 m (3 ft) thick compacted soil liner, $k = 10^{-8}$ m/s (10^{-6} cm/s), Q = 928 Ltd (gpad); and

- 2 m (6 ft) thick compacted soil liner, $k = 10^{-9}$ m/s (10^{-7} cm/s), Q = 800 Ltd (gpad).

It can be observed that increasing the thickness of the compacted soil bottom liner results in only a small improvement in the collection efficiency of the system. More important is the effect of hydraulic conductivity of the compacted soil liner on leachate collection efficiency. It can be observed that an order of magnitude increase in hydraulic conductivity results in zero leakage being collected from the LDCRS at the end of ten years for a rate of uniform top liner leakage in the range of 1000 Ltd (gpad).

3.6.5 Leakage Out of Unit

Leakage out of the unit is plotted as a function of time in Figure 3-9 for the following three scenarios with roughly equivalent top liner leakage rates (Q):

- 1 m (3 ft) thick compacted soil liner, $k_c = 10^{-9}$ m/s (10^{-7} cm/s), Q = 801 Ltd (gpad);

- 1 m (3 ft) thick compacted soil liner, $k_c = 10^{-8}$ m/s (10^{-6} cm/s), Q = 928 Ltd (gpad); and

- 2 m (6 ft) thick compacted soil liner, $k_c = 10^{-9}$ m/s (10^{-7} cm/s), and Q = 800 Ltd (gpad).

The results plotted in Figure 3-9 are for roughly equivalent top liner leakage rates in the range of approximately 1000 Ltd (gpad). At comparable leakage rates into the LDCRS, a significant increase (approximately 400%) in leakage out of the unit occurs when the hydraulic conductivity is decreased by an order of magnitude. In addition, increasing the thickness of the compacted soil bottom liner from 1 to 2 m (3 to 6 ft) has only minimal effect on the leakage out of the unit.

The plot of leakage from the unit as a function of time are approximately linear and the rate of leakage from the unit is the slope of the line. The rate of leakage from the unit is plotted as a bar chart in Figure 3-10. It can be observed from Figure 3-10 that almost all of the leakage through the top liner (approximately 1000 Ltd (gpad) for the cases considered here) can flow through the liner if the hydraulic conductivity is 10^{-8} m/s (10^{-6} cm/s).

3.6.6 Breakthrough Time

The effect of hydraulic conductivity and thickness on breakthrough time is presented in Table 3-7. For 1 and 2 m (3 and 6 ft) thick compacted soil liners with a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s), breakthrough will occur several years after leakage is detected in the drain. However, if the 1 m (3 ft) thick compacted soil liner has a hydraulic conductivity of only 10^{-8} m/s (10^{-6} cm/s), then breakthrough will occur very early in the life of the facility, without the leak ever being detected. Also, if the leakage rate is less than approximately 100 Ltd (gpad) then breakthrough will occur through a 1 m (3 ft) thick compacted soil liner with a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) before leakage is detected.

3.6.7 Summary

The results of two-dimensional numerical simulations of partially saturated flow in a LDCRS/compacted soil liner system were presented. These simulations were carried out by Radian Corporation using the finite element computer model UNSAT2D. The results presented above and summarized in Table 3-8 centered on the effect of soil liner thickness and hydraulic conductivity on the initial leak detection time, leachate collection efficiency, leakage from unit, and breakthrough time.

3.7 COMPARISON OF RESULTS

In this section, the results presented in sections 3.4, 3.5, and 3.6 are compared. The purpose of the comparison is to draw conclusions regarding both the methods used for analyzing bottom liner performance and on the performance of the bottom liners. The results of the one-dimensional saturated flow analyses are summarized in Table 3-3 and the results of the one-dimensional partially saturated flow analyses are presented in Table 3-4. The results of the two-dimensional partially saturated flow analyses are presented in Table 3-8. Comparison of the results will be made in terms of leak detection sensitivity, steady-state collection efficiency, steady-state leakage out of the unit, and breakthrough time.

Bar charts summarizing leak detection sensitivity are shown in Figures 3-11 and 3-12 for hydraulic conductivities of 10^{-9} m/s (10^{-7} cm/s) and 10^{-8} m/s (10^{-6} cm/s), respectively. The result in Figures 3-11 and 3-12 show good correlation in the prediction of leak detection sensitivity for all three methods of analysis. Therefore, one dimensional saturated flow can be used to evaluate detection sensitivity. The results also show that there is a direct relationship between the detection sensitivity and the hydraulic conductivity of the soil.

A comparison of calculated leachate collection efficiencies using the one-dimensional steady state saturated flow model and the two-dimensional partially saturated transient flow model, are shown in Figures 3-13 and 3-14, for a 1 m (3 ft) thick compacted soil liner with a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s). The results plotted in Figures 3-13 and 3-14 are for leakage rates through the top liner of approximately 100 Ltd (gpad) or 1000 Ltd (gpad). Good correlation between the two methods was obtained for the considered leakage rates.

Steady-state rates of leakage out of the unit are shown in Figures 3-15, 3-16, 3-17, for the following liner conditions:

- 1-m (3-ft) thick compacted soil ($k_c = 10^{-7}$ cm/s);

- 1-m (3-ft) thick compacted soil ($k_c = 10^{-6}$ cm/s); and

- 2-m (6-ft) thick compacted soil ($k_c = 10^{-7}$ cm/s).

It can be observed from these figures that the steady-state rates of leakage out of the unit predicted by all three methods are approximately the same, and therefore the rate of leakage out of the unit can be estimated using one-dimensional saturated flow analyses. The results also show that the hydraulic conductivity of the soil has a direct impact on the rate of leakage from the unit.

Breakthrough times for three different compacted soil bottom liners are compared in Figures 3-18, 3-19, and 3-20:

- 1-m (3-ft) thick compacted soil ($k_c = 10^{-7}$ cm/s);

- 1-m (3-ft) thick compacted soil ($k_c = 10^{-6}$ cm/s); and

- 2-m (6-ft) thick compacted soil ($k_c = 10^{-7}$ cm/s).

Comparison of the results presented in the three figures show that there is fairly good correlation between the breakthrough times predicted by the three methods of analysis. The one-dimensional steady-state saturated analysis appears to provide reasonable, but slightly unconservative, results. The results also show that breakthrough time can be increased by increasing liner thickness. Breakthrough time is inversely proportional to the hydraulic conductivity of the compacted soil used to construct the bottom liner.

3.8 SUMMARY

In this section the performance of compacted soil bottom liners was evaluated. First, review of the factors affecting the performance of compacted soil liner was made. Of all the factors which can affect the performance it was shown that the hydraulic conductivity of the soil is influenced by a wide range of events. Next, a literature review of the performance of compacted soil liners was presented and it was found that although a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) can be achieved, a variety of factors can prevent the desired hydraulic conductivity from being obtained. Therefore, hydraulic conductivities of 10^{-8} m/s (10^{-6} cm/s) and 10^{-7} m/s (10^{-5} cm/s) were subsequently analyzed.

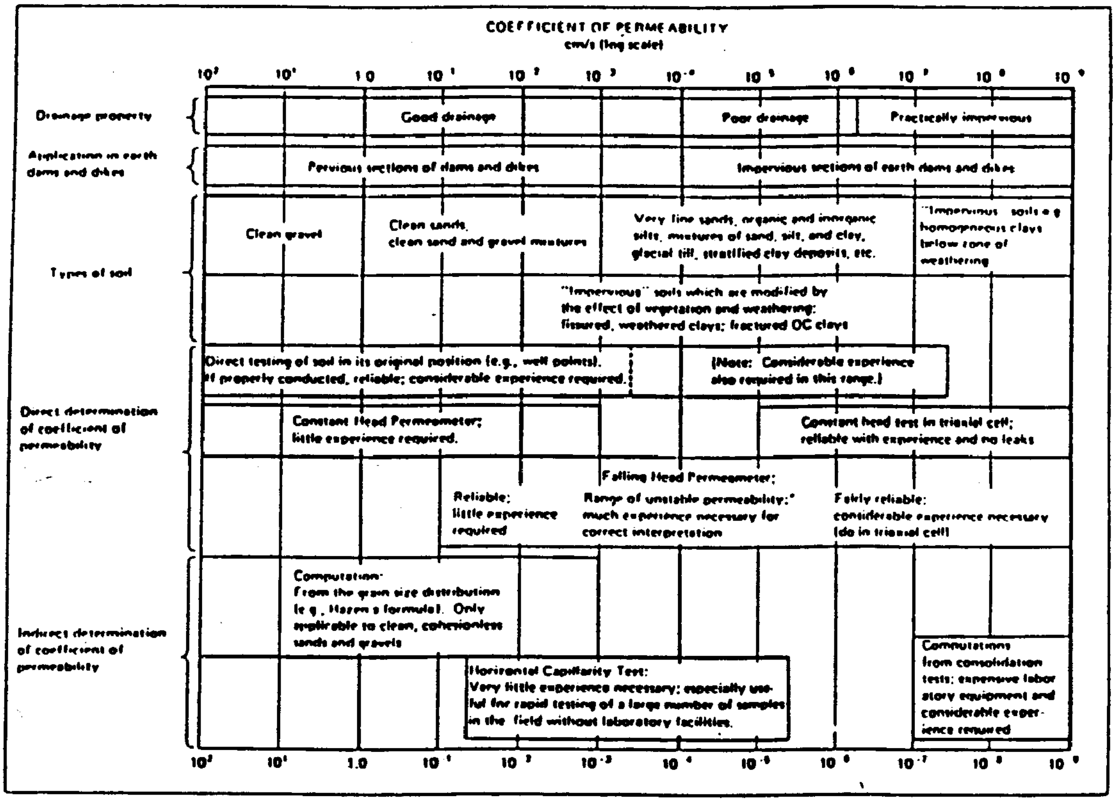
Analysis of compacted soil liner performance was made using three different approaches:

- saturated, steady-state, one-dimensional;
- partially saturated, transient, one-dimensional; and
- partially saturated, transient, two-dimensional.

The analyses revealed that the three methods of analysis give comparable results and that simple one-dimensional, steady-state saturated flow analyses are suitable for evaluating many aspects of bottom liner performance. Compacted soil bottom liner thickness was found to have only a minor effect on all aspects of bottom liner performance except breakthrough time. However, the hydraulic conductivity of a compacted soil liner was found to have a very significant effect on bottom liner performance. This is important because, as shown in Section 3.3, the in situ hydraulic conductivity of compacted soil liners can vary over several orders of magnitude. If the compacted soil hydraulic conductivity is less than the specified value:

- the leak detection sensitivity is diminished;
- the leachate collection efficiency is reduced;
- the rate of leakage from the unit is increased; and
- the breakthrough time is decreased.

Table 3-1. Typical soil hydraulic conductivities. Holtz and Kovacs [1981]



*Due to migration of fines, channels, and air in voids.

Table 3-2. Comparison of field and laboratory hydraulic conductivities.

Field Hydraulic Conductivity (m/s)	Laboratory Hydraulic Conductivity (m/s)	Probable Cause for Difference	Reference
8.4×10^{-10} to 2.5×10^{-8} [a,c]	3.3×10^{-11} to 2.7×10^{-10}	joints and fissures in natural material	Griffin et al. [1985]
3×10^{-6} [b,d]	2×10^{-9} to 2×10^{-7} [b]	cracks caused by drying	Daniel [1984]
1×10^{-7} to 2×10^{-7} [b,d]	1×10^{-9} to 4×10^{-9} [b]	cracking caused by drying	Daniel [1984]
1×10^{-8} m/s	$< 10^{-10}$ m/s	limitations of field placement and compaction procedure (even with construction quality assurance)	Auvinet and Espinosa [1981]
9×10^{-8} m/s 4×10^{-8} m/s	1×10^{-10} m/s 2×10^{-11} m/s	variation in liner due to soil clods, cracks, or variation in compactive effort	Day and Daniel [1985]

[a] - natural soil

[b] - compacted soil liner

[c] - measured in field test

[d] - backcalculated

Table 3-3. Summary of one-dimensional saturated flow analyses.

k_c =	$1x10^{-9}$ m/s ($1x10^{-7}$ cm/s)				$1x10^{-8}$ m/s ($1x10^{-6}$ cm/s)			
h =	25 mm (1 in.)		0.3 m (1 ft)		25 mm (1 in.)		0.3 m (1 ft)	
H =	1 m (3 ft)	2 m (6 ft)	1 m (3 ft)	2 m (6 ft)	1 m (3 ft)	2 m (6 ft)	1 m (3 ft)	2 m (6 ft)
Leak Detection Sensitivity Ltd (gpad)	86	86	86	86	860	860	860	860
Breakthrough Time (years)	15	31	12	28	1.5	3.1	1.2	2.8
Leakage Out of the Unit Ltd (gpad)	89	88	112	99	890	880	1120	990

Table 3-4. Summary of one-dimensional partially saturated flow analyses[a].

	$k_c = 1x10^{-9}$ m/s ($1x10^{-7}$ cm/s)		$k_c = 1x10^{-8}$ m/s ($1x10^{-6}$ cm/s)	
	h = 76 mm (3 in.)		h = 76 mm (3 in.)	
	H = 1 m (3 ft)	2 m (6 ft)	H = 1 m (3 ft)	2 m (6 ft)
Leak Detection Sensitivity Ltd (gpad)	-100	-100	-1000	-1000
Breakthrough Time (years)	11	25	7	2.5
Steady State Rate Leakage out of the Unit Ltd (gpad)	97	90	890	870

[a] $\psi = -274\ kN/m^2$ (-40 psi)

Table 3-5. Compacted soil liner scenarios analyzed by Radian using UNSAT2D.

BOTTOM LINER DESCRIPTION	LEAK TYPE MODELED	TOP LINER LEAKAGE RATE Ltd (gpad)
1 m (3 ft) thick compacted soil liner $k_c = 10^{-9}$ m/s (10^{-7} cm/s)	uniform	101
1 m (3 ft) thick compacted soil liner $k_c = 10^{-9}$ m/s (10^{-7} cm/s)	uniform	801
1 m (3 ft) thick compacted soil liner $k_c = 10^{-9}$ m/s (10^{-7} cm/s)	uniform	1419
1 m (3 ft) thick compacted soil liner $k_c = 10^{-8}$ m/s (10^{-6} cm/s)	uniform	928
1 m (6 ft) thick compacted soil liner $k_c = 10^{-9}$ m/s (10^{-6} cm/s)	uniform	800
1 m (3 ft) thick compacted soil liner $k_c = 10^{-9}$ m/s (10^{-7} cm/s)	sidewall	60
1 m (3 ft) thick compacted soil liner $k_c = 10^{-9}$ m/s (10^{-7} cm/s)	bottom	49

Table 3-6. Effect of compacted soil bottom liner hydraulic conductivity on initial leak detection time for various top liner leakage rates. [Data from Radian, 1987]

Bottom Liner Description	Top Liner Leakage Rate (Ltd or gpad)	Initial Leak Detection Time (Years)
compacted soil	1419	0.14
$k_C = 10^{-9}$ m/s (10^{-7} cm/s)	801	0.26
1 m (3 ft) thick	101	> 10
compacted soil $k_C = 10^{-8}$ m/s (10^{-6} cm/s) 1 m (3 ft) thick	928	> 10
compacted soil $k_C = 10^{-9}$ m/s (10^{-7} cm/s) 2 m (6 ft) thick	800	0.19

Table 3-7. Effect of bottom liner hydraulic conductivity on breakthrough time for top liner leakage rates of about 1000 Ltd (gpad). [Data from Radian, 1987]

Bottom Liner Description	Breakthrough Time (Years)	Initial Leak Detection Time (Years)
compacted soil $k_c = 10^{-9}$ m/s (10^{-7} cm/s) 1 m (3 ft) thick	4.4 4.5 9.6	0.14 0.26 > 10
compacted soil $k_c = 10^{-8}$ m/s (10^{-6} cm/s) 1 m (3 ft) thick	1.0	> 10
compacted soil $k_c = 10^{-9}$ m/s (10^{-7} cm/s) 2 m (6 ft) thick	~ 11	0.19

Table 3-8. Summary of two-dimensional partially saturated flow analyses. [Data from Radian, 1987]

	$k_c = 10^{-9}$ m/s (10^{-7} cm/s)				$k_c = 10^{-8}$ m/s (10^{-6} cm/s)			
	Leakage Rate = 100 Ltd (gpad)		Leakage Rate = 1000 Ltd (gpad)		Leakage Rate = 100 Ltd (gpad)		Leakage Rate = 1000 Ltd (gpad)	
H =	1 m (3 ft)	2 m (6 ft)	1 m (3 ft)	2 m (6 ft)	1 m (3 ft)	2 m (6 ft)	1 m (3 ft)	2 m (6 ft)
Steady State Leakage Out of the Unit Ltd (gpad)	94	-	174	142	100	100	909	-
Steady State Collection Efficiency Ltd (gpad)	- 0	- 0	- 80	- 80	0	0	- 0	- 0
Initial Leak Detection Time (years)	>10	-	0.3	0.2	>10	>10	>10	-
Breakthrough Time (years)	9.6	-	4.5	11	-	-	1.0	-

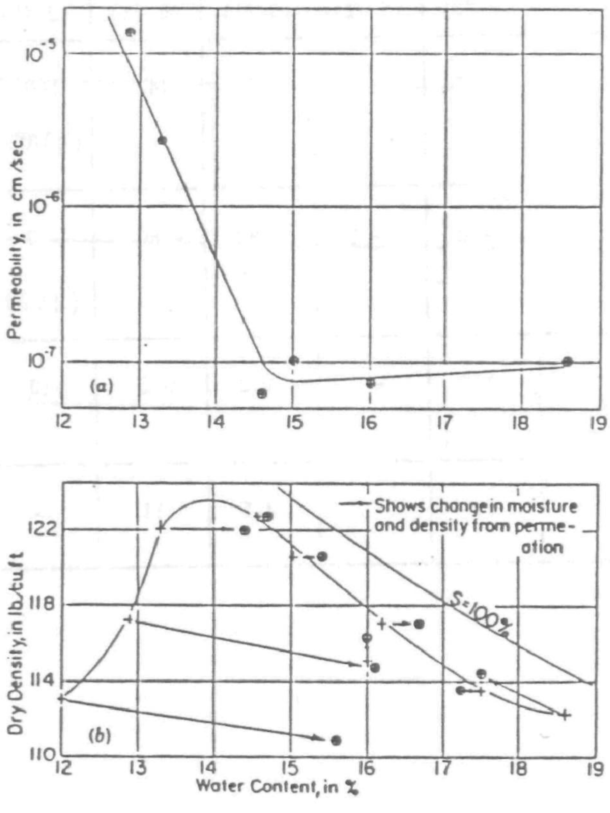


Figure 3-1. Examples of compaction curves and effect of compaction on hydraulic conductivity. [Lambe, 1958]

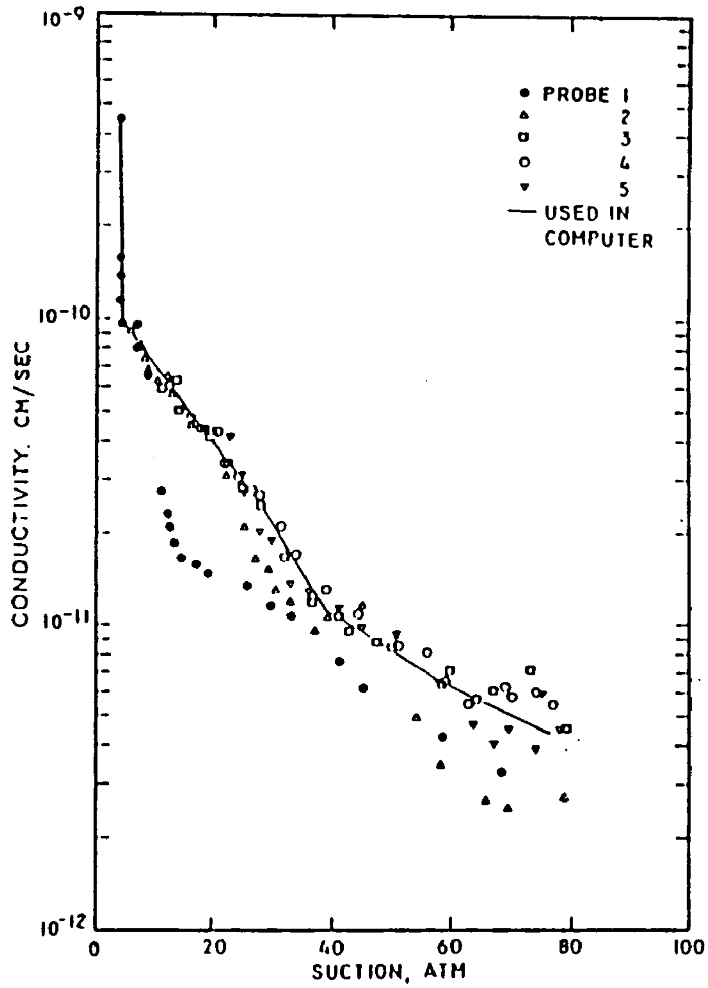


Figure 3-2. Effect of capillary stresses (suction) on hydraulic conductivity. [Hamilton et al., 1981]

Model	Solution Technique	Purpose	Major Assumption or Limitations
saturated flow (1-D)	hand calculations	straightforward analysis of a range of cases	only valid for saturated flow
partially saturated flow (1-D)	finite difference method	account for partial saturation	one-dimensional
partially saturated flow (2-D)	finite element method	account for partial saturation and 2-D	accuracy of analysis is limited by finite element mesh

Figure 3-3. Summary of models used to analyze lining systems.

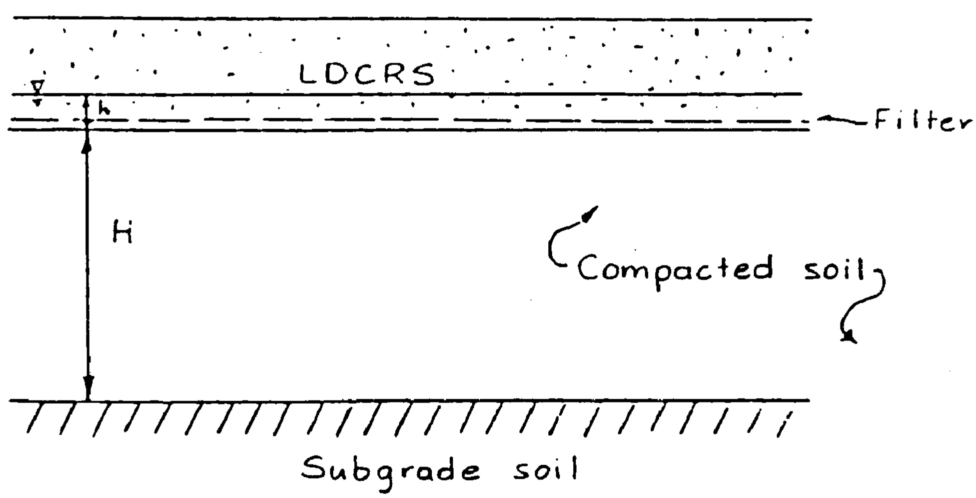


Figure 3-4. Illustration of a LDCRS and compacted soil liner.

RELATIONSHIP BETWEEN BREAKTHROUGH TIME, SATURATED HYDRAULIC CONDUCTIVITY OF BOTTOM LINER, AND THICKNESS OF BOTTOM LINER

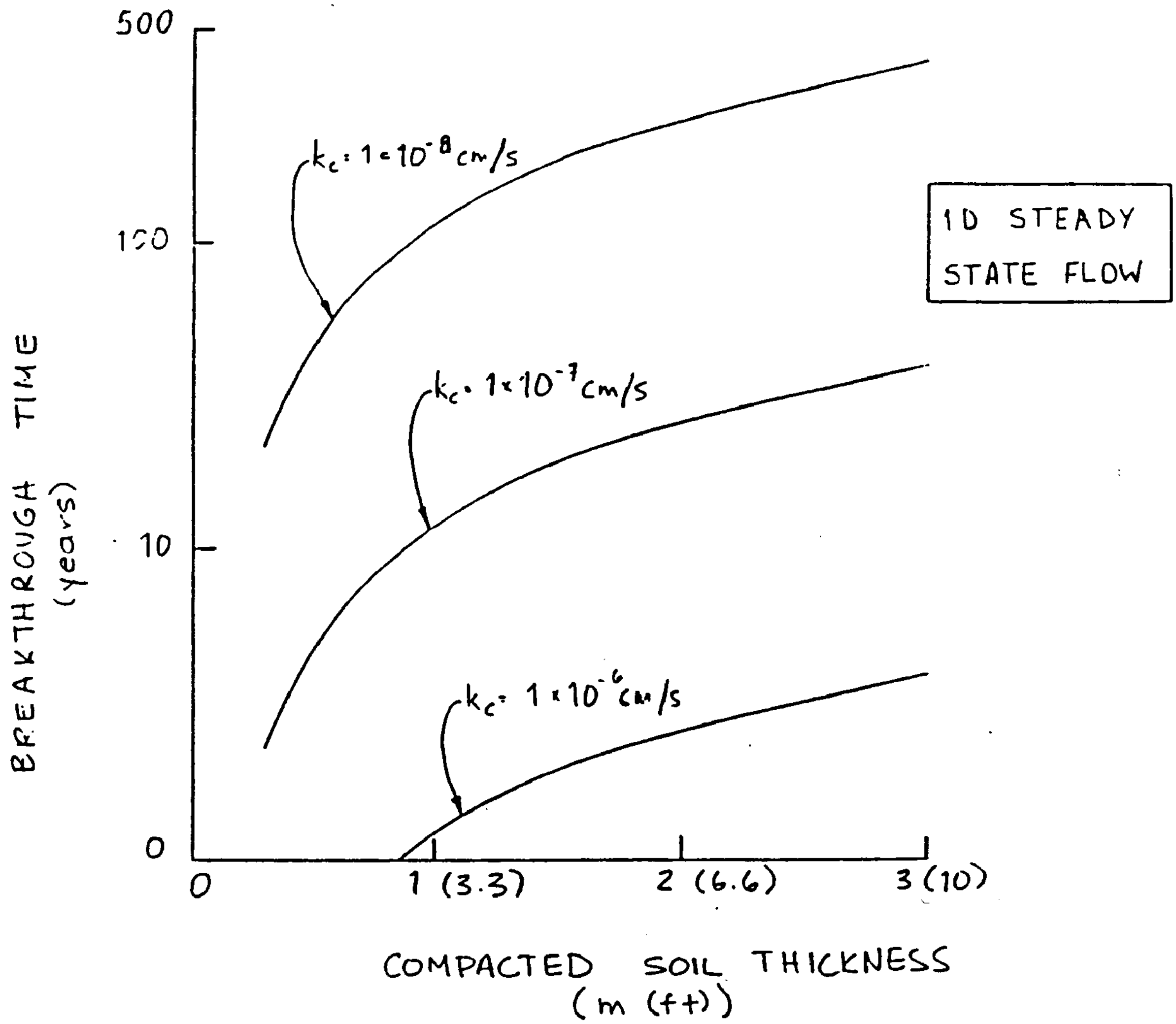


Figure 3-5. Variation of theoretical breakthrough time as a function of hydraulic conductivity and soil liner thickness (1D steady-state analysis).

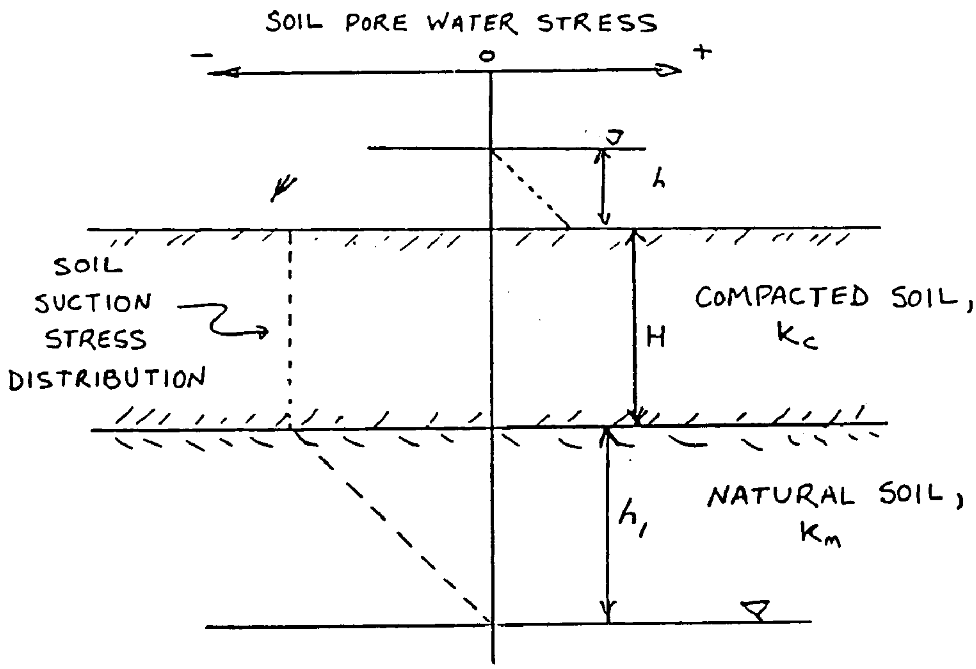


Figure 3-6. Idealization of compacted soil liner for analysis using one-dimensional partially saturated flow computer model SOILINER.

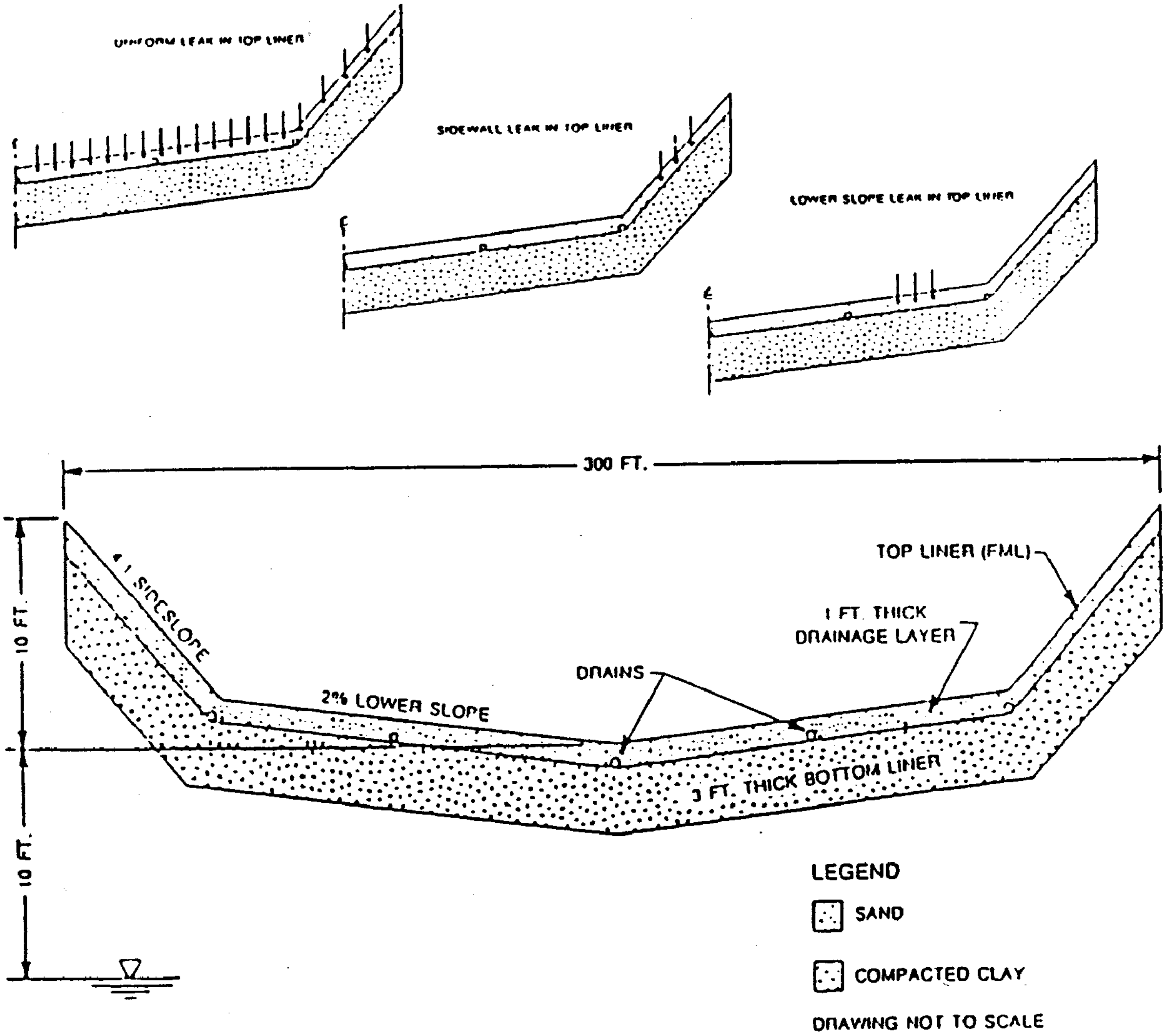


Figure 3-7. Lining system modeled using the UNSAT2D program, to study bottom liner performance. [Radian, 1987]

ACHATE COLLECTION EFFICIENCY AS A FUNCTION OF TIME
COMPACTED SOIL BOTTOM LINERS

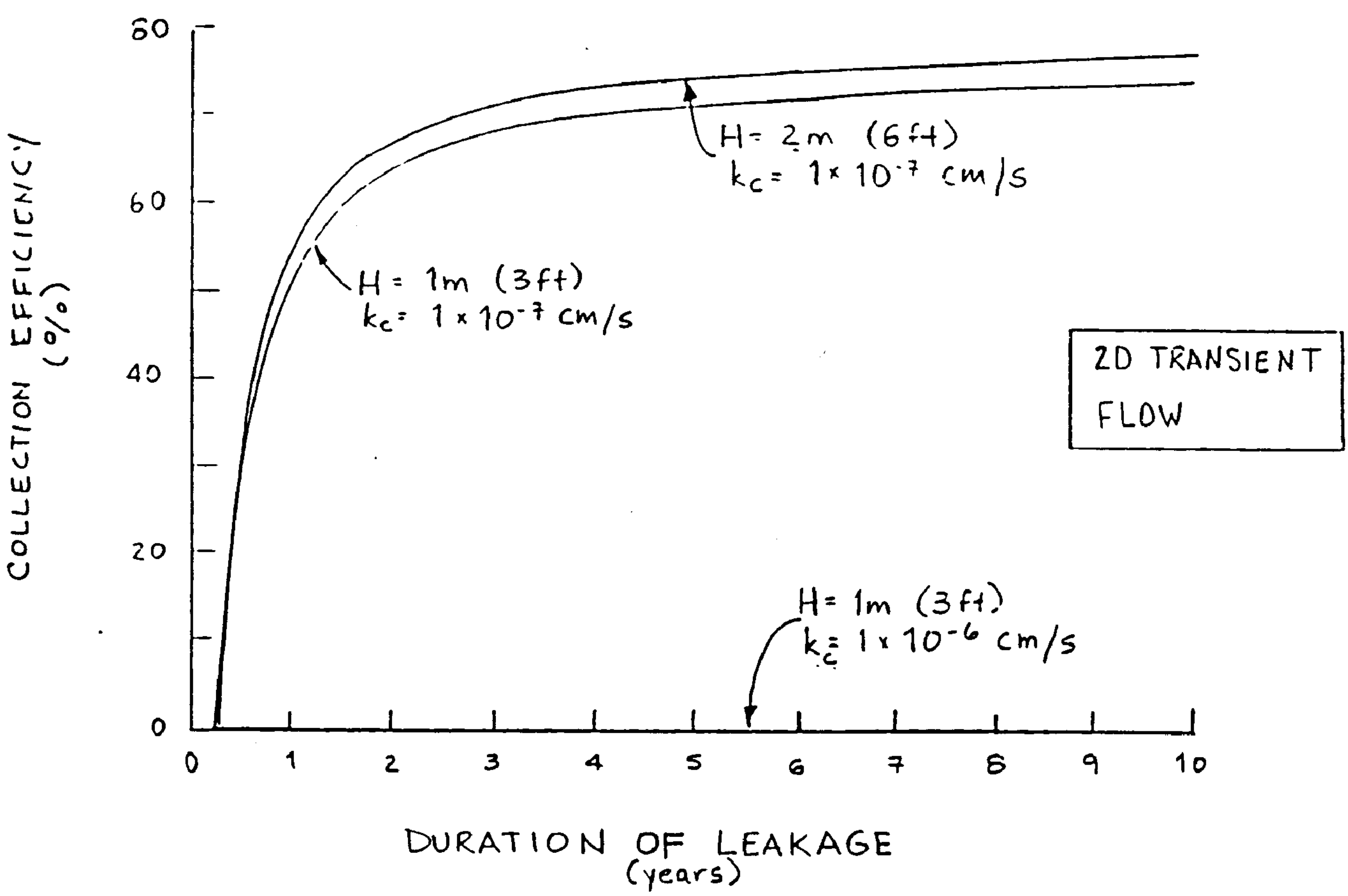


Figure 3-8. Collection efficiency as a function of time for a rate of uniform top liner leakage in the range of 1000 gpad (Ltd); 2D transient analysis using (UNSAT2D). [Data from Radian, 1987]

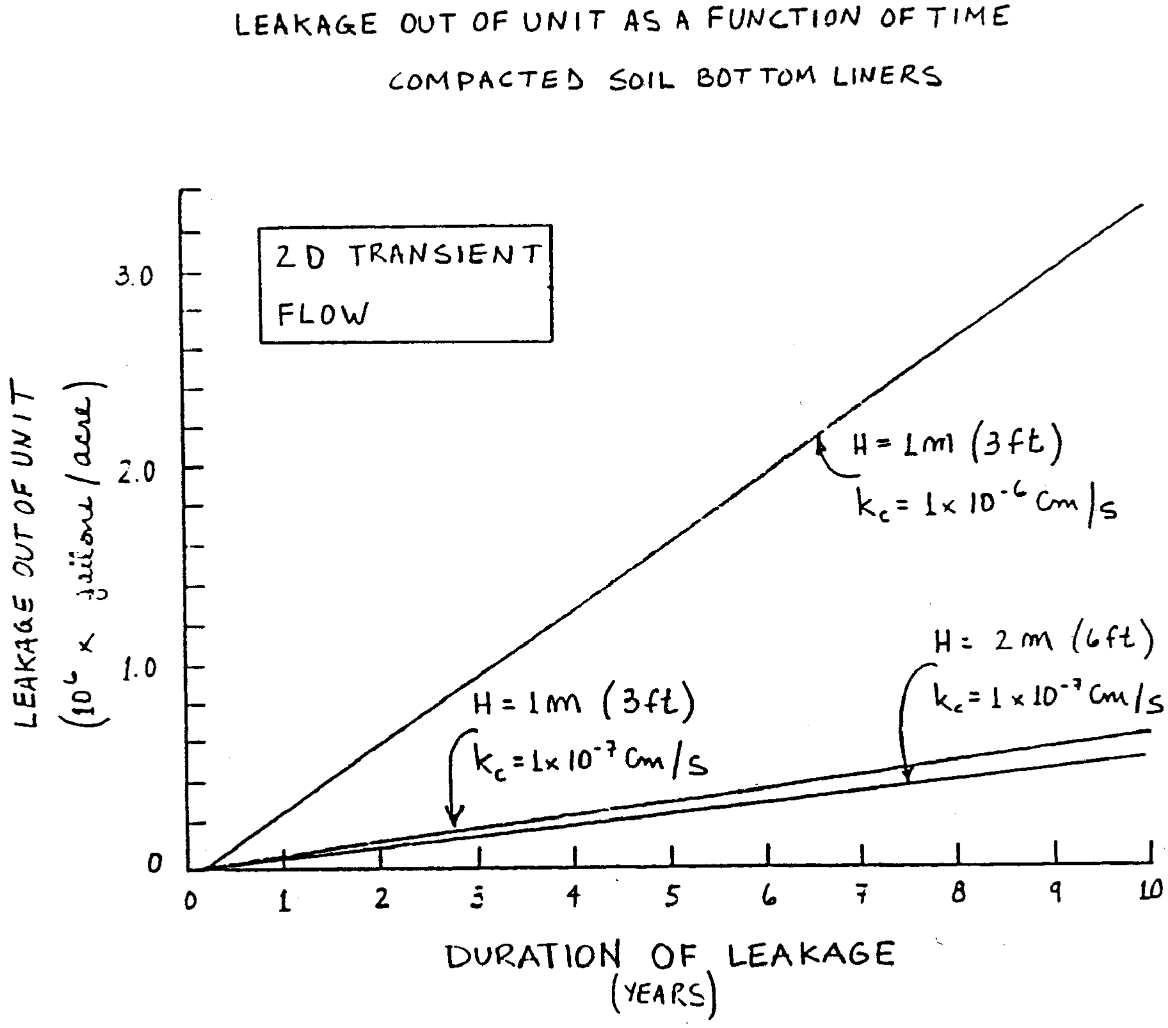


Figure 3-9. Leakage out of unit as a function of time for a rate of uniform top liner leakage in the range of 1000 gpad (Ltd); 2D transient analysis using (UNSAT2D). [Data from Radian, 1987]

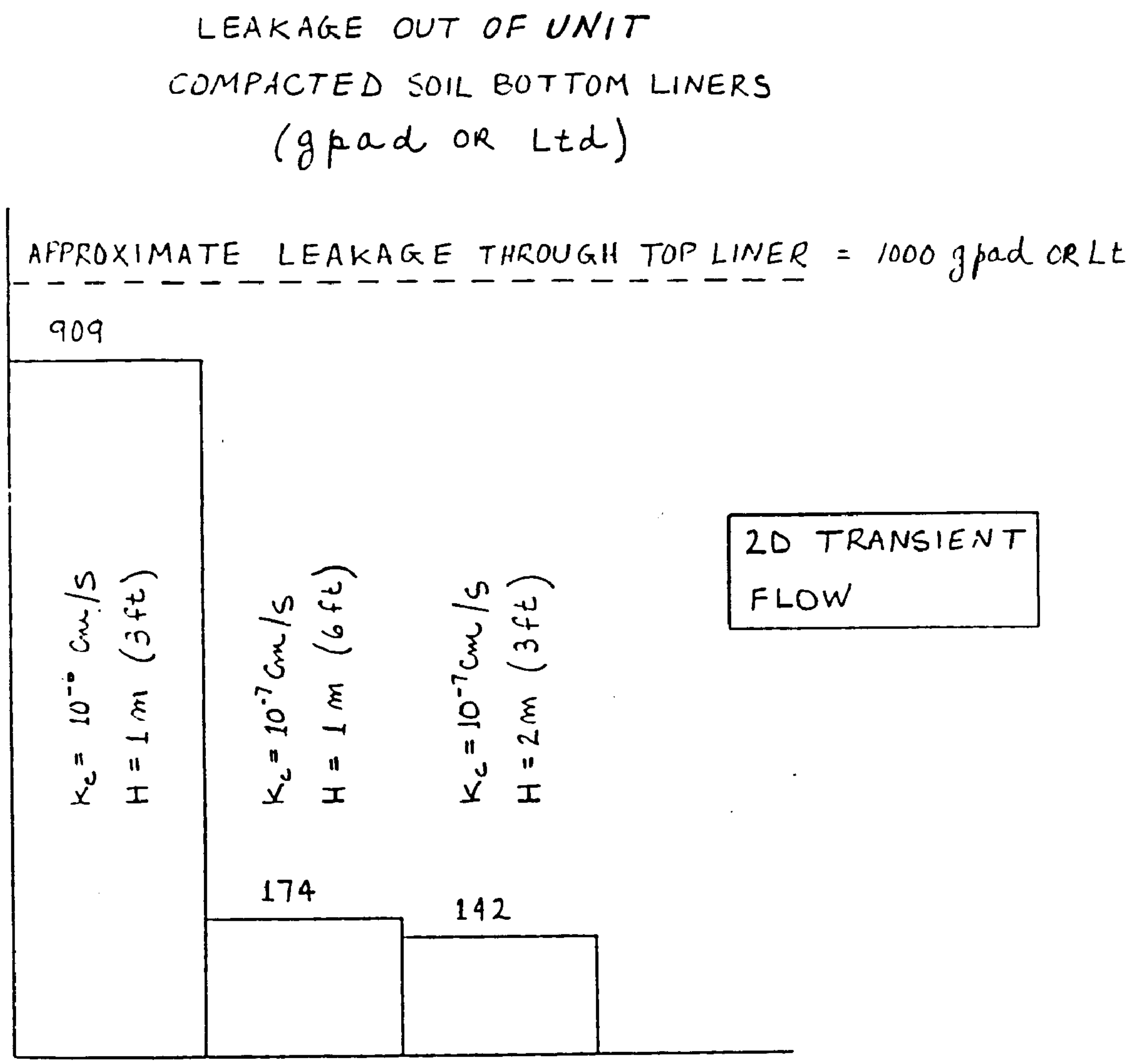


Figure 3-10. Comparison of leakage out of unit using 2D transient analysis (UNSAT2D). [Data from Radian, 1987]

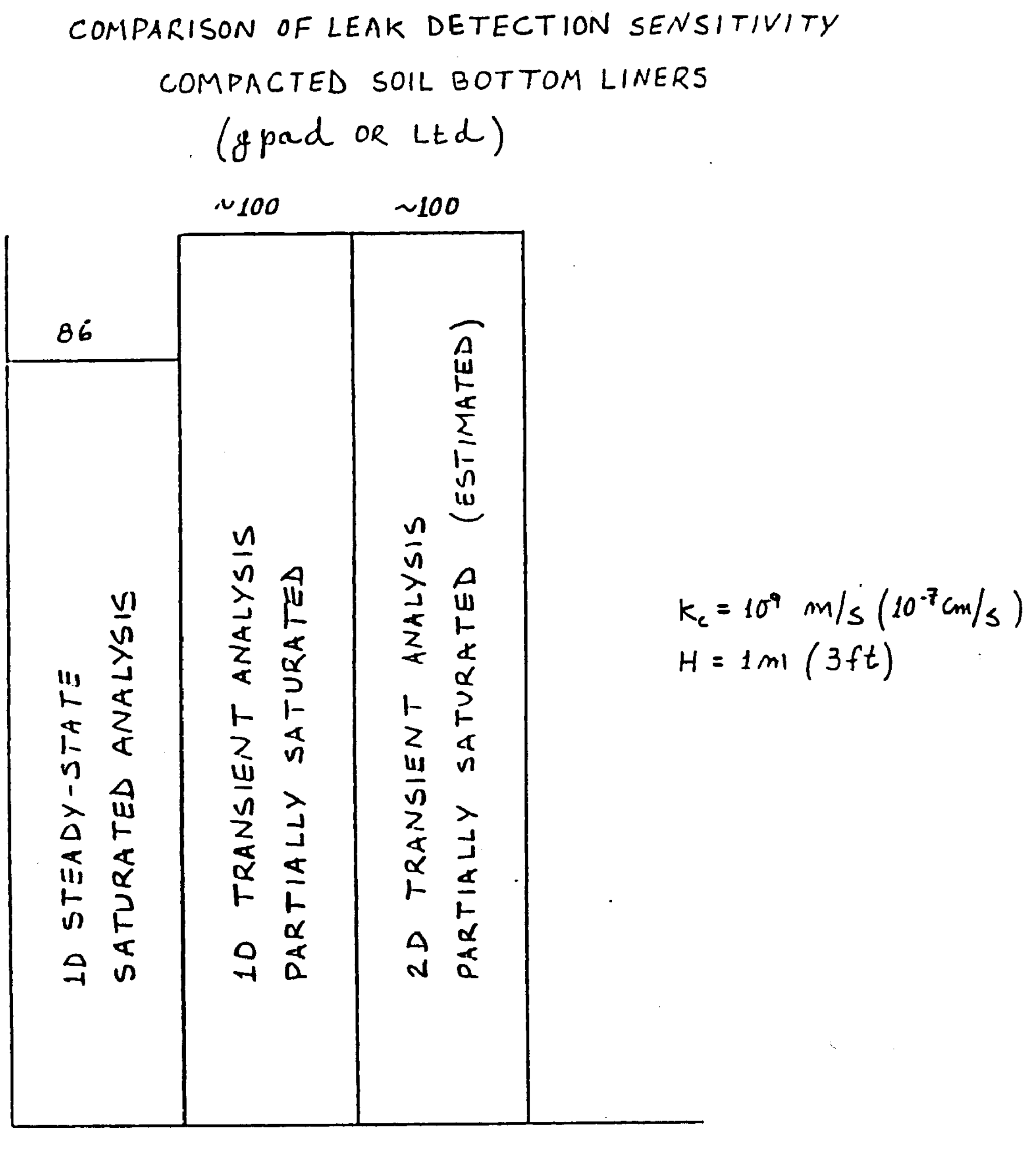


Figure 3-11. Comparison of leak detection sensitivity of compacted soil bottom liners obtained using different analysis methods.

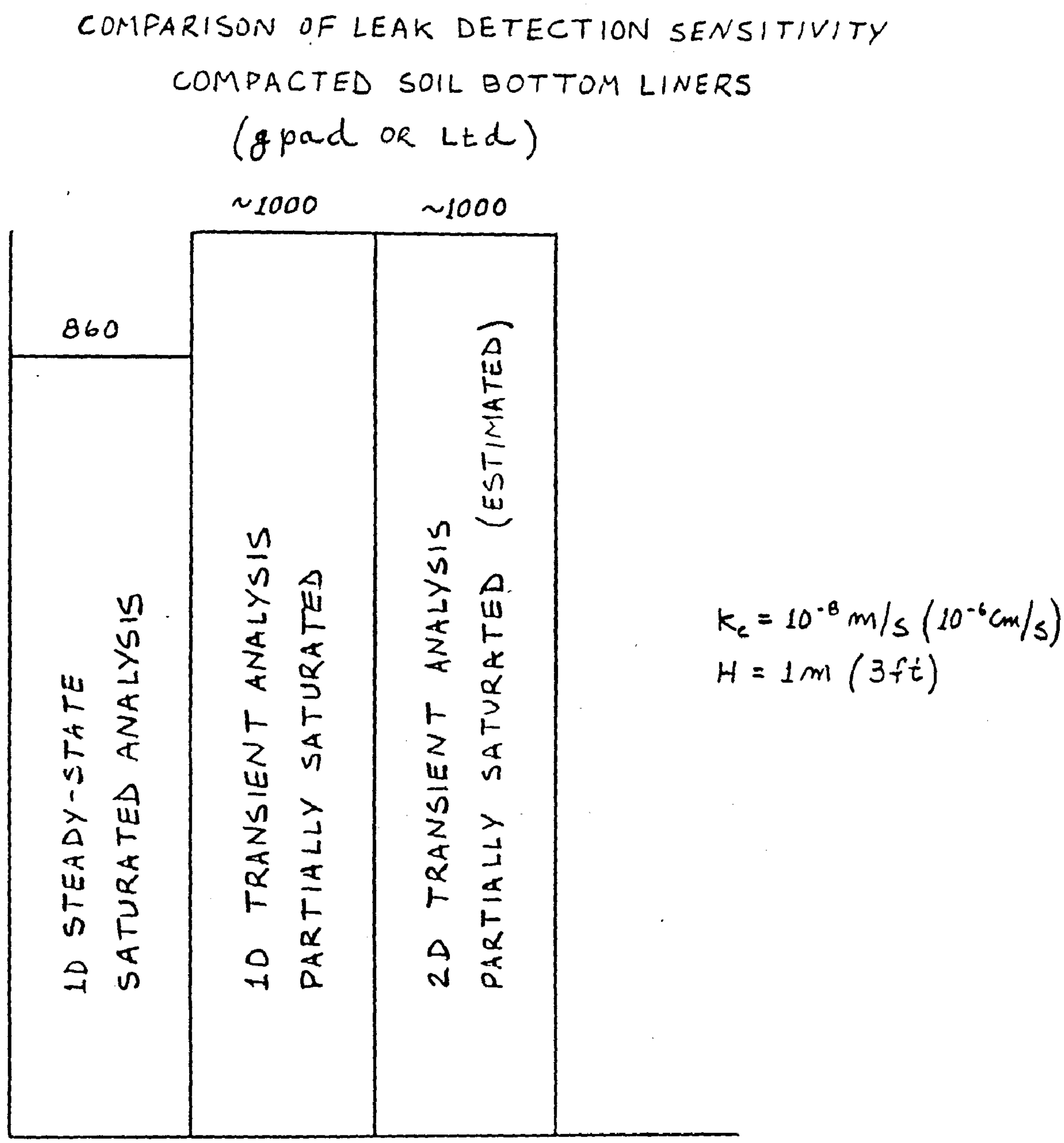


Figure 3-12. Comparison of leak detection sensitivity of compacted soil bottom liners obtained using different analysis methods.

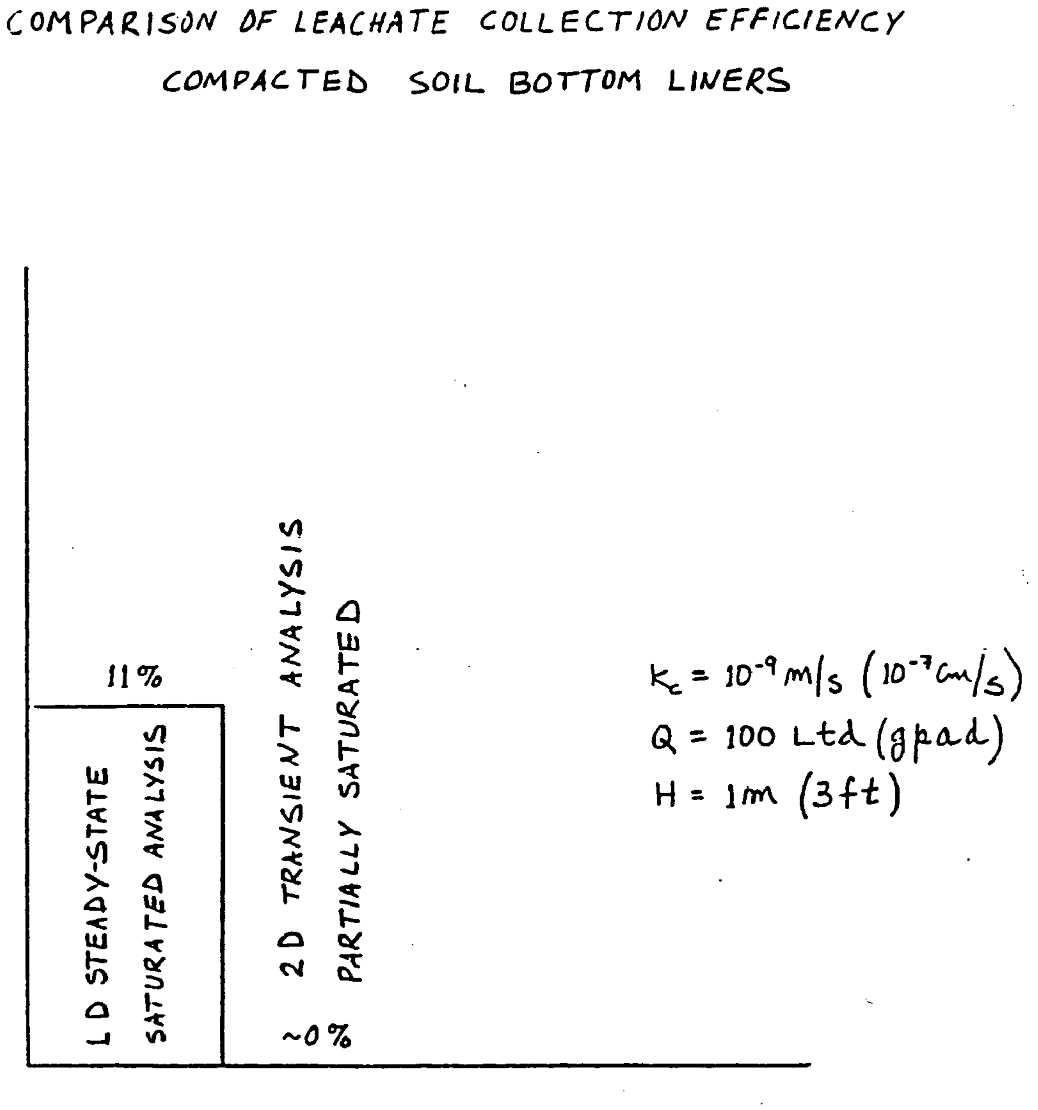


Figure 3-13. Comparison of collection efficiencies using different analysis methods and for a top liner leakage rate of 100 Ltd (gpad).

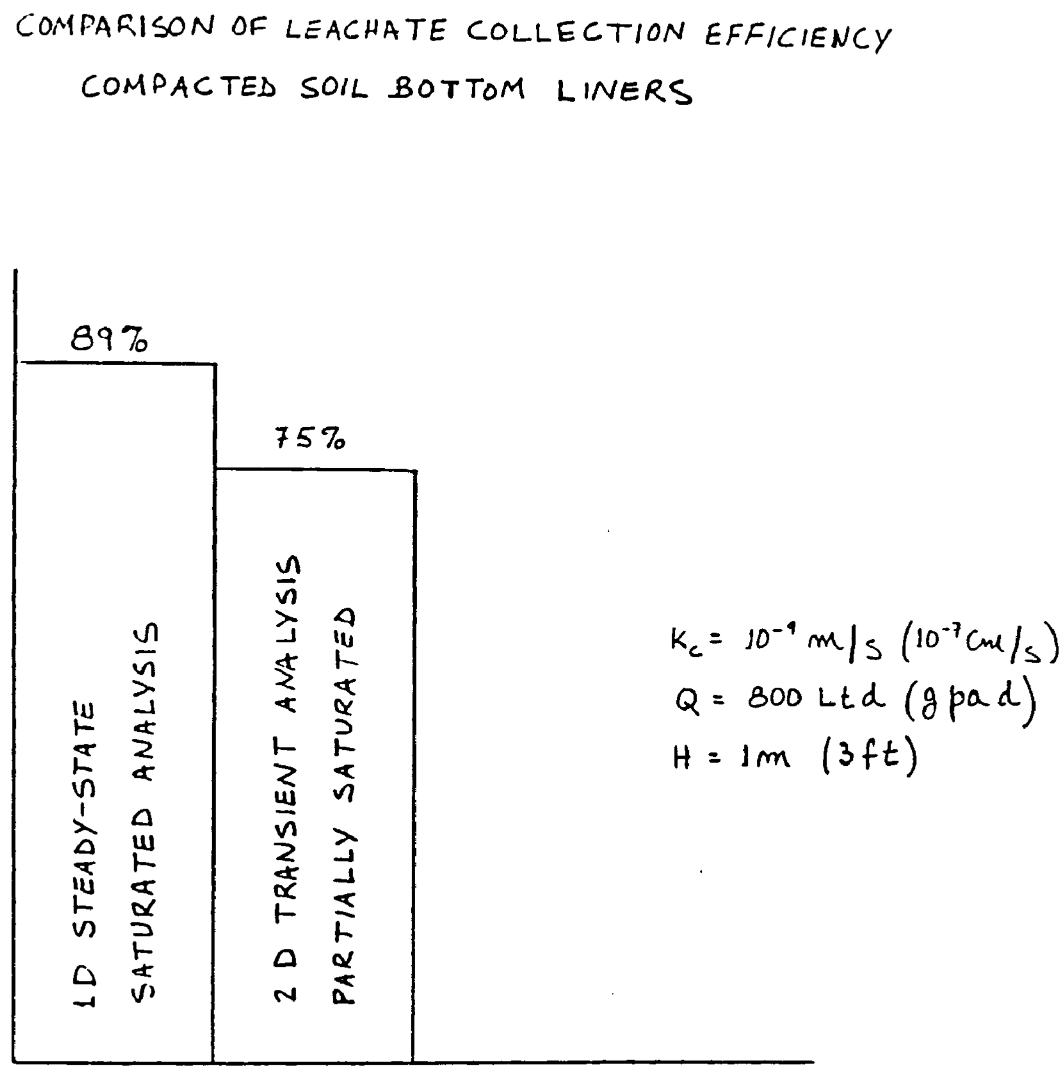


Figure 3-14. Comparison of collection efficiencies using different analysis methods and a top liner leakage rate of ~ 1000 Ltd (gpad).

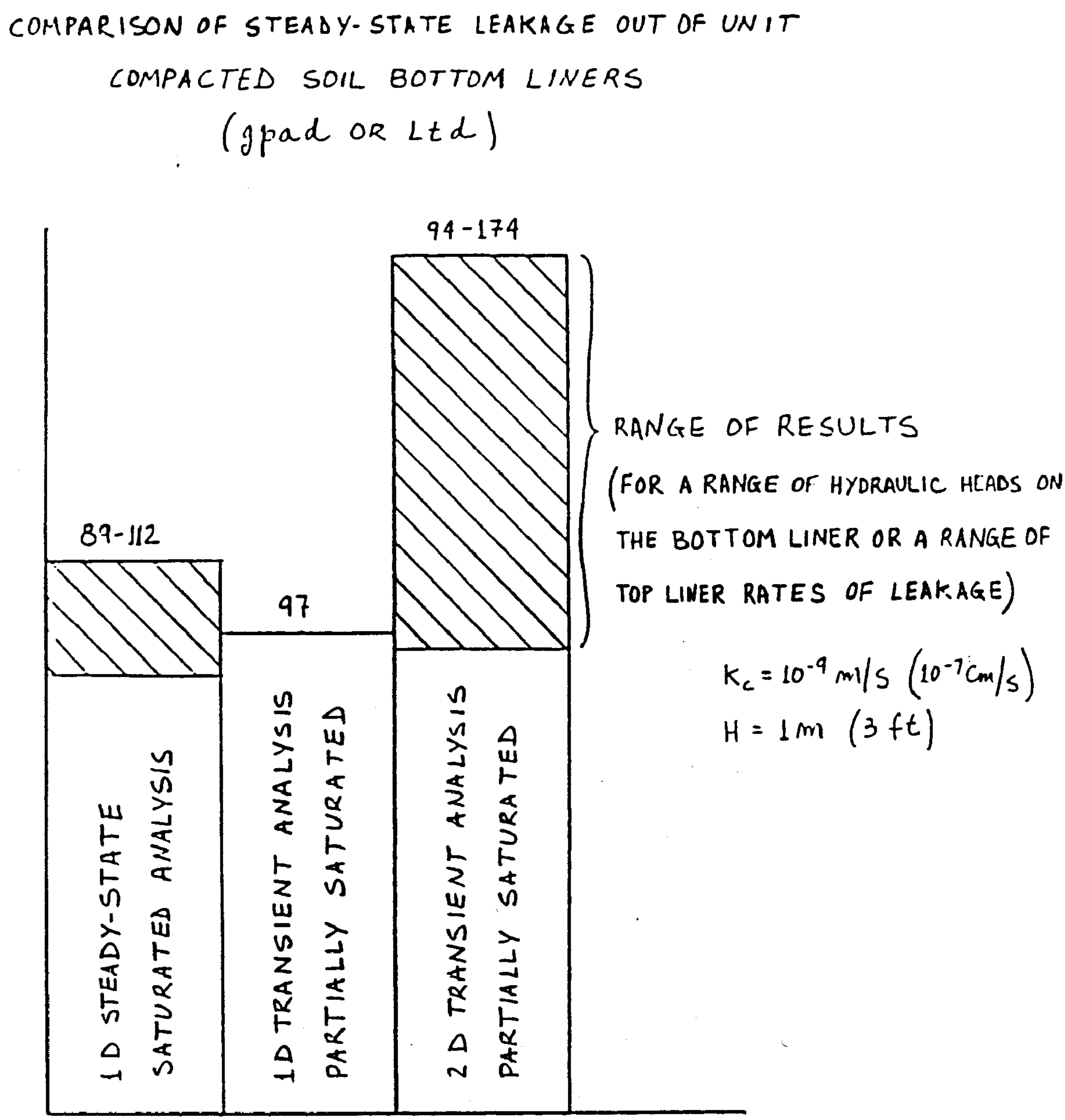


Figure 3-15. Comparison of steady-state rate of leakage out of unit for a 1-m (3-ft) thick compacted soil bottom liner with $k_c = 10^{-9}$ m/s (10^{-7} cm/s).

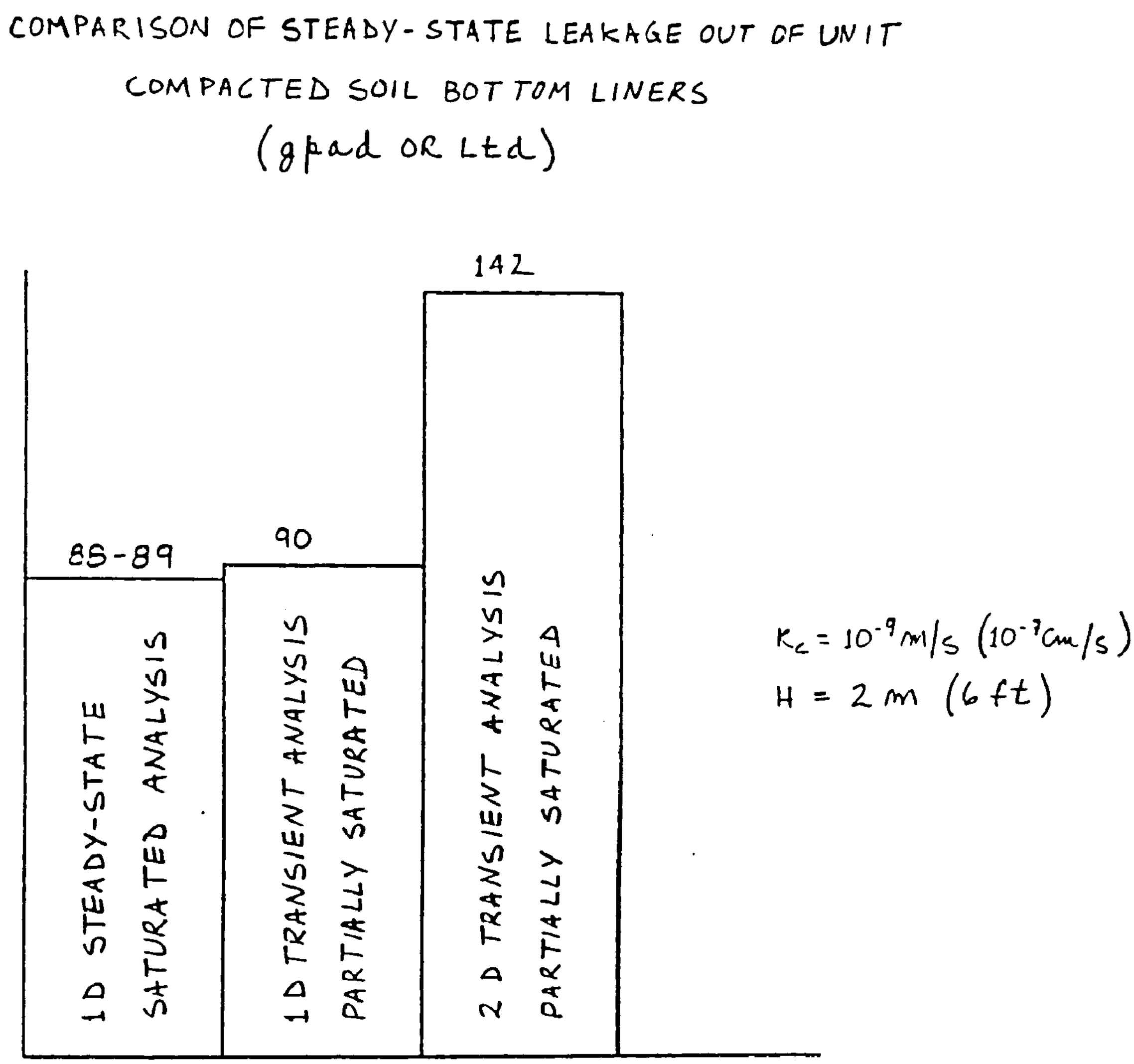


Figure 3-16. Comparison of steady-state rate of leakage out of unit for a 2-m (6-ft) thick compacted soil bottom liner with $k_c = 10^{-9}$ m/s (10^{-7} cm/s).

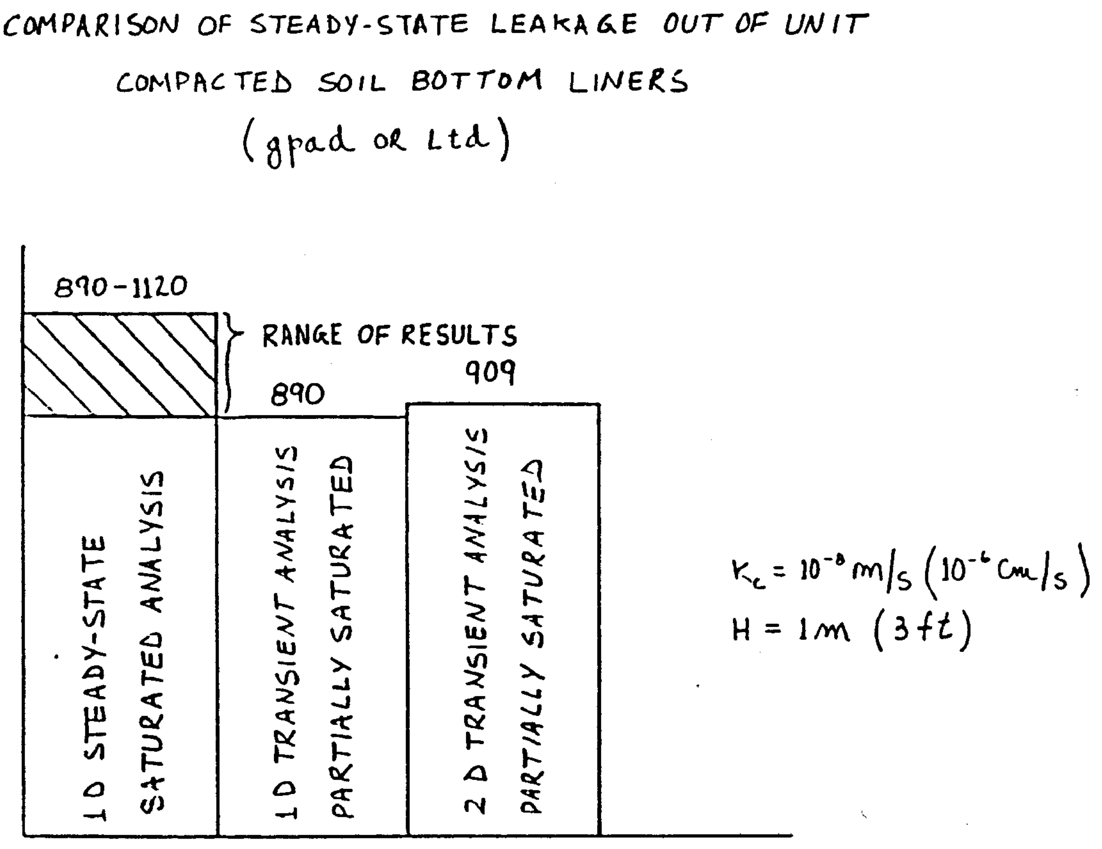


Figure 3-17. Comparison of steady-state rate of leakage out of unit for a 1-m (3-ft) thick compacted soil bottom liner with $k_c = 10^{-8}$ m/s (10^{-6} cm/s).

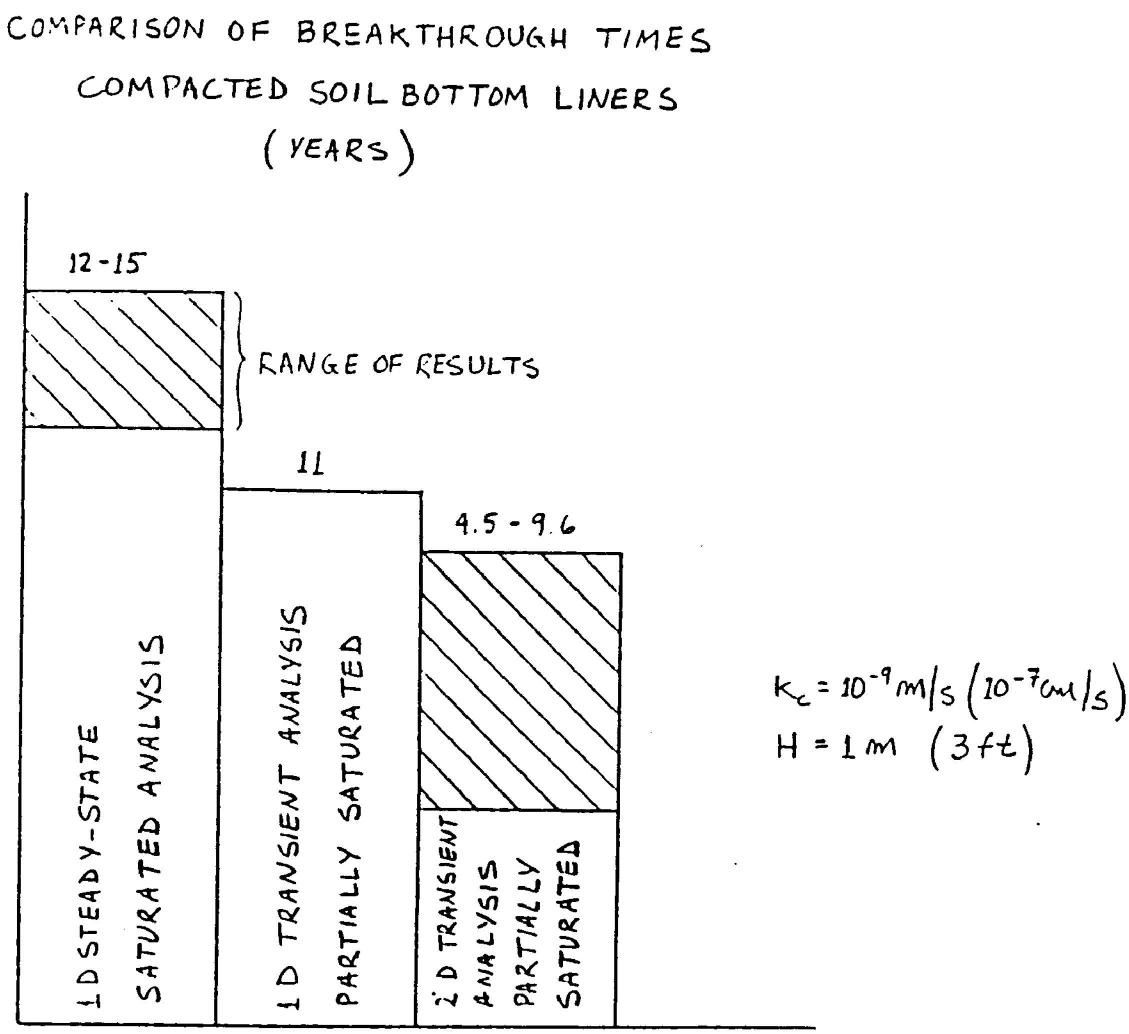


Figure 3-18. Comparison of breakthrough times for a 1-m (3-ft) thick compacted soil bottom liners with $k_c = 10^{-9}$ m/s (10^{-7} cm/s).

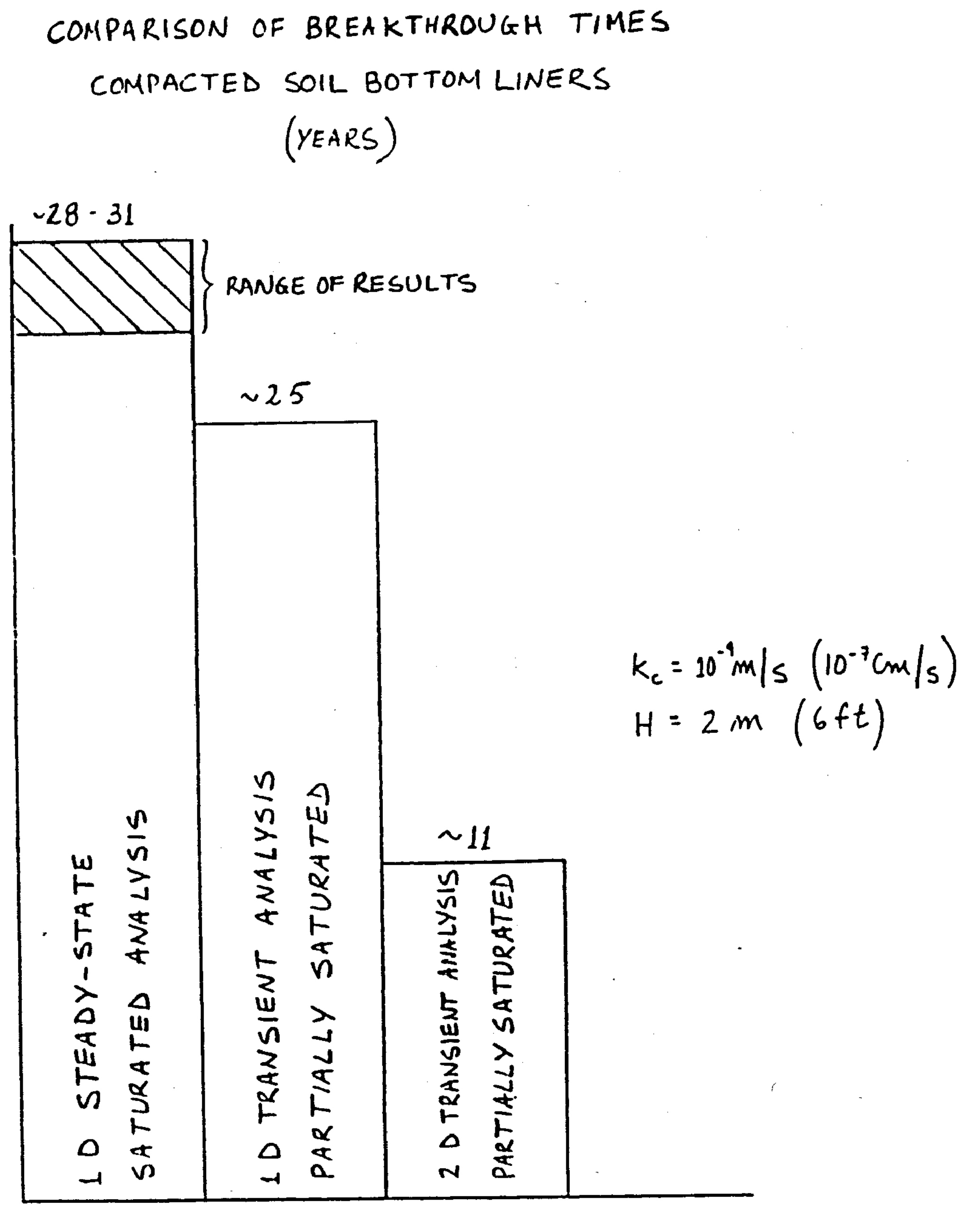


Figure 3-19. Comparison of breakthrough times for a 2-m (6-ft) thick compacted soil bottom liners with $k_c = 10^{-9}$ m/s (10^{-7} cm/s).

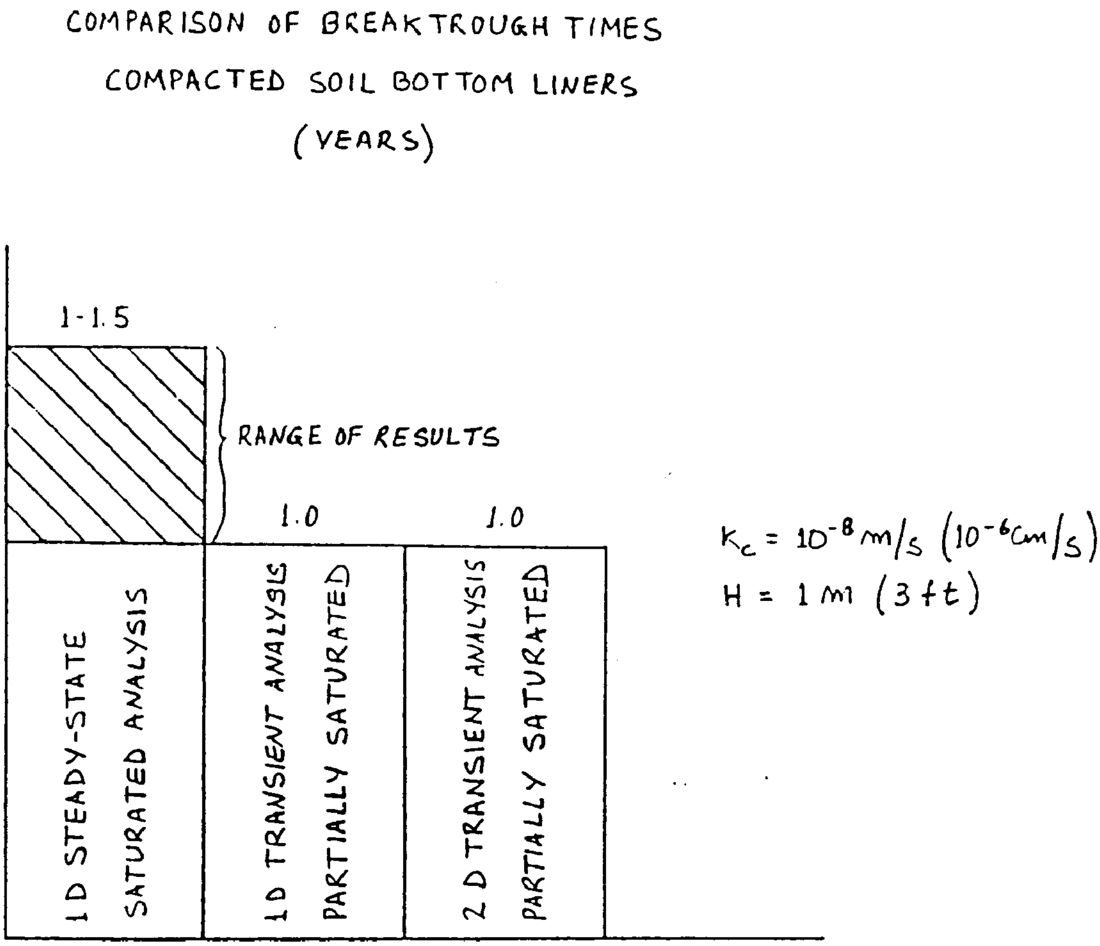


Figure 3-20. Comparison of breakthrough times for a 1-m (3-ft) thick compacted soil bottom liners with $k_c = 10^{-8}$ m/s (10^{-6} cm/s).

CHAPTER 4

PERFORMANCE OF COMPOSITE LINERS

4.1 INTRODUCTION

This chapter addresses the performance of composite bottom liners composed of FML top components and compacted soil bottom components. The performance of compacted soil liners was addressed in Chapter 3. In this chapter, the factors affecting the performance of composite liners are addressed and analyzed. To start, Section 4.2 presents a discussion of the factors which influence the performance of composite bottom liners. In Section 4.3, mechanisms for leakage through composite liners are reviewed. In Section 4.4, the results of an analytical (one-dimensional, steady-state) study of composite bottom liner performance are presented. In Section 4.5, the results of a numerical (two-dimensional, transient) study of composite bottom liner performance are presented. In Section 4.6, the results of the analytical and numerical studies are compared. In Section 4.7, conclusions are drawn.

In Sections 4.4, 4.5, and 4.6 the performance of composite liners is evaluated in terms of:

- leak detection sensitivity;
- leachate collection efficiency; and
- leakage out of the unit.

4.2 FACTORS AFFECTING THE PERFORMANCE OF COMPOSITE LINERS

4.2.1 FML Related Issues

4.2.1.1 Types of Geomembranes

Before addressing the factors affecting FML performance it is worthwhile to briefly introduce the types of FMLs available.

Geomembranes include polymeric and asphaltic materials. When reference is to polymeric materials only, the term FML can be used (as discussed in Chapter 2). Polymers are chemical compounds of high molecular weight. Only synthetic polymers are used to make FMLs. The most common types of polymers presently used as base products in the manufacture of FMLs can be classified as shown in Table 4-1. A description of the types of polymeric FMLs has been provided by Giroud and Frobel [1984] and Giroud [1984f].

4.2.1.2 FML Performance

4.2.1.2.1 FML Permeation

A common misconception regarding FMLs is that they are impermeable, that is, no fluid will pass through an intact FML. However, it is important to realize that all materials used as liners are at least slightly permeable to liquids or gases and a certain amount of permeation through liners should be expected. Additional leakage results from defects such as cracks, holes and faulty seams [Giroud, 1984c].

4.2.1.2.2 Defects

As mentioned above, a certain amount of leakage can occur through FML defects. The most common type of FML defects are holes that result from improper design, defective manufacturing or defective installation. The size of holes may vary from pinholes up to seam defects or tears several centimeters (several inches) long. In general, FML holes control the amount of leakage through the FML. A number of references are available which discuss the various types of defects which have been observed in FML lined waste management units [Bass, et al., 1985; Giroud, 1984a; Giroud, 1984b; Mitchell, 1984].

4.2.1.2.3 Damage During Manufacture, Fabrication or Installation

FML performance can be affected by events during manufacture, fabrication, shipping, handling, storage and installation.

There are essentially five types of defects that can develop in FML sheeting material during the manufacturing process. All are caused by some irregularity or eccentricity of the sheet extrusion process. These include:

- pinholes caused by moisture in the system during extrusion;

- holes caused by moisture or other irregularity during extrusion;

- craters created by foreign matter in the extrudate;

- small bumps caused by excess concentrations of carbon black;

- insufficient thickness caused by the extrusion setting or feed process; and

- scratches or gouges, caused by impact or contact with external objects.

FMLs are susceptible to damage if improperly shipped, stored or handled. Improper handling can puncture or tear the rolls. Dragging rolls or panels of material can cause abrasion-related damage that is usually not repairable. In this case, the damaged FML must be rejected or wasted.

Storage of the FML on site requires a location that provides protection from damage or contamination due to wind, dust, dirt, rain, or ultraviolet exposure.

Proper installation is required to ensure that the FML functions as designed. Installation problems can be caused by improper seaming, vehicular traffic, or debris.

The purpose of the seam is to provide liner continuity between individual FML panels. For this reason the seam must exhibit, at a minimum:

- continuity along the entire length of the seam; and

- seam strength and ductility consistent with that of FML panels.

Leakage through a FML liner is more likely to occur at defects in the seam than anywhere else in the FML. Welds, whether involving fusion, extrusion or chemical bonding must be carried out with the utmost care.

Weather can affect seam quality. It is often difficult to meet seam performance criteria under adverse weather conditions. Usually seaming is not permitted during periods of either very hot or very cold temperatures. Seaming should not be undertaken when moisture is present on the FML. The quality of seams is also affected by the presence of dust, dirt or other impurities. The FML should be as clean as possible prior to seaming.

Construction equipment should never be allowed directly on a FML. Usually, a protective cover about 0.3 m (1 ft.) thick is specified to protect the FML. During placement of the protective cover, equipment should only operate on the already placed protective cover and not on the FML.

Debris can damage a FML liner. Cigarette butts can burn a hole through a FML. Sharp tools and knives should never be used directly on a FML but rather on a protective surface (e.g., a piece of wood or scrap FML).

4.2.1.2.4 Operational Damage

In addition to the damage which can occur during manufacture, fabrication or installation, FML damage can occur during the operation of a waste management unit. In general, operational damage will result from the improper use of heavy equipment on the lining system. A properly designed lining system will have a protective cover to distribute vehicle loads and minimize the effect of operational errors. On the bottom of landfills, a 0.6 m (2 ft.) thickness of soil is used as a protective cover against equipment damage. However, it is sometimes difficult to place a protective cover on side slopes and they may have only minimal protection.

In general, equipment does not operate within a surface impoundment. As a result surface impoundments are not always constructed with a protective cover. Therefore, the FMLs in surface impoundments may be more susceptible to accidental damage than landfills.

4.2.1.2.5 Conclusions

Leakage through a FML can occur because of fluid permeation through "intact" portions of the FML and through defects in the FML. Defects are by far the largest cause of leakage through FMLs. FML defects can occur during FML manufacture, FML installation or unit operation. The number and size of defects for composite bottom liners will be quantified (based on case histories and judgment) subsequently, and in Appendix B, and will serve as the basis for leakage calculations.

4.2.2 Composite Liner Performance

4.2.2.1 Effect of Compacted Soil Hydraulic Conductivity

In Chapter 3 it was demonstrated that if the desired hydraulic conductivity of a compacted soil is not achieved, a significant increase in flow through the compacted soil would result. The hydraulic conductivity of a compacted soil portion of composite bottom liner is also important to overall liner performance. However, the hydraulic conductivity of the compacted soil component of a composite is not as important as the hydraulic conductivity of a compacted soil liner. This is because in a composite, the upper FML limits access of leachate to any pathways through the compacted soil. In the event there is a hole in the FML, flow through the composite liner will be influenced by the hydraulic conductivity of the lower compacted soil component. The larger the hydraulic conductivity, the larger the flow through the hole.

4.2.2.2 Effect of Contact Between Soil and FML

The effect that a hole in the FML component of a composite liner will have on flow through the liner also depends on the quality of the contact between FML and soil. Perfect contact over the entire bottom liner is not achievable. There will always be wrinkles in the FML or unevenness in the subgrade soil surface. As a result, flow through a leak in the FML will be larger than that predicted by theoretical solutions assuming perfect contact. The effect of imperfect contact and the quantification of the increase in leakage is addressed subsequently and in Appendix B.

4.3 LEAKAGE MECHANISMS THROUGH COMPOSITE LINERS

4.3.1 Introduction

In Section 4.2 it was pointed out that leakage can occur through either an intact FML or through holes in the FML. In Appendix B to this report, a detailed discussion and analysis of leakage into and through composite liners is presented. The purpose of Section 4.3 is to briefly present the conclusions of Appendix B. The four main topics of Appendix B are:

- leakage due to permeation through a FML;
- frequency and size of FML defects;
- analytical and model studies related to leakage through composite liners due to a holes in the FML; and
- conclusions on leakage through composite bottom liners.

4.3.2 Leakage Due to Permeation Through FML

In Section B.2 of Appendix B an extensive discussion of permeation through "intact" FMLs is presented. FML permeation may be attributed to vapor diffusion, flow through microscopic holes and possibly other mass transfer mechanisms. Results from permeameter tests (Figure B-1) and vapor transmission tests are interpreted in terms of the coefficient of migration of the FML, μ_g, which has been defined by Giroud et al. [1987]:

$$v = Q/A = \mu_g/T \qquad \text{(Equation 4-1)}$$

and

$$k_g = \mu_g/h \qquad \text{(Equation 4-2)}$$

where: Q = flow rate due to permeation through the FML (m^3/s); μ_g = coefficient of migration of the FML (m^2/s); T = FML thickness (m); k_g = "equivalent hydraulic conductivity" of FML to be used with Darcy's Equation (m/s); and h = hydraulic head acting on the FML (m).

Values of the coefficient of migration derived from the results of permeameter tests and water vapor transmission tests are given in Appendix B and summarized below:

	h = 1 mm	h = 30 mm
CSPE	1.3×10^{-18}	3.3×10^{-16}
HDPE	3×10^{-20}	1.5×10^{-17}
	Values of μ (m^2/s)	

From these values of μ and from a knowledge of the hydraulic heads acting in the permeameter and water vapor transmission tests, the following "equivalent hydraulic conductivities" can be calculated:

	h = 1 mm	h = 30 mm
CSPE	1.3×10^{-15}	1.1×10^{-14}
HDPE	3×10^{-27}	5×10^{-16}
	Values of k_g (m/s)	

From the above results it appears that a FML "equivalent hydraulic conductivity" of $k_g = 1 \times 10^{-14}$ m/s (1×10^{-12} cm/s) would provide a conservative measure of permeation through an FML. This value of k_g will therefore be used in subsequent calculations of permeation through an FML. In addition, a value of $k_g = 1 \times 10^{-13}$ m/s (1×10^{-11} cm/s) will be used in subsequent calculations to assess the sensitivity of bottom liner performance to the selected value of k_g. This latter value of k_g is very conservative and might be considered to represent a "worst case scenario" for permeation through an intact FML.

4.3.3 Frequency and Size of FML Defects

Sections B.3.2 and B.3.3 of Appendix B present data from six case histories on the observed frequency of seam defects in FMLs installed with and without construction quality assurance monitoring. In Sections B.3.4 and B.3.6 the data from these case histories are analyzed and the following conclusions are drawn on "standard" defect frequencies and sizes which are used in subsequent calculations of leakage through holes in FML composite liners.

- the "standard" defect (hole) area selected is 1 cm^2 (10^{-4} m^2 or 0.16 in^2);

- the "standard" frequency of defect (hole) is one per 4000 m^2 (one per acre).

The standard hole size and frequency have been selected with the assumption that intensive quality assurance monitoring will be performed. The standards given above are believed to be conservative for project where there is intensive quality assurance. These standards do not, however, take into account cases where design flaws or poor construction practices would lead to many seam defects or a large tear in the FML.

4.3.4. Analytical and Model Studies

Sections B.4 and B.5 of Appendix B present the results of analytical calculations and model scale tests of leakage through holes in FMLs (alone and as part of a composite liner). The analytical calculations (B.4) and the model scale test results (B.5) are described in detail. From the analytical calculations, conclusions can be drawn on the quantities of leakage that would flow through a hole in the FML component of a composite bottom liner. These conclusions are presented in the next section.

4.3.5 Conclusions on Leakage Through Composite Liners

Section B.6 of Appendix B provides detailed conclusions regarding leakage through composite liners. From these conclusions, Figure 4-1 and Table 4-2 have been developed.

- Figure 4-1 gives the leakage rate and the radius of the wetted area for the case of leakage through an FML hole in the bottom composite liner.

- Table 4-2 gives the leakage rate through composite bottom liners due to FML permeation and FML holes.

Table 4-2 was established using the information on permeation through FMLs presented in Section 4.3.2 and on leakage through FML holes summarized in Figure 4-1. To the best of our knowledge, Table 4-1 summarizes the best demonstrated available technology (BDAT) on leakage rates through composite bottom liners.

Table 4-2 will be conservatively interpreted (a poor contact between the FML and compacted soil components of the composite bottom liner will be considered) in subsequent calculations when assessing composite bottom liners performance. For this condition leakage through a "standard" FML defect (hole) will equal 1 Ltd (gpad) if k_C = 1 x 10^{-8} m/s (1 x 10^{-6} cm/s), and 0.1 Ltd (gpad) if k_C = 1 x 10^{-9} m/s (1 x 10^{-7} cm/s).

4.4 PERFORMANCE OF COMPOSITE LINERS - 1-D STEADY-STATE ANALYSIS

4.4.1 Introduction

In this section, the results of analytical calculations are presented and are used to evaluate the performance of composite bottom liners. As discussed in Section 4.3, leakage through an FML can be due to either of two causes:

- Leakage due to permeation through a FML without any holes, as discussed in Section 4.3 and Appendix B. In this case, the rate of liquid or vapor movement through the FML is not significantly affected by the hydraulic conductivity of the compacted soil under the FML since even low-permeability soils are much more permeable than FMLs and act as permeable media when placed under FMLs.

- Leakage through holes in a FML placed on a layer of compacted low-permeability soil to form a composite liner.

The calculations presented in Section 4.4 are based on the procedures developed in Appendix B and summarized in Section 4.3. The calculations are presented first (Section 4.4.2) for the case of liquid migration through an intact FML (no holes). Second (Section 4.4.3), calculations are presented based on leakage through a hole in the FML of a composite liner. Third (Section 4.4.4), the two types of leakage are added together to evaluate the overall performance of composite liners. In all three cases, the performance of composite liners is evaluated in terms of leak detection sensitivity, leachate collection efficiency, and leakage out of the unit.

4.4.2 Leakage Through an Intact FML

4.4.2.1 Procedure

In Section 4.3 "equivalent hydraulic conductivities", k_g, of 10^{-14} to 10^{-13} m/s (10^{-12} to 10^{-11} cm/s) were conservatively selected for FMLs based on the results of permeameter tests and water vapor transmission tests. These "equivalent hydraulic conductivities" are valid only for small hydraulic heads on the bottom liner (up to 0.03 m to 0.1 m (0.1 to 0.3 ft)). This range of hydraulic heads is larger than the range expected on the bottom liner and are therefore also conservative. For this limited range of hydraulic heads, Darcy's Equation can be used to approximate the performance of an intact FML:

$$v = k_g \, h/T \qquad \text{(Equation 4-3)}$$

$$Q = k_g \, h \, A/T \qquad \text{(Equation 4-4)}$$

where: Q = leakage rate (m^3/s); k_g = "equivalent hydraulic conductivity" of the FML (m/s); h = hydraulic head (m); A = surface area of the FML (m^2); and T = thickness of the FML (m).

In order to ensure the validity of Darcy's Equation for permeation of an FML; a hydraulic head of not more than 30 mm (0.1 ft.) was considered to act on the FML. FML thicknesses, T, of 1 mm (40 mil) or 2 mm (80 mil) were considered, along with "equivalent hydraulic conductivities" of 10^{-14} and 10^{-13} m/s (10^{-12} and 10^{-11} cm/s). These values will be used along with Equations 4-1 and 4-2 to determine:

- leak detection sensitivity;
- leachate collection efficiency; and
- leakage out of the unit;

for an intact FML.

4.4.2.2 Leak Detection Sensitivity

In general, leak detection sensitivity is dependent upon the properties of both the LDCRS and the bottom liner. In the event of concentrated leakage through the top liner a two-dimensional analysis is required to evaluate leak detection sensitivity. However, if uniform leakage through the top liner is considered, it is possible to establish a lower bound for leak detection sensitivity using a one-dimensional steady-state saturate flow analysis.

The minimum leakage rate that can be detected must be greater than the rate at which liquid can flow by gravity into the bottom liner, without having liquid build up in the LDCRS. Under this condition, the minimum leakage rate will be independent of the hydraulic head on the liner (it is zero) or the thickness of the liner (the hydraulic gradient is one). Therefore, the minimum detectable leakage rates for hydraulic conductivities of 10^{-14} and 10^{-13} m/s (10^{-12} and 10^{-11} cm/s) are:

Hydraulic Conductivity m/s	(cm/s)	Leakage Rate Ltd or (gpad)
10^{-13}	(10^{-11})	0.01
10^{-14}	(10^{-12})	0.001

It should be noted that these rates are the theoretical minimum detectable leakage rates for uniform leakage. For concentrated leakage, the theoretical minimum detectable leakage rates will be smaller because the area of bottom liner wetted by the leak is smaller. However, these leakage rates are so small that no collection system is sensitive enough to detect this level of leakage. In practical terms, therefore, an intact FML provides "absolute" detection sensitivity. The above rates of leak detection sensitivity for $k_g = 1 \times 10^{-14}$ m/s (1×10^{-12} cm/s) is very consistent with the value given for FML permeation in Table 4-2. Also, the detection sensitivity will not be influenced by the hydraulic conductivity of the underlying compacted soil layer, because even a low-permeability soil is much more permeable than an intact FML.

4.4.2.3 Leachate Collection Efficiency

In general, the steady-state leachate collection efficiency is dependent upon the properties of both the LDCRS and the bottom liner. To evaluate leachate collection efficiency using one-dimensional steady-state saturated flow, three simplifying assumptions are required. The first assumption is that leakage through the top liner is uniform. The second assumption is that a head of 30 mm (0.1 ft) acts on the bottom liner, regardless of the flow through the top liner. The third assumption is that any liquid that does not flow into the bottom liner is collected.

Using the above assumptions, the calculated steady-state leachate collection efficiencies (%) for a range of leakage rates and hydraulic conductivities of 10^{-14} m/s (10^{-12} cm/s) and 10^{-13} m/s (10^{-11} cm/s) are (T = 1 mm (40 mil)):

Top Liner Leakage Rate Ltd (gpad)	Steady-State Collection Efficiency (%)	
	$k_g=10^{-14}$ m/s (10^{-12} cm/s)	$k_g=10^{-13}$ m/s (10^{-11} cm/s)
0.01	0	0
0.1	80	0
1.0	98	80
10	99.8	98

The above results are conservative, because at low rates of top liner leakage the hydraulic head on the bottom liner will be less than that assumed for the steady-state calculations (30 mm (0.1 ft)).

The above results indicate that even with this conservative assumption, high steady-state collection efficiencies can be achieved in LDCRS systems underlain by intact FMLs (even when the top liner leakage rate is small, e.g., 1.0 Ltd (gpad)). Also, the steady-state leachate collection efficiency of an intact FML will not be influenced by the hydraulic conductivity of the underlying compacted soil layer.

4.4.2.4 Leakage Out of Unit

The rate of liquid permeation through an intact FML can be approximated using Equation 4-4 and a hydraulic head of 30 mm (0.1 ft):

FML Thickness		Rate of Permeation Ltd (FML)	
mm	(mil)	k_g=10^{-14} m/s (10^{-12} cm/s)	k_g=10^{-13} m/s (10^{-11} cm/s)
1	(40)	0.02	0.2
2	(80)	0.01	0.1

These results give higher permeation rates than Table 4-2 because the results in this section are based on the conservative assumption that h = 30 mm (0.1 ft) and use k_g values larger than those reported in Section 4.3.2 and used to establish Table 4.2. Even with these very conservative assumptions, however, the rate of liquid permeation through an intact FML is very small. Also, the rate of liquid permeation through an intact FML is not influenced by the hydraulic conductivity of the underlying soil layer.

4.4.2.5 Summary

The calculated leak detection sensitivity, steady-state collection efficiency and leakage out of the unit for an intact FML overlying a compacted soil layer are summarized in Table 4-3. This table has been established using conservative assumptions regarding FML performance. From this summary it can be observed that a composite liner with an intact FML provides a very high level of performance in terms of the lining system performance criteria important to EPA's liquid management strategy. In Section 4.4.3 the effect of a hole in the FML will be addressed.

The effect of FML defects on composite liner performance is evaluated next, in Section 4.4.3.

4.4.3 Leakage Through Holes in FML Component of Composite Liner

4.4.3.1 Procedure

The mechanism by which leakage occurs through a defect or hole in a FML component of a composite liner was described in detail in Appendix B and summarized in Section 4-3. The conclusions drawn in Appendix B and Section 4-3 will be used to evaluate:

- leak detection sensitivity;
- leachate collection efficiency; and
- leakage out of the unit

of a composite liner with a hole in the FML component.

4.4.3.2 Leak Detection Sensitivity

In general, the presence of a hole will not influence the leak detection sensitivity of a FML, because the area of the hole is very small in comparison to that of the surrounding intact FML. Therefore, leak detection sensitivity can be taken to be that of an intact FML. It was shown in Section 4.4.2.2 that detection sensitivity is 0.01 Ltd (gpad) for $k_g = 10^{-13}$ m/s (10^{-11} cm/s) and 0.001 Ltd (gpad) for $k_g = 10^{-14}$ m/s (10^{-12} cm/s)).

4.4.3.3 Leachate Collection Efficiency

The steady-state leachate collection efficiency will be dependent upon the number of holes in the FML, as shown in Figure 4-2. A FML installed with good construction quality assurance would be expected to have not more than 3 to 5 defects per hectare (1 to 2 per acre), and possibly fewer. It can be observed from Figure 4-2 that the steady-state collection efficiency of the lining system would be affected by a few FML holes only at very low rates of leakage through the top liner. Even in the extreme event of 25 defects per hectare (10 defects per acre) a relatively high steady-state collection efficiency (95%) would be achieved at a leakage rate equal to 20 Ltd (gpad).

4.4.3.4 Leakage Out of Unit

The leakage that can occur through a hole in the FML component of a composite liner can be obtained from the results summarized in Table 4-2. The leakage that can occur through a single "standard" FML defect under a hydraulic head of 30 mm (0.1 ft) and conservatively assuming poor contact between FML and compacted soil layers is:

Soil Hydraulic Conductivity m/s	(cm/s)	Rate of Leakage Out of Unit Ltd	(gpad)
10^{-9}	(10^{-7})	0.4	(0.1)
10^{-8}	(10^{-6})	4	(1)

A comparison of the amount of leakage due to one "standard" FML defect per acre and due to permeation through an intact FML is shown in Figure 4-1.

4.4.3.5 Summary

The leak detection sensitivity, steady-state leachate collection efficiency, steady-state leakage out of the unit that can be expected through a "standard" FML defect are summarized in Table 4-4. It can be observed from the results in Table 4-4 that a 1 cm^2 (10^{-4} m^2 or 0.16 in^2.) standard defect will not substantially impact the leak detection sensitivity, leachate collection efficiency and leakage out of the unit. The evaluation made in this section, along with the evaluation of composite liners with intact FML components made in Section 4.4.2, will be drawn together in Section 4.4.4 and conclusions will be made for the case of leakage through a composite due to both FML permeation and FML defects.

4.4.4 Leakage Through a Typical Composite Liner

The performance of a composite liner will depend upon the number of FML defects and the amount of liquid that migrates through the intact portions of the FML. The performance of an intact FML was evaluated in Section 4.4.2 and the influence of a FML defect was evaluated in Section 4.4.3. These results are combined in this section to evaluate the overall performance of a composite bottom liner. In this evaluation, 5 defects per hectare (2 defects per acre) are considered. This number of defects is considered to be an upper bound of the number expected in a properly installed FML with a good construction quality assurance program. For this composite liner the calculated performance under 30 mm (0.1 ft) of head is summarized in Table 4-5. From this table, and Table 4-3, it can be observed that the presence of a few "standard" FML defects does not greatly alter the overall performance of the lining system.

Several observations can be made regarding leak detection sensitivity, steady-state collection efficiency and leakage out of the unit.

- The theoretical leak detection sensitivity of an LDCRS with a properly designed and constructed composite bottom liner is much less than one Ltd (gpad). A few "standard" FML defects have a negligible effect on the leak detection sensitivity of a lining system with a composite bottom liner.

- The theoretical steady-state leachate collection efficiency for composite bottom liners with an intact FML component is high and remains high even when the FML has several "standard" defects.

- The theoretical steady-state leakage out of a unit with a composite bottom liner having an intact FML is much less than 1 Ltd (gpad). Just as important, the leakage out of the unit remains less than 1 Ltd (gpad) even when the FML has several "standard" defects.

With respect to breakthrough time, the time to breakthrough a composite bottom liner with an intact FML is very long. The time to breakthrough a composite liner with a FML component having macroscopic defects will not be much different than that for a compacted soil liner alone. However, the quantity of leakage associated with breakthrough of the composite will be at least several orders of magnitude less than the quantity of leakage associated with breakthrough a compacted soil liner. Since the quantity of leakage associated with breakthrough of a composite is very small, the use of breakthrough time as a lining system performance criterion becomes unnecessary.

4.5 PERFORMANCE OF COMPOSITE LINERS - 2-D TRANSIENT ANALYSIS

4.5.1 Introduction

The evaluation of composite bottom liner performance in the previous section was limited to one dimensional, steady-state saturated conditions. Two-dimensional transient analyses of partially saturated flow has been carried out by Radian Corporation, Austin, TX, using the UNSAT2D finite element computer program [Radian, 1987]. The Radian evaluation is an extension of their work on compacted soil bottom liners, presented previously in Chapter 3. Details of the UNSAT2D computer program can be found in Chapter 3. Detailed results from the Radian numerical simulations are presented in Appendix C.

An overview of the analysis and results obtained are presented in Section 4.5.2. Leak detection sensitivity of composite bottom liners is discussed in Section 4.5.3. Leachate collection efficiency of composite liners is discussed in Section 4.5.4. Leakage into and through composite bottom liners is reviewed in Section 4.5.5.

4.5.2 Overview of Analysis and Results

The basic lining system analyzed using UNSAT2D was reviewed in Section 3.6.2.2 and is not repeated. The only addition to the simulations carried out for compacted soil liners is a thin, very low-permeability layer with zero liquid storage capacity. This thin layer is placed over the compacted soil bottom liner to simulate the FML component of a composite bottom liner. In the UNSAT2D simulations, the migration of liquid across this very thin layer is described by the FML leakance, L, which has units of s^{-1}. The velocity of liquid migration across the membrane is equal to the leakance of the FML multiplied by the hydraulic head differential across the FML. In a double-liner system, the hydraulic head on top of the bottom liner is almost always very small. However, in the UNSAT2D simulations the capillary suctions acting on the bottom of the FML component of the bottom liner is significant. In these simulations, this capillary suction is equivalent to a hydraulic head of 3.4 m (11.1 ft) acting on the FML. To counteract the effect of the large hydraulic gradient set up in the numerical simulations by the action of capillary suction pulling water through the FML, a very low leakance value was selected by Radian. In UNSAT2D simulations, a leakance of 7×10^{-14} s^{-1} was selected to be used with a compacted soil capillary suction of 3.4 m (11.1 ft) of negative head. These values correspond almost exactly to a 1-mm (40-mil) thick FML with $k_g = 1 \times 10^{-14}$ m/s (1×10^{-12} cm/s) subjected to a hydraulic head of 30 mm (0.1 ft). Radian also carried out simulations with a FML leakance of 3×10^{-11} s^{-1}. This leakance is 430 times larger than the one for an "intact" FML and can be considered to approximately represent an FML bottom liner that has undergone "significant" deterioration. Finally, Radian carried out several numerical simulations with an intermediate leakance value, $L = 3 \times 10^{-12}$ s^{-1}, that has undergone "some" deterioration.

The analysis of composite bottom liners is more limited in scope than the analysis of compacted soil liners presented in Chapter 3. The parameters which were varied were leakage rate, leak location, and rate of permeation of the bottom liner. Four different combinations of the above parameters were analyzed, and the parameters and results are summarized in Table 4-6.

4.5.3 Leak Detection Sensitivity

Leak detection sensitivities estimated from numerical simulations using UNSAT2D are presented in Table 4-5. The detection sensitivity for leakance, $L = 7 \times 10^{-14}\ s^{-1}$, and a hydraulic gradient of one is estimated to be about 0.001 Ltd (gpad). This value of detection sensitivity is very good. In fact the bottom liner leakage rates associated with this detection sensitivity are so small that no collection system is sensitive enough to detect this level of leakage. Table 4-5 also shows the leak detection sensitivity of a FML with L = $3 \times 10^{-11}\ s^{-1}$. This sensitivity can be interpreted as being one associated with an FML that has undergone extensive deterioration over much of its area. The detection sensitivity for this case is on the order of 0.4 Ltd (gpad). From this, it can be observed that the leak detection sensitivity of a composite bottom liner with an FML component that has undergone some degree of deterioration is still good.

4.5.4 Leachate Collection Efficiency

The steady-state leachate collection efficiency results obtained from the UNSAT2D numerical simulations are shown in Table 4-5. It can be seen that for an intact FML with $L = 7 \times 10^{-14}\ s^{-1}$ the steady-state leachate collection efficiency is very high for top liner leakage rates of 60 Ltd (gpad). From Table 4-5, it can be deduced that even for a very small top liner leakage rate of 1 Ltd (gpad), the steady-state leachate collection efficiency is about 98%. It can also be seen that as the FML leakance increases, the steady-state collection efficiency decreases. For instance, for a FML leakance of $L = 3 \times 10^{-11}\ s^{-1}$, the steady-state collection efficiency will be about 50% for top liner leakage rates of about 15 Ltd (gpad). Figure 4-4 shows the generalized relationship between steady-state collection efficiency, rate of uniform top liner leakage and FML leakance derived from the results of the UNSAT2D numerical simulations performed by Radian.

4.5.5 Leakage Out of the Unit

The computer program UNSAT2D was used to obtain results for leakage into the bottom liner for several different FML likenesses and rates of uniform top liner leakage. These results are shown in Table 4-6. For the most part, leakage into the bottom liner is close to but slightly larger than leakage out of the unit. The difference between leakage into and leakage out of the bottom liner is due to the fact that some of the liquid that migrates into the bottom liner remains held in the pore space of the bottom liner by capillary suction.

Table 4-6 shows that the steady-state leakage into the bottom liner is very small for a composite bottom liner having an intact FML with $L = 7 \times 10^{-14}\ s^{-1}$. Even for an FML with a "relatively high" leakance of $3 \times 10^{-12}\ s^{-1}$, leakage into the bottom liner is only on the order of 1 Ltd (gpad). Figure 4-5 shows the relationship between cumulative leakage into the bottom liner FML leakance and time. For comparative purposes the cumulative leakage into a compacted soil liner with $k_C = 1 \times 10^{-7}$ cm/s is also shown in Figure 4-5.

4.6 COMPARISON OF RESULTS OBTAINED FROM ANALYTICAL AND NUMERICAL MODELS

A comparison of the results obtained using the one-dimensional steady-state analytical model and the two-dimensional transient numerical model (UNSAT2D) is presented in this section. The analytical results were presented in Section 4.4 and the numerical results can be found in Section 4.5.

The numerical results indicate a leak detection sensitivity on the order of 0.001 Ltd (gpad) for a composite liner with an intact FML (leakance equal to $7 \times 10^{-14}\ s^{-1}$). The analytical calculations resulted in a leak detection sensitivity of about 0.001 Ltd (gpad) for an FML with an "equivalent hydraulic conductivity" $k_C = 1 \times 10^{-12}$ cm/s. The numerical and analytical results are therefore consistent.

Leachate collection efficiencies for an LDCRS underlain by an intact FML can be estimated from Tables 4-4 and 4-6 for top liner leakage rates of 1 Ltd (gpad) and 10 Ltd (gpad). For the comparison presented below, the FML thickness is assumed to be 1.0 mm (40 mils) and the "equivalent hydraulic conductivity", k_C, is assumed to be 1×10^{-12} cm/s ($L = 7 \times 10^{-14}\ s^{-1}$):

Model	Collection Efficiency (%) 1 Ltd (gpad)	Collection Efficiency (%) 10 Ltd (gpad)
analytical	98%	99.8%
numerical	98%	99.8%

The analytical calculations using an FML with 2 "standard" defects can be compared to the numerical simulations using a leakance of $L = 3 \times 10^{-12}\ s^{-1}$. Comparison of the steady-state leachate collection efficiencies (assuming $k_c = 1 \times 10^{-7}$ cm/s) are shown below:

Model	Collection Efficiency (%) 1 Ltd (gpad)	Collection Efficiency (%) 10 Ltd (gpad)
analytical	80%	98%
numerical	10%	91%

The above comparisons are very consistent for the case of intact FMLs. In fact, the results for the "defective" FMLs also compare favorably, considering the differences in assumptions between the analytical and numerical models. The results show that the numerical simulations using a FML with a leakance of $L = 3 \times 10^{-12}\ s^{-1}$ result in collection efficiencies somewhat less than those from the analytical calculations using a FML with 2 "standard" defects.

The steady-state leakage into (or out of) a composite bottom liner with an intact FML can be estimated from Tables 4-3 and 4-6 and the following assumptions: $k_g = 1 \times 10^{-12}$ cm/s, $L = 7 \times 10^{-14}\ s^{-1}$, $k_c = 1 \times 10^{-12}$ cm/s, T = 1 mm (40 mils), and H = 1 m (3 ft). For these conditions:

Model	Leakage out of Unit Ltd (gpad)
analytical	0.02
numerical	0.02

Below, the analytical calculations using a FML with 2 "standard" defects are again compared to the numerical simulations using a leakance, $L = 3 \times 10^{-12}\ s^{-1}$. The following comparisons are for steady-state leakage out of the unit:

Model	Leakage out of Unit Ltd (gpad)
analytical	0.2
numerical	0.9

The comparisons again show good consistency between the analytical and numerical approaches.

4.7 SUMMARY AND CONCLUSIONS

In Chapter 4 the performance of composite liners was evaluated. It was shown that leakage can result from liquid migration through an intact FML and from flow through FML holes. Analytical procedures for calculating liquid migration through an intact FML and leakage due to holes were summarized from a detailed presentation of these subjects in Appendix B. It was found that leakage through holes is much larger than leakage due to liquid migration through an intact FML. It was also shown that a properly installed FML with good construction quality assurance monitoring should have not more than 3 to 5 defects (holes) per hectare (1 to 2 per acre), and possibly less. It was shown that leakage through a composite bottom liner with this number of FML defects is not large.

The analytical procedure presented and the observations regarding defects were used to evaluate the performance of composite bottom liners. The evaluation showed that a LDCRS underlain by composite liner containing two standard defects per acre and subjected to a conservative 30 mm (0.1 ft) hydraulic head can be used to detect leaks much smaller than 1 Ltd (gpad). In addition, a LDCRS underlain by a composite liner can collect almost all of the liquid leaking through the top liner and can limit the rate of leakage out of the unit to less (and possibly much less) than 1 Ltd (gpad). This level of performance is considered to be very good.

The results of numerical simulations of composite bottom liner performance were also presented. These simulations were carried out using the 2-D finite element computer program UNSAT2D. The simulations are valuable because they can account for the operation of the entire unit, from start-up through the post-closure care period. They are also useful because they account for the effects of partial saturation of the soil components of the lining system. The results obtained from UNSAT2D were used to evaluate leak detection time, leachate collection efficiency and leakage out of the unit for lining systems with composite bottom liners. The results obtained from this evaluation were shown to be very consistent with the results obtained from the simpler 1-D steady-state analytical calculations. Taken together, the analytical and numerical analyses provide a consistent evaluation of composite bottom liner performance.

Table 4-1. Summary of FML Polymers used to manufacture FMLs.

CATEGORY	POLYMER	SYMBOL[a]
Thermoplastics	Polyvinyl Chloride	PVC
	Oil-resistant PVC	OR-PVC
	Thermoplastic Nitrile-PVC	TN-PVC
	Ethylene Interpolymer Alloy	EIA
Crystalline Thermoplastics	Low Density Polyethylene	LDPE
	High Density Polyethylene	HDPE
	High Density Polyethylene-Alloy	HDPE-A
	Polypropylene	-
	Elasticized Polyolefin	-
Thermoplastic Elastomers	Chlorinated Polyethylene	CPE
	Chlorinated Polyethylene-Alloy	CPE-A
	Chlorosulfonated Polyethylene ("Hypalon")	CSPE
	Thermoplastic Ethylene-Propylene Diene Monomer	T-EPDM
Elastomers	Isoprene-Isobutylene Rubber ("Butyl Rubber")	IIR
	Ethylene-Propylene Diene Monomer	EPDM
	Polycholoroprene ("Neoprene")	CR
	Epichlorohydrin Rubber	CO

[a] symbols used by the National Sanitation Foundation (NSF) Joint Committee on Flexible Membrane Liners (FML))

Note: Polymers are usually compounded with various additives such as fillers, fibers, carbon black, plasticizers, stabilizers, antioxidants, fungicides, and other polymers. These additives perform various functions without altering the very low permeability of the base product.

Table 4-2. Leakage rates through composite liners. Leakage due to permeation is obtained from Table B-6 (rounding up the figures) and leakage due to holes is obtained from Figure 4-1, as a function of the quality of contact between the FML component and the compacted soil component of the composite liner. This table has been established with: hole area = 1 cm^2 (0.16 in^2.); compacted soil thickness = 0.9 m (3 ft); FML thickness = 1 mm (40 mils); and frequency of holes = 1 per 4000 m^2 (1 per acre).

		Low-Permeability Compacted Soil Hydraulic Conductivity, k_C	
Quality of contact	Leakage mechanism	10^{-8} m/s (10^{-6} cm/s)	10^{-9} m/s (10^{-7} cm/s)
Good	Permeation	0.001	0.001
	Hole	0.2	0.02
	TOTAL	0.2	0.02
Poor	Permeation	0.001	0.001
	Hole	1	0.1
	TOTAL	1	0.1
		Values of leakage rate in Ltd or gpad	

Table 4-3. Performance of an intact FML (Note: Analysis assumes 1-D steady-state saturated flow).

	$k_g = 10^{-14}$ m/s (10^{-12} cm/s)				$k_g = 10^{-13}$ m/s (10^{-11} cm/s)			
	$k_c = 10^{-8}$ m/s (10^{-6} cm/s)		$k_c = 10^{-9}$ m/s (10^{-7} cm/s)		$k_c = 10^{-8}$ m/s (10^{-6} cm/s)		$k_c = 10^{-9}$ m/s (10^{-7} cm/s)	
	1 mm[b] (40 mil)	2 mm (80 mil)	1 mm (40 mil)	2 mm (80 mil)	1 mm (40 mil)	2 mm (80 mil)	1 mm (40 mil)	2 mm (80 mil)
Detection Sensitivity Ltd (gpad)	0.001	0.001	0.001	0.001	0.01	0.01	0.01	0.01
Steady-State Collection Efficiency, %[a]	98	99	98	99	80	90	80	90
Steady-State Leakage Out of Unit Ltd (gpad)	0.02	0.01	0.02	0.01	0.2	0.1	0.2	0.1

a - leakage rate through top liner assumed to be 1 Ltd (gpad) for collection efficiency calculation;

b - numbers refer to FML thickness.

Table 4-4. Performance of a composite liner with a single "standard" defect in the upper FML component.[a] (Note: This table assumes zero liquid migration through intact portions of FML. Analysis assumes 1-D steady-state flow.)

	$k_c = 10^{-8}$ m/s (10^{-6} cm/s)	$k_c = 10^{-9}$ m/s (10^{-7} cm/s)
Leak Detection[b, c] Sensitivity Ltd (gpad)	0.01	0.01
Steady-State Collection[c, d] Efficiency, %	95	99.5
Steady-State Leakage Out of Unit Ltd (gpad)	4 (1)	0.4 (0.1)

a - hole area = 1 cm^2 (10^{-4} or 0.16 in^2) and hydraulic head on composite liner = 30 mm (0.1 ft);

b - $k_g = 10^{-13}$ m/s (10^{-11} cm/s);

c - one hole per acre;

d - leakage rate through top liner assumed to be 20 Ltd (gpad) for collection efficiency calculation.

Table 4-5. Performance of composite bottom liners with 2 "standard" FML defects per acre. (Note: This table includes liquid migration due to FML permeation (Table 4-3). Analysis assumes 1-D steady-state flow.)

	$k_g = 10^{-14}$ m/s (10^{-12} cm/s)				$k_g = 10^{-13}$ m/s (10^{-11} cm/s)			
	$k_c = 10^{-6}$ cm/s		$k_c = 10^{-7}$ cm/s		$k_c = 10^{-6}$ cm/s		$k_c = 10^{-7}$ cm/s	
	1 mm[c] (40 mil)	2 mm (80 mil)	1 mm (40 mil)	2 mm (80 mil)	1 mm (40 mil)	2 mm (80 mil)	1 mm (40 mil)	2 mm (80 mil)
Leak Detection Sensitivity Ltd (gpad)	0.001	0.001	0.001	0.001	0.01	0.01	0.01	0.01
Steady-state Collection Efficiency, %[b]	90	90	99	99	89	89	98	98
Steady-state Leakage Out of Unit Ltd (gpad)	2.0	2.0	0.2	0.2	2.2	2.1	0.4	0.3

a - hole area = 1 cm^2 (10^{-4} m^2 or 0.16 in^2) and hydraulic head on composite liner = 30 mm (0.1 ft);

b - leakage rate through top liner = 20 Ltd (gpad);

c - numbers refer to FML thickness.

Table 4-6. Performance of composite bottom liners based on results of UNSAT2D numerical simulations carried out by Radian. (Note: $L = 7 \times 10^{-14}\ s^{-1}$ corresponds to an intact FML; $L = 3 \times 10^{-11}\ s^{-1}$ corresponds to a highly deteriorated FML).

	$L = 7 \times 10^{-14}\ s^{-1}$		$L = 3 \times 10^{-12}\ s^{-1}$		$L = 3 \times 10^{-11}\ s^{-1}$	
	Q = 780 Ltd (gpad)	Q = 60 Ltd (gpad)	Q = 1240 Ltd (gpad)	90 Ltd (gpad)	Q = 780 Ltd (gpad)	90 Ltd (gpad)
Leak Detection Sensitivity Ltd (gpad)	.001[a]	. 001	.04	.04	0.4	0.4
Steady - state Collection Efficiency (%)	100	99.9	99.9	99	99	92
Steady - state Leakage Into Bottom Liner Ltd (gpad)	0.02	0.02	0.9	0.9	7.6	7.6

Notes: a - leak detection sensitivity results are estimated rather than calculated values.

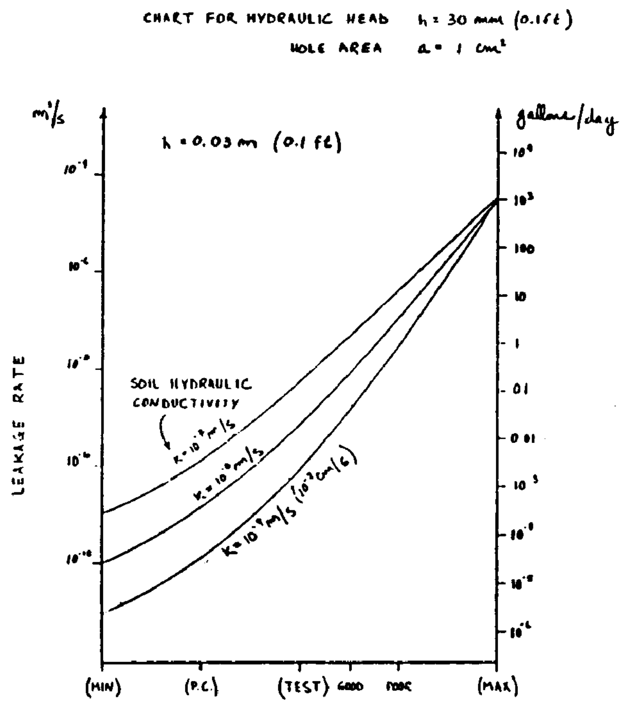


Figure 4-1. Graph giving the leakage rate and the radius of the soil wetted area for the case of leakage through a FML hole. The hydraulic head is 30 mm (0.1 ft) and the hole area is 1 cm² (i.e., diameter of 11.3 mm). Because of uncertainties in the analytical analyses as well as the large influence of soil conditions and contact between the FML and the soil, only a range of values can be given. Field conditions can be anywhere between the two extremes: (1) best, i.e., the soil is well compacted, flat and smooth, has not been deformed by rutting during construction, and has no clods and cracks, and the FML is flexible and has no wrinkles; and (2) the soil is poorly compacted, has an irregular surface and is cracked, and the FML is stiff and exhibits a pattern of large, connected wrinkles.

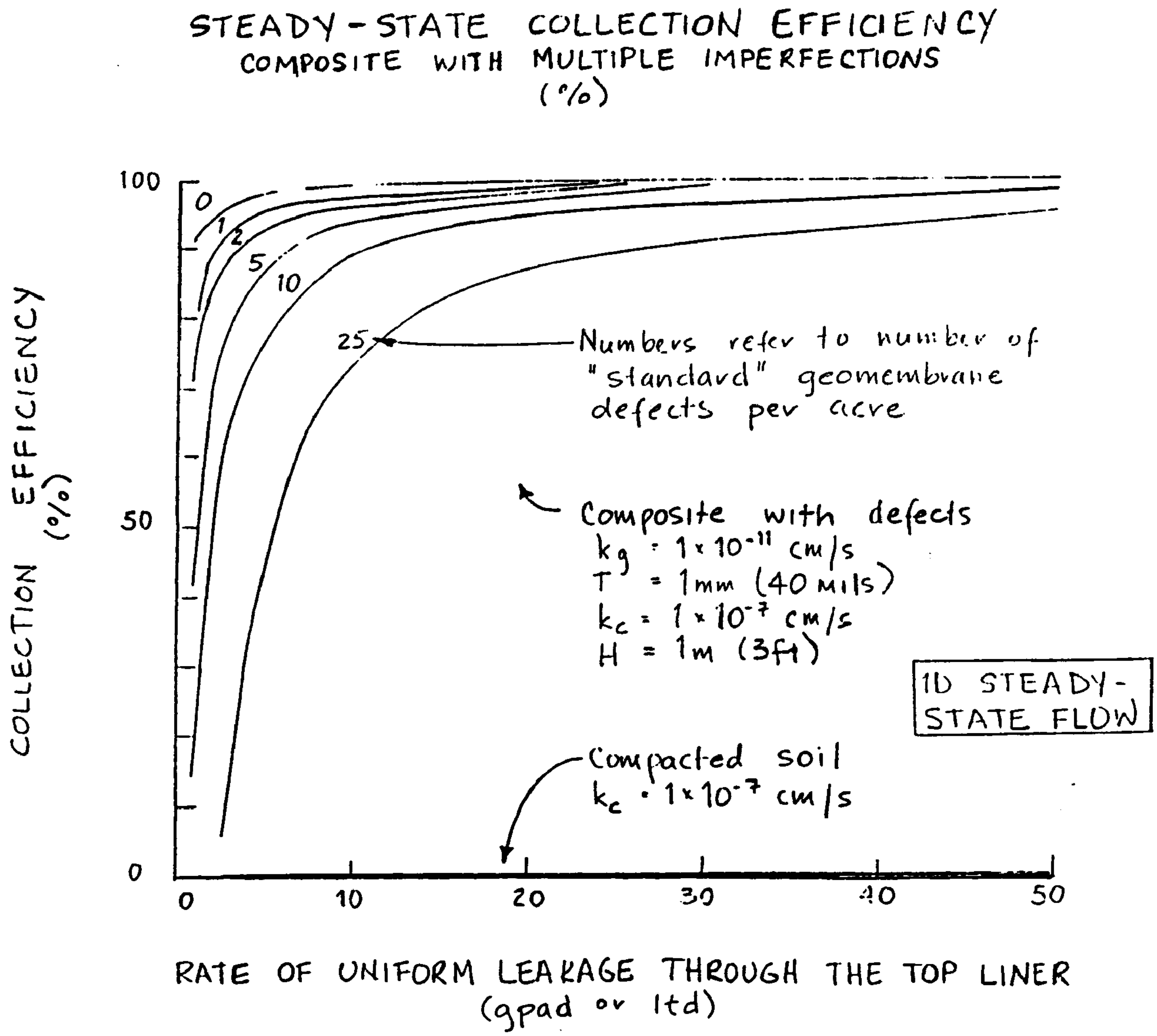


Figure 4-2. Steady-state leachate collection efficiency of a composite liner with multiple imperfections.

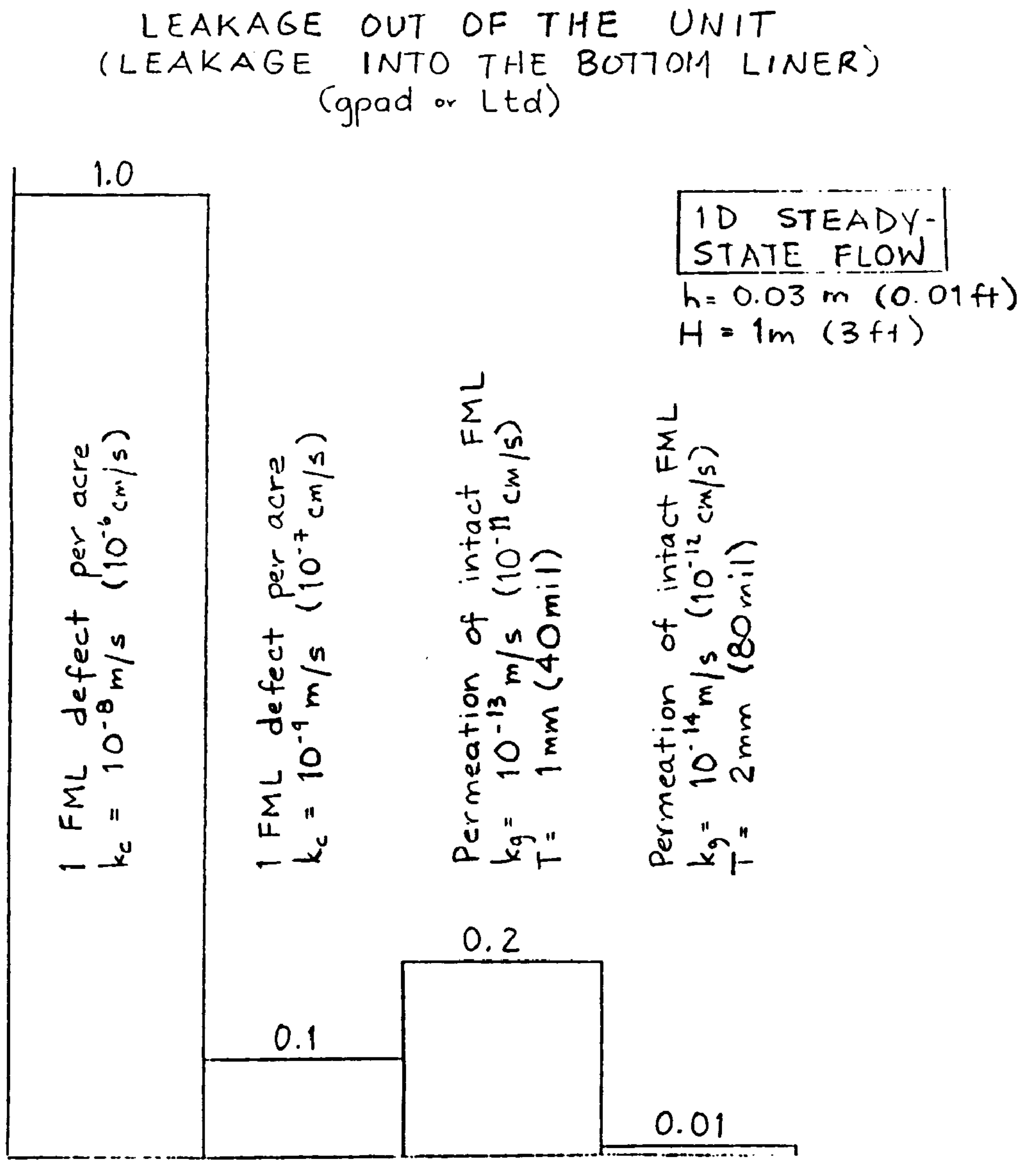


Figure 4-3. Comparison of the amount of leakage through the FML component of a composite liner due to one "standard" FML defect and due to permeation of an intact FML. [Note: This comparison is based on several conservative assumptions: h = 30 mm (0.1 ft); $k_g = 10^{-13}$ m/s (10^{-11} cm/s) or $k_g = 10^{-10}$ m/s (10^{-12} cm/s) and the quality of contact between the FML and compacted soil is poor.]

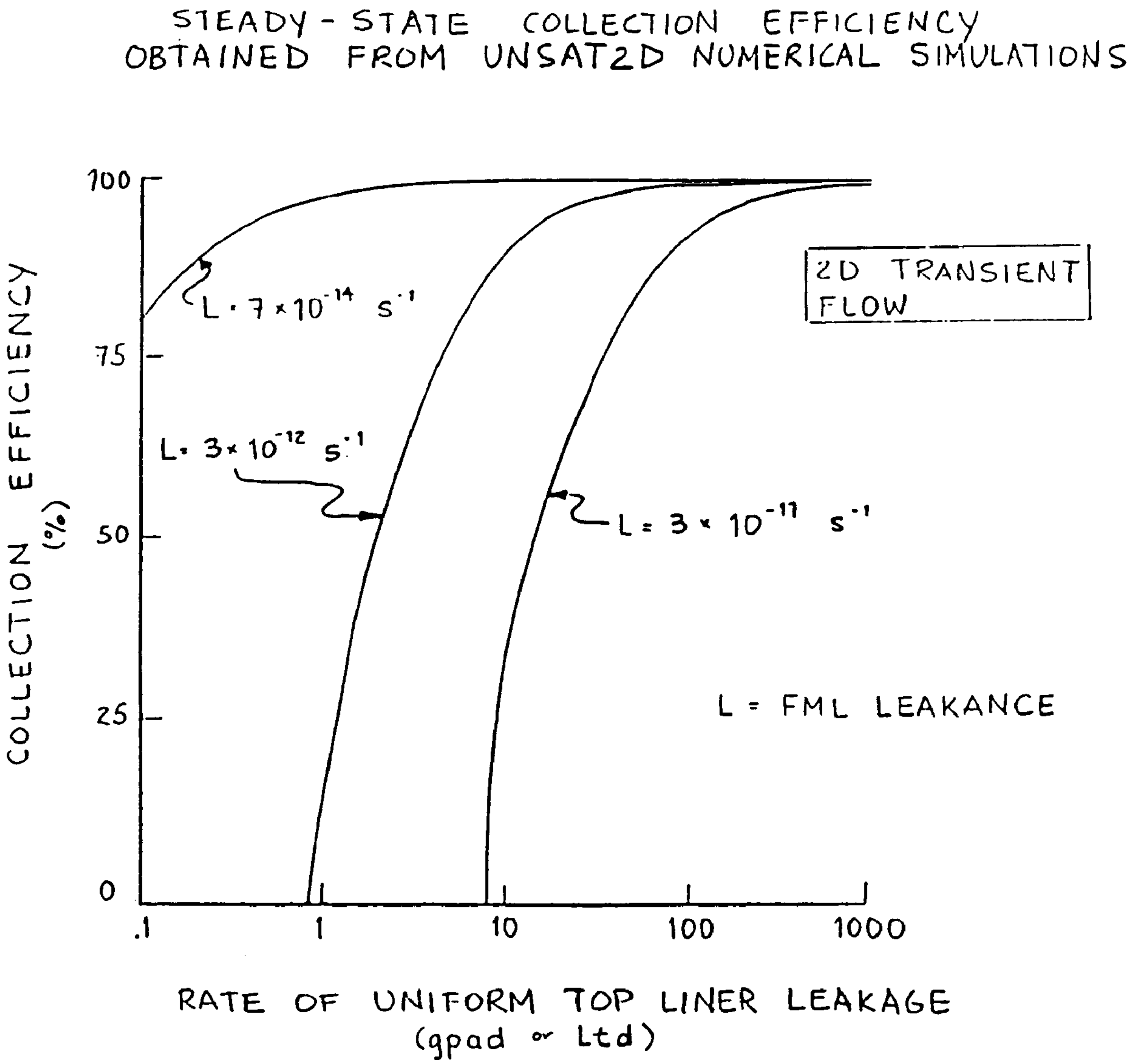


Figure 4-4. Comparison of steady-state leachate collection efficiencies of LDCRS with composite bottom liners of various leakances. [Data from Radian, 1987]

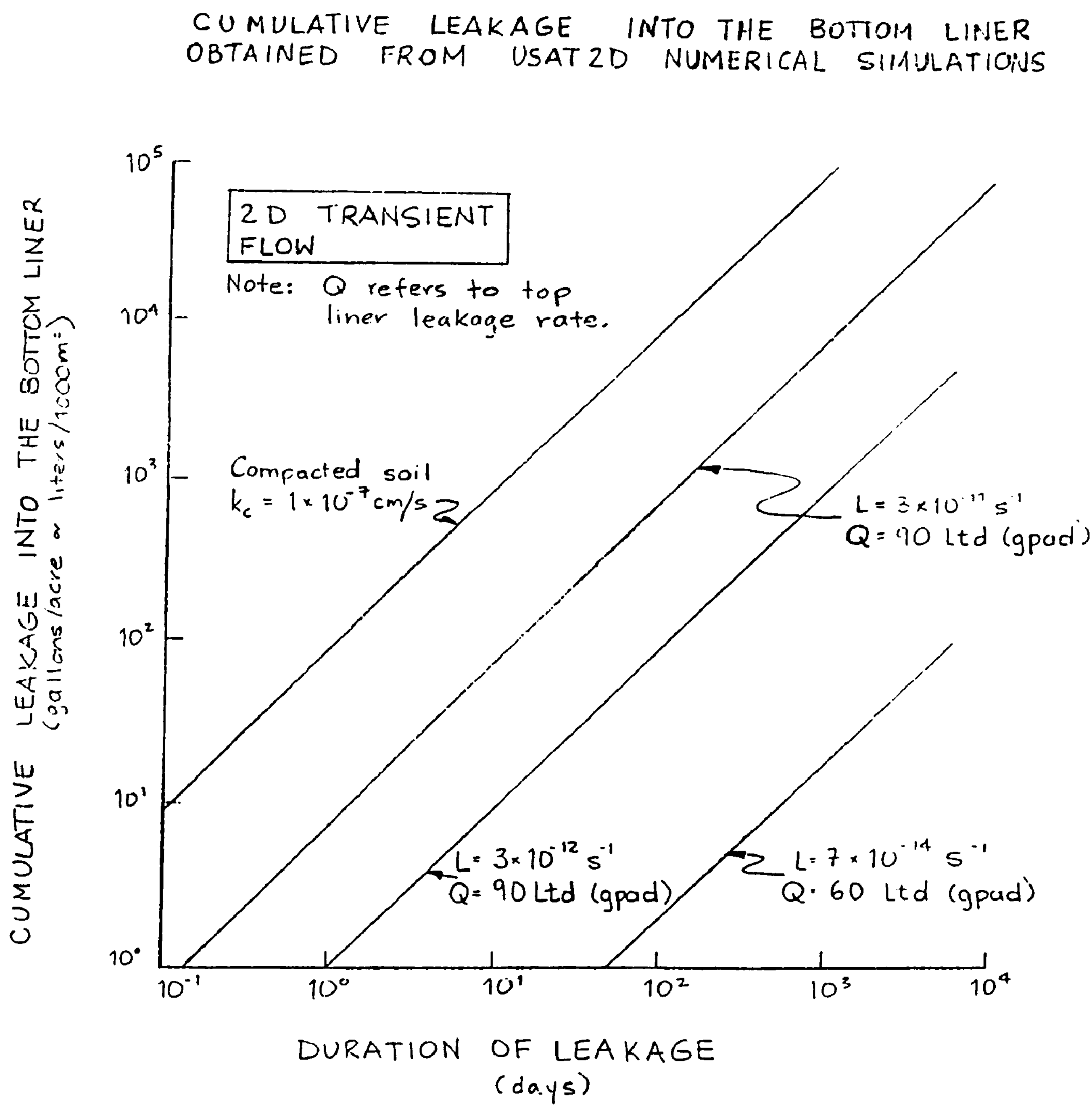


Figure 4-5. Cumulative leakage into the bottom liner for different FML leakances and for a rate of top liner leakage, Q, in the range of 100 Ltd (gpad). [Data from Radian, 1987]

CHAPTER 5

COMPARISON OF COMPACTED SOIL AND COMPOSITE BOTTOM LINER PERFORMANCE

5.1 INTRODUCTION

5.1.1 Purpose

The purpose of this chapter is to summarize and compare the performance of compacted soil and composite bottom liners. This comparison is presented in terms of the system performance criteria which are believed to be most critical to meeting EPA's goals of preventing migration of hazardous constituents from landfill and surface impoundment units to the extent technically feasible. These criteria are:

- leak detection sensitivity of the LDCRS;
- leachate collection efficiency of the LDCRS; and
- leakage into the bottom liner and out of the unit.

5.1.2 Organization of this Chapter

The remainder of this chapter is comprised of four sections organized as follows:

- Section 5.2 presents data on leak detection sensitivity. Specifically, this section compares the sensitivity of equivalent LDCRS having either compacted soil or composite bottom liner systems.
- Section 5.3 presents data on leachate collection efficiency. Specifically, this section compares the collection efficiency of equivalent LDCRS having either compacted soil or composite bottom liner systems. Comparisons are made in terms of both steady-state and cumulative collection efficiencies.
- Section 5.4 presents data on total leakage into the bottom liner and out of the unit. Specifically, this section compares the steady-state and cumulative leakage out of equivalent waste management units having either compacted soil or composite bottom liner systems.

• Section 5.5 presents a summary of comparisons and draws conclusions.

5.1.3 Comments on Data

The data presented in this chapter were developed from studies, literature reviews, field reviews and calculations which were presented in Chapter 3 for compacted soil bottom liners and Chapter 4 for composite bottom liners. The reader is encouraged to study Chapters 3 and 4 so as to better understand the comparisons presented in this chapter.

The numerical data presented in this chapter were developed from calculations assuming either one-dimensional, saturated steady-state flow or two-dimensional transient flow. In Chapter 3 it was shown that one-dimensional saturated steady-state analysis results are in good agreement with results obtained from more detailed calculations assuming one-dimensional transient flow through partially saturated soils (using the SOILINER computer model) and two-dimensional transient flow through partially saturated soils (using data from Radian obtained with the UNSAT2D computer model). In Chapter 4 it was shown that the one-dimensional saturated steady-state analysis gives results which are very consistent with those obtained from the two-dimensional partially saturated transient analysis (UNSAT2D).

The one-dimensional steady-state analyses presented in this report are appropriate for investigating the leakage through a section of bottom liner due to an overlying hydraulic head. This type of analysis is not appropriate to evaluate overall facility performance (which includes modeling: (i) the entire lining system; (ii) time from the start of a unit's active life through the post-closure care period; and (iii) the time-dependent unit boundary conditions). For this, a two-dimensional (and ideally three-dimensional) model which can account for time dependence is needed. The UNSAT2D model fits into this category. It can be used to compare the performance of equivalent facilities subject to equal top liner leakage rates and having either compacted soil or composite bottom liners.

5.1.4 Presentation of Data

For the sake of clarity of presentation, the data presented in this chapter is primarily in the form of simple bar charts comparing leak detection sensitivity, leachate collection efficiency and total leakage out of the unit for compacted soil and composite bottom liners. These bars charts were derived from more detailed data tables and graphs presented in Chapters 3 and 4.

Table 5-1 presents a summary of bottom liner dimensions and properties used to generate the bar charts for one-dimensional, saturated steady-state leakage analysis presented in this chapter.

5.2 LEAK DETECTION SENSITIVITY

5.2.1 Definition and Importance

The leak detection sensitivity is the smallest leakage rate through the top liner (E in Figure 2-4) that can be detected in the LDCRS sump within a reasonable period of time. The RCRA amendments of November 1984 create a statutory requirement for leak detection systems at hazardous waste management units. A small detection sensitivity standard, based on BDAT for leachate collection and removal systems, is an important feature of leak detection capability. It ensures that the owner or operator will have the ability to monitor his unit for even very small rates of leakage through the top liner. Detection of small rates of leakage is important to ensure they are collected. Detecting small rates of leakage is also crucial for compliance with the statutory requirement to detect leakage at the earliest practicable time.

5.2.2 Comparison of Compacted Soil and Composite Bottom Liners

Figure 5-1 compares the "steady-state" leak detection sensitivity of compacted soil and composite bottom liners. It was shown in Chapters 3 and 4 that steady-state, saturated analyses and transient, partially saturated analyses provide comparable detection sensitivities. It can be seen that the detection sensitivity of an LDCRS underlain by a 3 ft (1 m) thick layer of compacted soil with a hydraulic conductivity of 1 x 10^{-7} cm/s is about 86 gallons per acre per day (gpad) or liters per 1000 m^2 per day (Ltd). In other words, based on the one-dimensional steady-state analysis, a uniform top liner leakage rate smaller than 86 Ltd (gpad) would never be collected.

In reality, a concentrated top liner leak smaller than 86 Ltd (gpad) may be detected because the wetted area associated with a concentrated leak will be just a portion of the bottom liner surface area. However, establishing a detection sensitivity criterion based on an assumed uniform leak is entirely acceptable.

From Figure 5-1 it can be seen that an LDCRS with a composite bottom liner can theoretically detect leakage rates 10,000 to 100,000 times smaller than a compacted soil bottom liner. This difference in detection capability is dramatic. The magnitude of the difference may be better illustrated on a logarithmic scale, as shown in Figure 5-2. In fact, the detection sensitivity associated with a composite bottom liner exceeds the practical capabilities of typical liquids removal systems (sumps and pumps) to collect and remove the leakage. It is further noted that a few small "standard defects" (see Table 5-1) have a negligible influence on the leak detection sensitivity of a composite bottom liner.

Figure 5-1 also shows that hydraulic conductivity has a significant influence on the detection sensitivity of LDCRS with compacted soil bottom liners. This figure clearly demonstrates the importance of achieving specified soil hydraulic conductivities in the field.

5.3 LEACHATE COLLECTION EFFICIENCY

5.3.1 Definition and Importance

The leachate collection efficiency is the ratio of the leachate collected in the LDCRS sump (G in Figure 2-4) divided by the leakage entering the LDCRS through the top liner (E in Figure 2-4). There are two measures of leachate collection efficiency: (i) cumulative leachate collection efficiency which is based on the total leakage entering the LDCRS from the beginning of a unit's active life to any other point in time; and (ii) the steady-state leachate collection efficiency at any point in time. The cumulative leachate collection efficiency is smaller than the steady-state leachate collection efficiency because the cumulative efficiency considers the leakage held in the LDCRS drainage media by capillary tension as uncollected leakage.

Leachate collection efficiency is a very important concept in EPA's liquids management strategy for protecting human health and the environment. This strategy for management of land disposal units (except land treatment units) has two parts: (i) minimize leachate generation in the waste management unit; and (ii) maximize collection and removal of leachate from the unit at the earliest practicable time. Clearly, a high leachate collection efficiency is a prerequisite for meeting the second part of EPA's liquids management strategy. Without a high collection efficiency, leachate collection and removal cannot be maximized.

5.3.2 Comparison of Compacted Soil and Composite Bottom Liners

The steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners are compared in Figure 5-3. This comparison has been made for an FML with an "equivalent hydraulic conductivity", $k_g = 1 \times 10^{-11}$ cm/s. (This value represents a very conservative upper bound of "equivalent hydraulic conductivities" for FML liners. As was shown in Table 4-2, the "equivalent hydraulic conductivities" of most FMLs will be at least an order of magnitude smaller than the value used to generate Figure 5-3.) It can be seen that the collection efficiency for an LDCRS with a compacted soil bottom liner is zero until the rate of uniform leakage exceeds the leak detection sensitivity. In contrast, the collection efficiency of a LDCRS with an intact composite bottom liner is very high, even for top liner leakage rates as low as 1 Ltd (gpad).

Figure 5-3 also shows the effect of a small hole ("standard defect") in the FML component of a composite bottom liner. It was shown in Chapter 4 and Appendix B that one small defect per acre is probably a reasonable, conservative assumption for a well designed and constructed facility with a good construction quality assurance program. This small defect is assumed to be square with a side dimension of 0.4 in (10 mm). Figure 5-3 shows that the effect of one "standard defect" on collection efficiency is small, even at top liner rates of uniform leakage of 1 Ltd (gpad). Figure 5-3 also shows the effect of a composite bottom liner with one standard defect in the FML and with a compacted soil component hydraulic conductivity of 1 x 10^{-6} cm/s. This case represents a composite liner having an FML component with a defect and a compacted soil component that does not meet specification. Under this set of "problem" conditions, the leak detection sensitivity of the LDCRS reduces to 1 gpad (which is still almost 1000 times greater than the leak detection sensitivity of the compacted soil alone). It is also clear from Figure 5-3 that the leachate collection efficiency for compacted soil liners increase rapidly once the rate of leakage exceeds the liner's leak detection sensitivity. At a top liner leakage rate of 100 Ltd (gpad), the collection efficiency for a compacted soil liner with $k_c = 1 \times 10^{-7}$ cm/s in all areas is only 11%. At a top liner leakage rate of 1000 Ltd (gpad), however, the collection efficiency has increased to 91%. EPA believes that most leaks will be in the range of 100 Ltd (gpad) or less.

Figure 5-4 compares the leachate collection efficiencies of composite liners with varying numbers of FML "standard defects". It can be seen that even with 25 "standard defects" per acre (which is an unrealistically high number for a unit with good CQA), the leachate collection efficiency of the LDCRS is very good and is far better than those for the compacted soil bottom liners shown in Figure 5-3. This result is significant and shows that even a very poorly installed composite liner provides a system with a much higher collection efficiency than provided by a compacted soil bottom liner with $k_c = 1 \times 10^{-7}$ cm/s in all areas.

Figure 5-5, 5-6, and 5-7 present bar charts comparing the leakage collection efficiencies (based on the 1D steady-state analysis) of LDCRS with various types of bottom liners. These charts are included for completeness and clarity of presentation.

Figure 5-8 presents the steady-state leachate collection efficiencies obtained from waste management unit simulations using the two-dimensional numerical model UNSAT2D. Figure 5-8 corresponds to a top liner uniform leakage rate of about 1000 Ltd (gpad). Figure 5-8 is similar to Figure 5-7 (1D steady-state analysis) as they both compare the performance of LDCRS at top liner rates of uniform leakage of 1000 Ltd (gpad). The following comparisons are made:

	Leachate collection efficiency	
	1D steady-state	2D transient
Composite (intact)	> 99.9	> 99.9
Compacted soil ($k_c = 1 \times 10^{-7}$ cm/s)	91	78
Compacted soil ($k_c = 1 \times 10^{-6}$ cm/s)	11	10

Inspection of these results show that the 1D steady-state analysis and the 2D transient analysis give very consistent results for LDCRS leachate collection efficiencies. In both cases, the composite bottom liner provides a more efficient system than the compacted soil bottom liner with $k_c = 1 \times 10^{-7}$ cm/s, which in turn provides a significantly more efficient system than the compacted soil bottom liner with $k_c = 1 \times 10^{-6}$ cm/s.

The steady-state leachate collection efficiencies obtained from UNSAT2D and from the 1D analyses can be compared for top liner rates of uniform leakage in the 50 Ltd (gpad) range. When this is done, the following results are obtained:

	Leachate collection efficiency	
	1D steady-state	2D transient
Composite (intact)	> 99	> 99
Compacted soil ($k_c = 1 \times 10^{-7}$ cm/s)	0	0
Compacted soil ($k_c = 1 \times 10^{-6}$ cm/s)	0	0

Inspection of these results shows that at this rate of uniform top liner leakage, the compacted soil liners provide zero leachate collection efficiency, while the intact composite provides a very high collection efficiency. This difference is dramatic.

Figures 5-9 and 5-10 present cumulative leachate collection efficiencies from waste management unit simulations using UNSAT2D and a top liner rate of uniform leakage of about 1000 Ltd (gpad). It can be seen that the cumulative efficiency increases with time after unit start-up. The efficiency is low at the time of unit start-up since much of the initial leakage is held within the LDCRS by capillary tension. Depending on the leakage rate and the hydraulic conductivity of the LDCRS drainage media, the duration of this transient "wetting up" period can be significant. This period will be relatively short, however, for a large top liner leakage rate of 1000 Ltd (gpad). Once the "wetting-up" of the LDCRS is complete, the cumulative collection efficiency begins to approach the steady-state efficiency; the difference between the two is largely accounted for by the leakage stored in the LDCRS by capillary tension (as noted in Figures 5-9 and 5-10).

Figures 5-11 and 5-12 present collection efficiencies from waste management unit simulations using UNSAT2D and a top liner rate of leakage in the range of 50 Ltd (gpad). The leak type used in these numerical simulation is a sidewall leak. Figure 5-11 presents the steady-state collection efficiency 10 years after facility start-up. It can be seen that the compacted soil collection efficiency is zero, which is logical since the rate of leakage is below the detection sensitivity of the bottom liner. The steady-state collection efficiency associated with the intact composite bottom liner is in excess of 99%. The cumulative collection efficiencies after 10 years are shown in Figure 5-12. The collection efficiency for a LDCRS underlain by an intact FML is 95%. This efficiency is "relatively low" because, even after 10 years of unit operation, the LDCRS continues to entrap new leakage through capillary tension. Almost 5% of the liquid that has passed through the top liner is held in the LDCRS sand by capillary tension. In the UNSAT2D numerical simulations, the drainage media in the LDCRS is assumed to have a saturated hydraulic conductivity of 1 x 10^{-3} cm/s. This corresponds to an initial capillary tension of about 0.5 m (1.5 ft) of negative hydraulic head. Thus, there exists sufficient capillary tension to essentially saturate the entire LDCRS drainage media. For a 0.3 m (1 ft) thickness of sand with a porosity of 30%, the void space in the sand that is available to entrap leakage is approximately 100,000 gallons/acre. If this capillary tension is destroyed (either through the use of a more permeable drainage medium such as gravel or a synthetic drainage material), the leakage storage capacity of the

LDCRS would be dramatically reduced and the associated collection efficiencies would be increased.

Figures 5-11 and 5-12 are interesting because they show the effect of a major imperfection in the FML component of a bottom composite liner. These results from the UNSAT2D numerical simulations indicate a significant effect of a major bottom liner FML defect. The imperfection modeled in UNSAT2D consists of an approximately 3 m (10 ft) long bottom liner sidewall leak directly under a top liner sidewall leak. This represents a very major breach of the FML component of a composite bottom liner. The leak is simulated in the numerical model by increasing the hydraulic conductivity of the leaking portion of the FML.

5.4 LEAKAGE OUT OF WASTE MANAGEMENT UNIT

5.4.1 Definition and Importance

Leakage out of the unit refers to leakage that passes through the bottom liner into the ground (J in Figure 2-4). A related performance variable is leakage into the bottom liner (H in Figure 2-4).

Leakage out of the unit is a very important concept in EPA's liquids management strategy. As described in Section 5.3.1, one part of this strategy is to maximize leachate collection and removal from the unit. This can only be achieved if leakage out of the unit is minimized to the extent technically feasible. Further, EPA's goal for lining systems since promulgation of technical and permitting standards under Part 264 on July 26, 1982 (47 FR 32274) has been to prevent migration of wastes to the subsurface soil or ground water. While EPA recognizes that absolutely achieving this goal is not technically achievable at present, they believe that BDAT can come very close to preventing migration. The degree to which a lining system satisfies this goal is reflected by the leakage out of the unit.

5.4.2 Comparison of Compacted Soil and Composite Bottom Liners

Steady-state leakage out of the unit (or leakage into the bottom liner) for compacted soil and composite bottom liners with a 0.03 m

(0.1 ft) hydraulic head on the bottom liner are compared in Figure 5-13. This figure is based on one-dimensional, saturated steady-state analysis. A bottom liner hydraulic head of 0.03 m (0.1 ft) is believed to represent a worst case scenario. (Also, 0.03 m (0.1 ft) corresponds approximately to the capillary rise in a sand LDCRS drainage media with a hydraulic conductivity equal to about 1 cm/s.)

From Figure 5-13 it can be seen that an intact composite bottom liner with an "equivalent hydraulic conductivity" of the FML component of $k_g = 1 \times 10^{-12}$ cm/s permits almost 5,000 times less leakage out of a unit than a 1×10^{-7} cm/s compacted soil liner alone. Figure 5-14 indicates that increasing the thickness of the compacted soil has a negligible effect on the steady-state leakage out of the unit. Figure 5-15 is interesting because it shows total leakage out of the unit for composite liners having FMLs with defects. It can be seen that the leakage through a composite liner with $k_g = 1 \times 10^{-12}$ cm/s and $k_c = 1 \times 10^{-7}$ cm/s and with one "standard defect" per acre (which is believed to be conservative for a properly designed and constructed unit) is still on the order of one thousand times smaller than the leakage through a compacted soil liner with $k_c = 1 \times 10^{-7}$ cm/s in all areas. Even if the number of defects were increased to 10 (which might be considered to represent a "problem" site) leakage through the composite is on the order of 100 times smaller than leakage through the compacted soil.

Figure 5-16 compares cumulative leakage out of the unit for times up to 10 years, for units with compacted soil and composite bottom liners. Figure 5-17 presents the same information as Figure 5-16, but on a log-log plot and for a duration of leakage up to 27 years (10,000 days). The presentation of data in the format given in Figure 5-17 allows for the evaluation of cumulative leakage out of the unit, for any duration of leakage and for any type of bottom liner.

Figures 5-18 to 5-22 present comparative results on cumulative leakage into the bottom liner which were obtained using UNSAT2D numerical simulations. Figures 5-18 to 5-22 correspond to a top liner rate of uniform leakage on the order of 1000 Ltd (gpad). In these simulations, the leakage into the bottom liner associated with an intact composite liner is on the order of 5000 times smaller than that associated with a compacted soil liner with $k_c = 1 \times 10^{-7}$ cm/s.

Figures 5-21 and 5-22 present UNSAT2D simulations for a sidewall leak and a leakage rate of about 50 Ltd (gpad). These results from the UNSAT2D numerical simulations indicate a significant effect of a major bottom liner FML defect (i.e., a defect 3 m (10 ft) long). This represents a very major breach of the FML component of a composite bottom liner.

5.5 SUMMARY OF COMPARISONS

A summary is presented in Table 5-2 of the comparisons made using results from the one-dimensional steady-state analyses. These results are based on uniform leakage through the top liner, on a hydraulic head on the bottom liner equal to 0.3 m (0.01 ft), and on $k_c = 1 \times 10^{-7}$ cm/s and $k_g = 1 \times 10^{-12}$ cm/s. From this summary, the following observations are drawn regarding the performance criteria critical to establishing BDAT for LDCRS and bottom liner systems and fundamental to EPA's liquids management strategy.

- Leak detection sensitivity - The theoretical leak detection sensitivity of an LDCRS with a properly designed and constructed composite bottom liner is much less than one Ltd (gpad). A few "standard" FML defects have a negligible effect on the detection sensitivity of a lining system with a composite bottom liner. By comparison, the leak detection sensitivity of a compacted soil bottom liner is on the order of 100 Ltd (gpad) with $k_c = 1 \times 10^{-7}$ cm/s in all areas of the liner.

- Leachate collection efficiency - The theoretical steady-state leachate collection efficiency for composite bottom liners with intact FML is in excess of 99%, even for relatively low top liner leakage rates such as 20 Ltd (gpad). Just as important, the leachate collection efficiency remains high even when the FML component of a composite bottom liner has several "standard" defects (more defects than would be expected in a properly designed and constructed lining system). In contrast, the theoretical steady-state collection efficiency of a compacted soil bottom liner is zero for all rates of uniform top liner leakage up to approximately the leak detection sensitivity (on the order of 100 Ltd (gpad) for a compacted soil bottom liner with $k_c = 1 \times 10^{-7}$ cm/s, and on the order of 1000 Ltd (gpad) for a compacted low-permeability soil bottom liner with $k_c = 1 \times 10^{-6}$ cm/s).

- Leakage into the bottom liner and out of the unit - The theoretical steady-state leakage out of a unit with a composite bottom liner with an intact FML is much less than 1 Ltd (gpad). Just as important, the leakage out of the unit remains less than 1 Ltd (gpad) even when the FML component of a composite bottom liner has several "standard" defects (more defects than would be expected in a properly designed and constructed lining system). In contrast, for a uniform hydraulic head on the bottom liner of 0.03 m (0.1 ft), the leakage out of a unit with a compacted soil bottom liner and $k_c = 1 \times 10^{-7}$ cm/s in all areas of the liner is on the order of 100 Ltd (gpad).

TABLE 5-1. Bottom liner dimensions and properties for one-dimensional, saturated steady-state leakage analysis.

Compacted Soil

Thickness	-	H = 1 m (3 ft)
Hydraulic conductivity		
standard	-	$k_c = 1 \times 10^{-7}$ cm/s
alternate	-	$k_c = 1 \times 10^{-6}$ cm/s
Hydraulic head on liner	-	h = 0.03 m (0.1 ft)

Composite (Intact)

Compacted soil thickness	-	H = 1 m (3 ft)
Hydraulic conductivity		
standard	-	$k_c = 1 \times 10^{-7}$ cm/s
alternate	-	$k_c = 1 \times 10^{-6}$ cm/s
FML thickness		
standard	-	T = 1.0 mm (40 mils)
alternate	-	T = 2.0 mm (80 mils)
Hydraulic conductivity		
standard	-	$k_g = 1 \times 10^{-12}$ cm/s
alternate	-	$k_g = 1 \times 10^{-11}$ cm/s
Hydraulic head on liner	-	h = 0.03 m (1 ft)

Composite (with defect)

Same as intact composite except for defect.

FML defect size	-	1 cm x 1 cm (0.4 in x 0.4 in)
Number of defects		
standard	-	1 defect per acre
alternate	-	multiple defects per acre

TABLE 5-2. Summary of comparative results based on one-dimensional steady-state analysis[1].

	1 Compacted soil (meet design spec.) $k_c = 1 \times 10^{-7}$ cm/s	2 Compacted Soil (doesn't meet spec.) $k_c = 1 \times 10^{-6}$ cm/s	3 Composite (no defects) $k_g = 1 \times 10^{-12}$ cm/s	4 Composite (one defect) $k_g = 1 \times 10^{-12}$ cm/s	5 Composite (ten defects) $k_g = 1 \times 10^{-12}$ cm/s
Detection Sensitivity (gpad)	86	860	0.001	0.001	0.001
Steady-state collection efficiency (Q = 20 gpad)	0	0	99.9%	99.4%	95%
Steady-state collection efficiency (Q = 100 gpad)	11%	0	99.98%	99.9%	99%
Steady-state collection efficiency (Q = 1000 gpad)	91%	11	> 99.99%	> 99.99%	> 99.99%
Steady-state leakage out of the unit (gpad) (Q = 20 gpad)	20	20	0.02	0.12	1.0
Steady-state leakage out of unit (gpad) Q = 1000 gpad)	89	890	0.02	0.12	1.0
Cumulative leakage out of unit after 10 years (gal/acre) (Q = 20 gpad)	7×10^4	7×10^4	7×10^1	4×10^2	4×10^3
Cumulative leakage out of unit after 10 years (gal/acre) (Q = 1000 gpad)	3×10^5	3×10^6	7×10^1	4×10^2	4×10^3

Note: [1] In all cases, H = 1 m (3 ft); h = 0.03 m (0.1 ft); T = 1 mm (40 mils); $k_g = 1 \times 10^{-12}$ cm/s; and $k_c = 1 \times 10^{-7}$ cm/s unless otherwise noted.

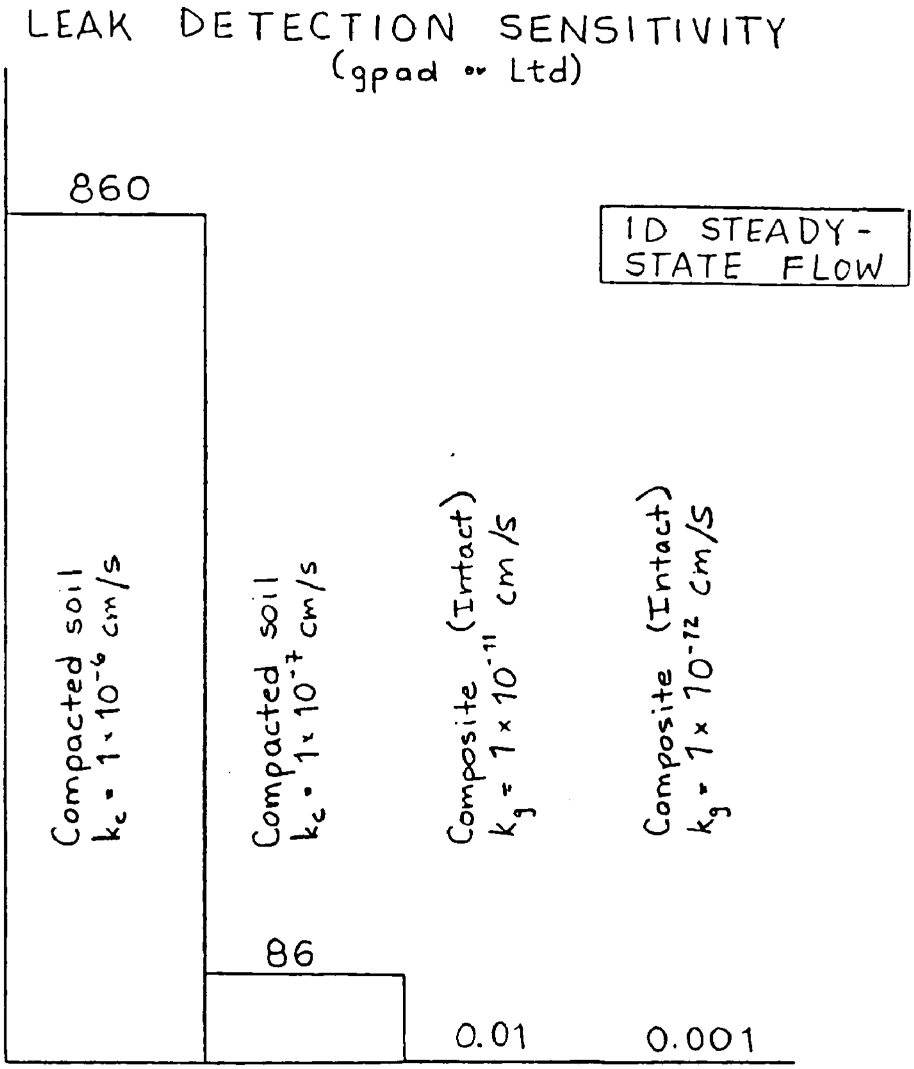


Figure 5-1. Comparison of leak detection sensitivity (minimum leakage rate through the top liner needed to detect leakage) of LDCRS with compacted soil and composite bottom liners (1D steady-state analysis).

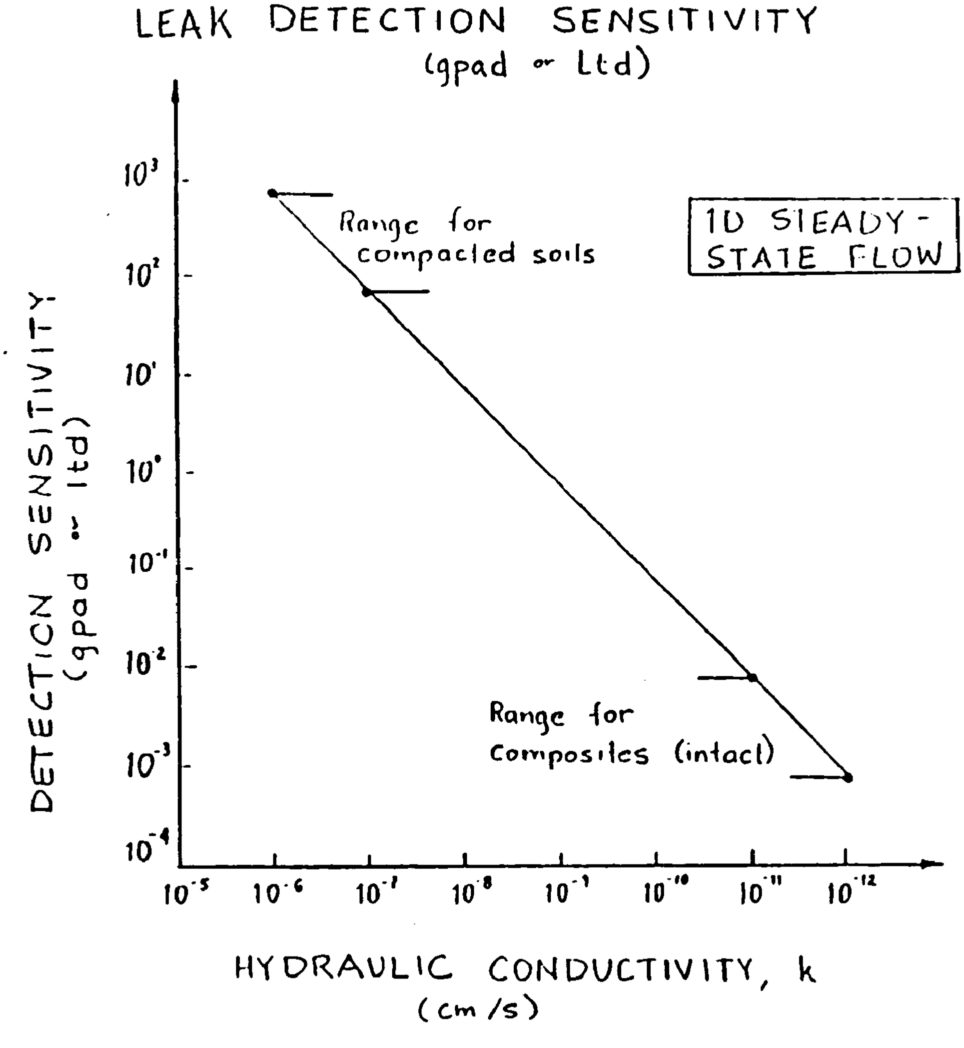


Figure 5-2. Comparison of leak detection sensitivity of LDCRS with compacted soil and composite bottom liners (1D steady-state analysis).

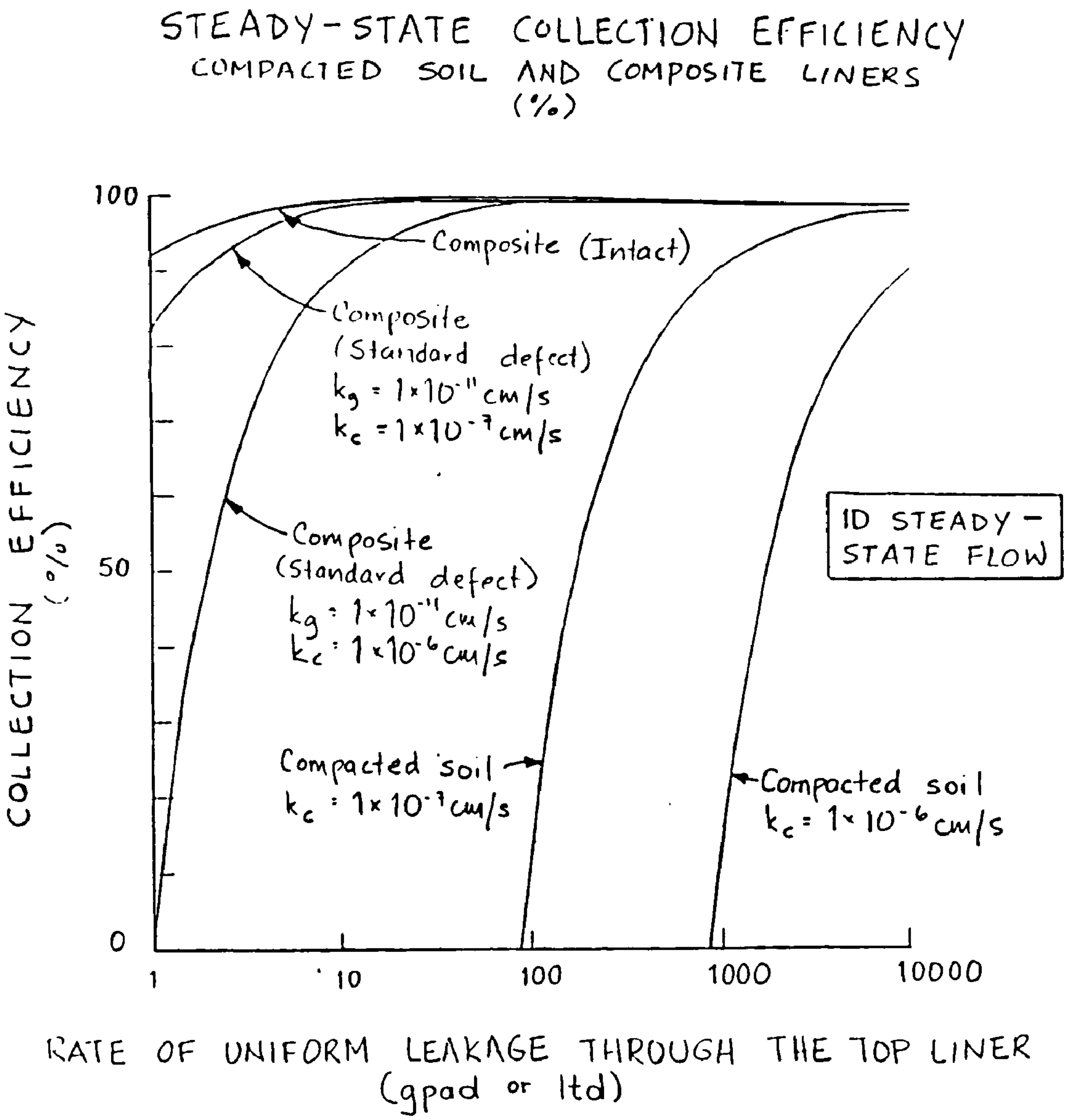


Figure 5-3. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (1D steady-state analysis).

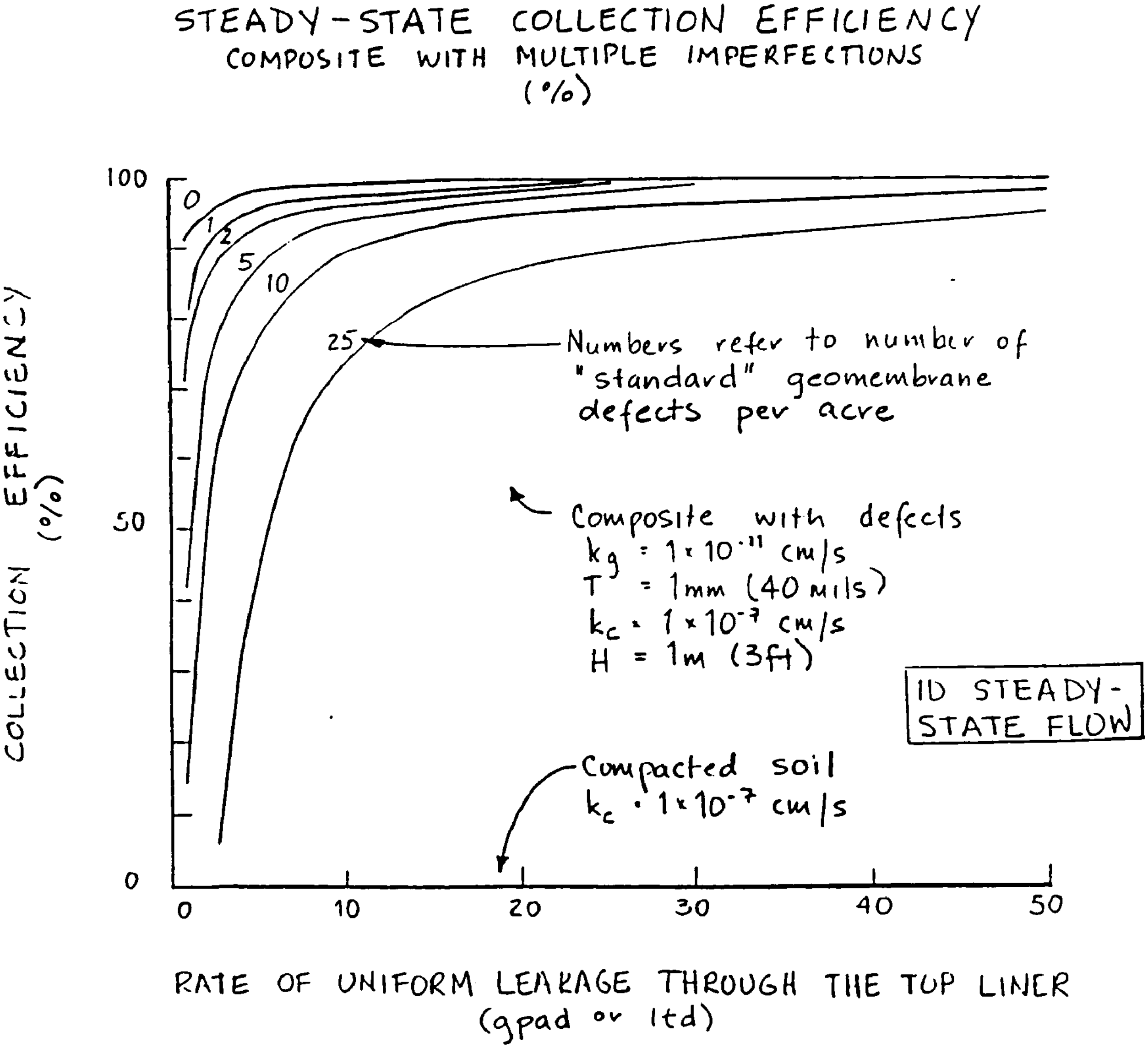


Figure 5-4. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners. Composite bottom liners include FMLs with defects (1D steady-state analysis).

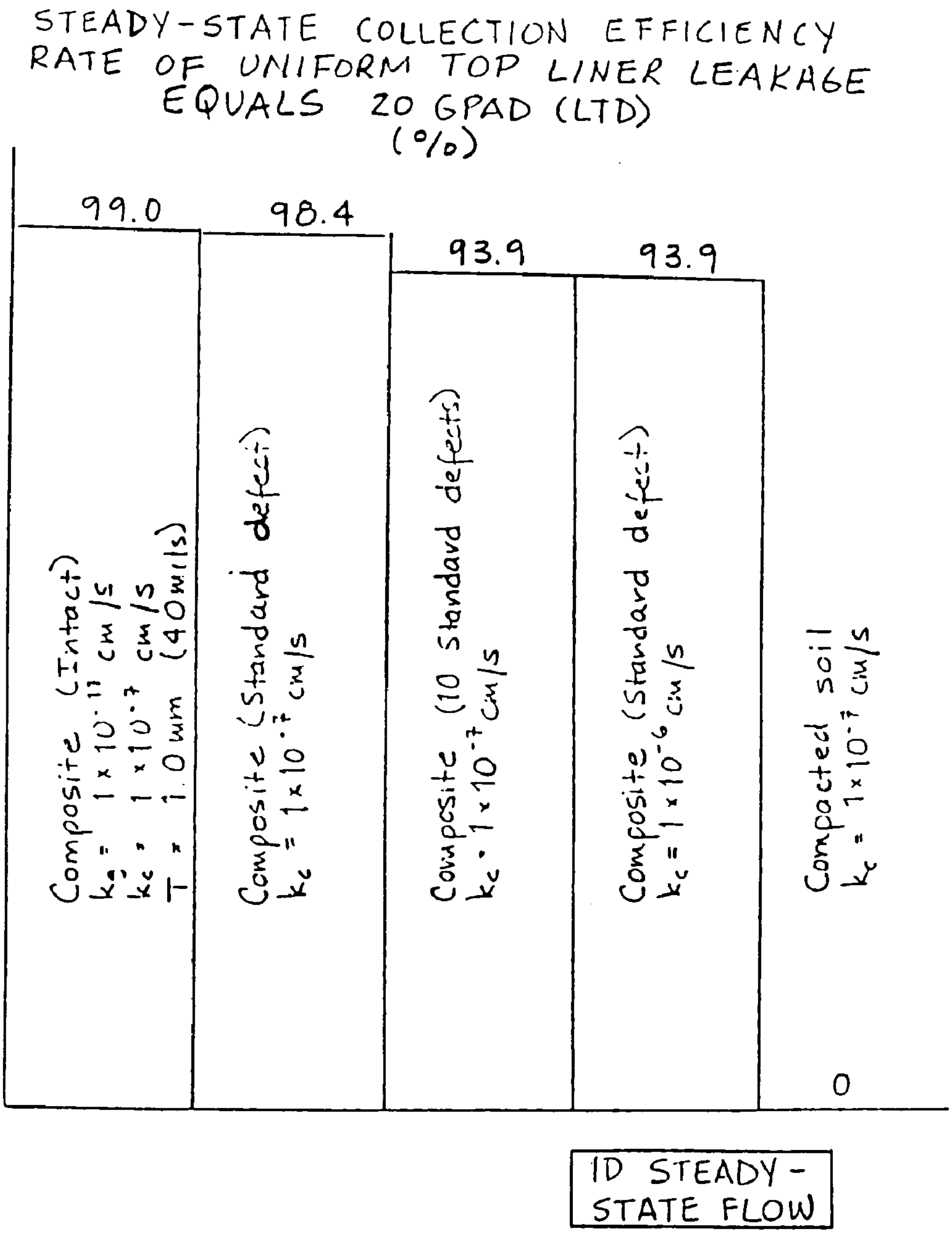


Figure 5-5. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (1D steady-state analysis).

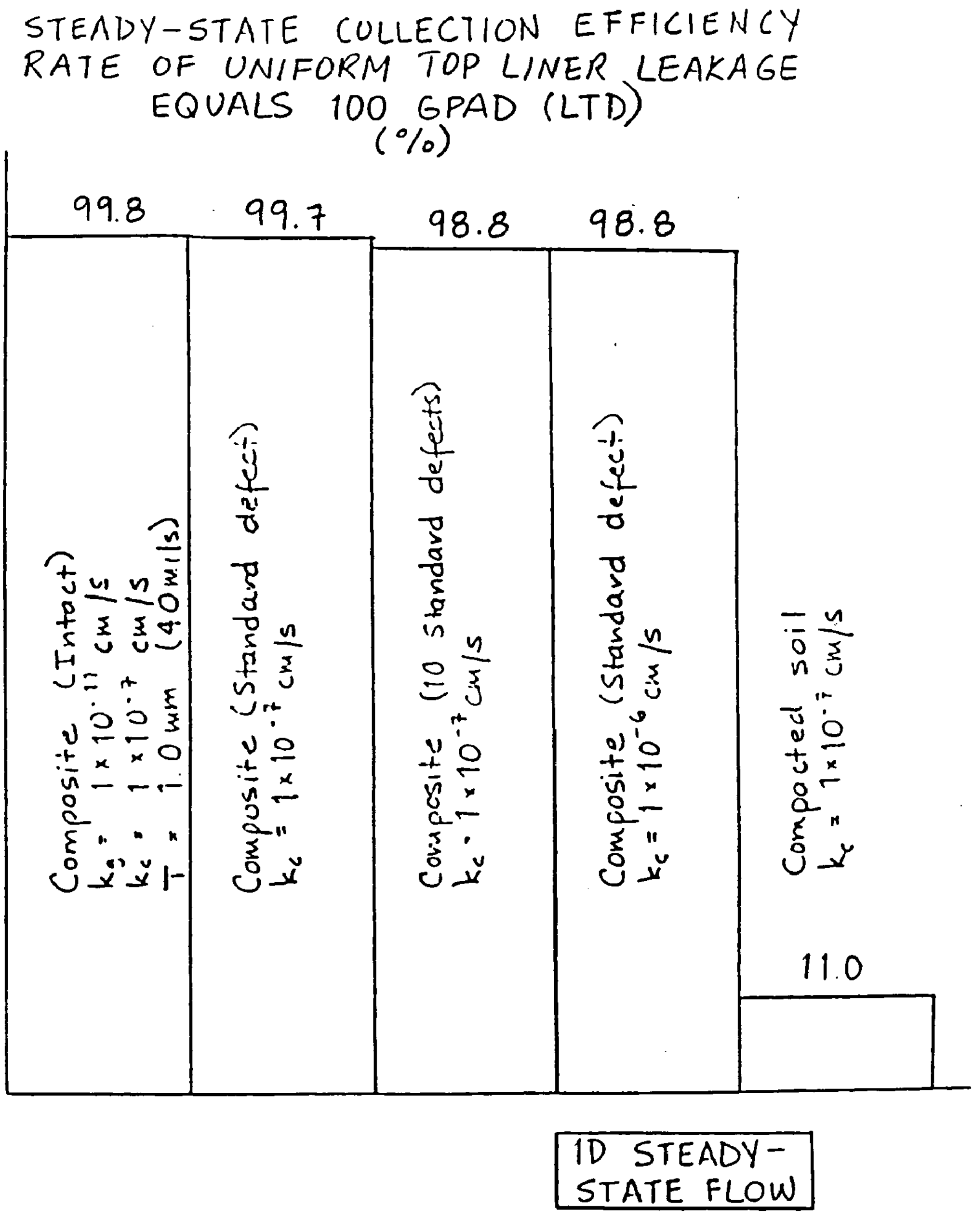


Figure 5-6. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (1D steady-state analysis).

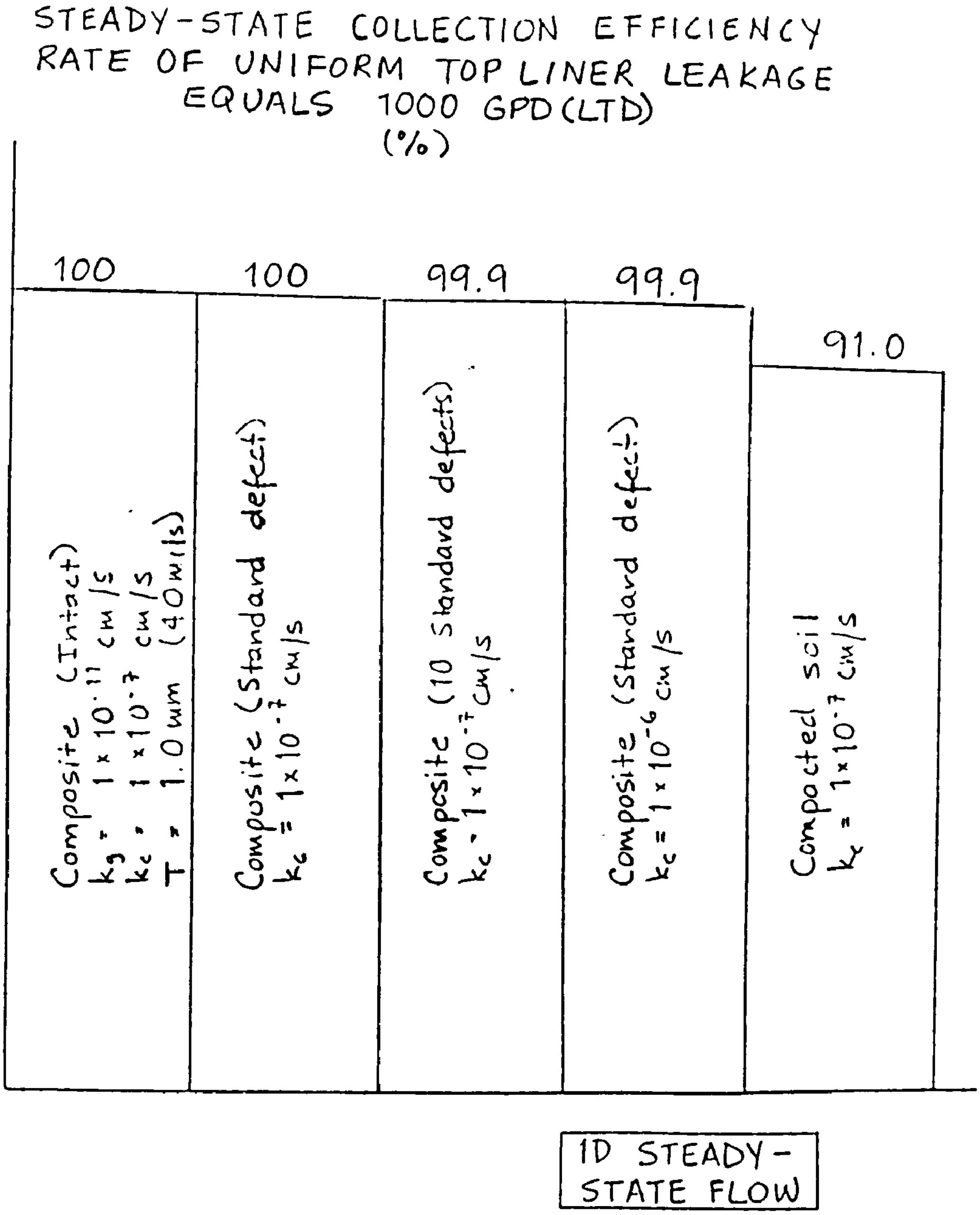


Figure 5-7. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (1D steady-state analysis).

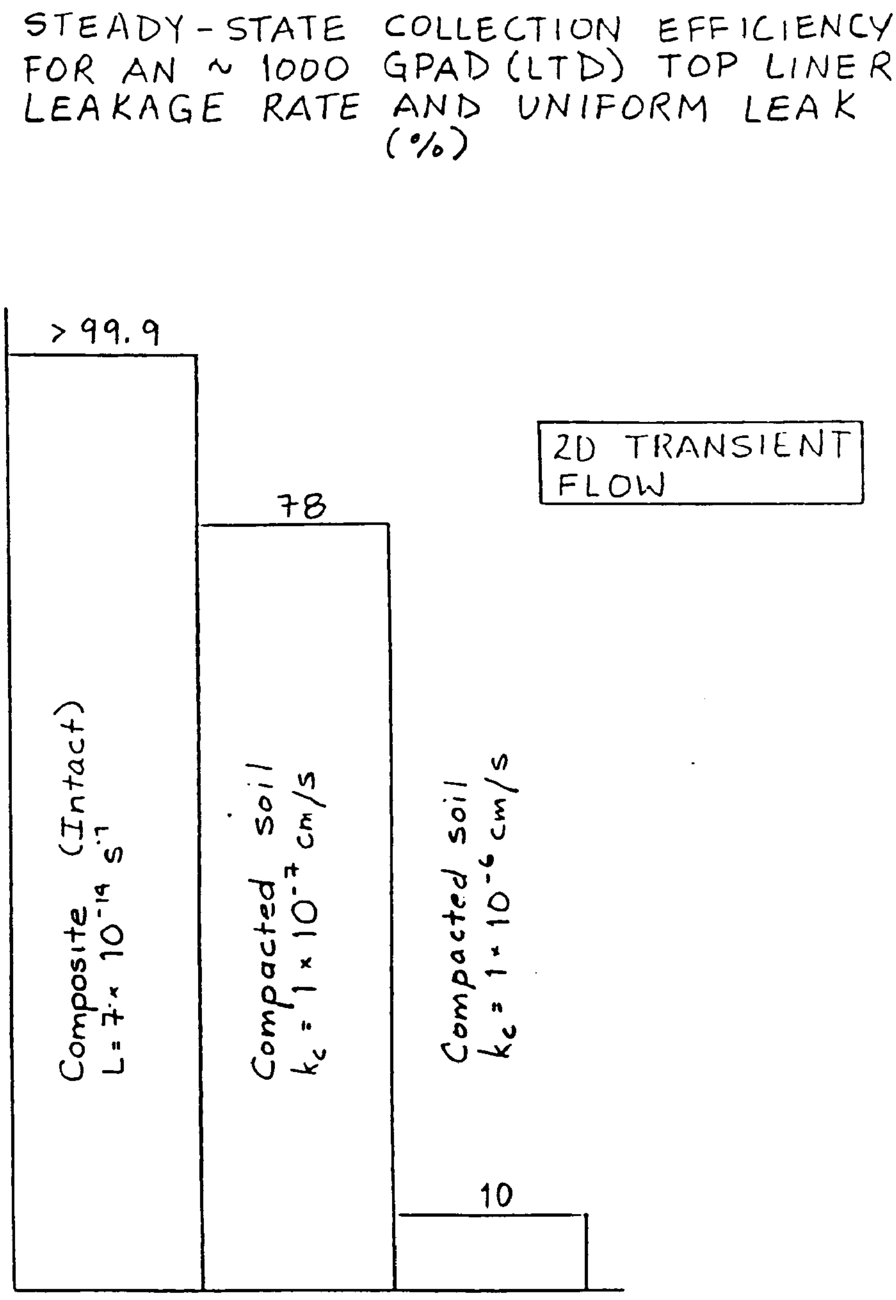


Figure 5-8. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

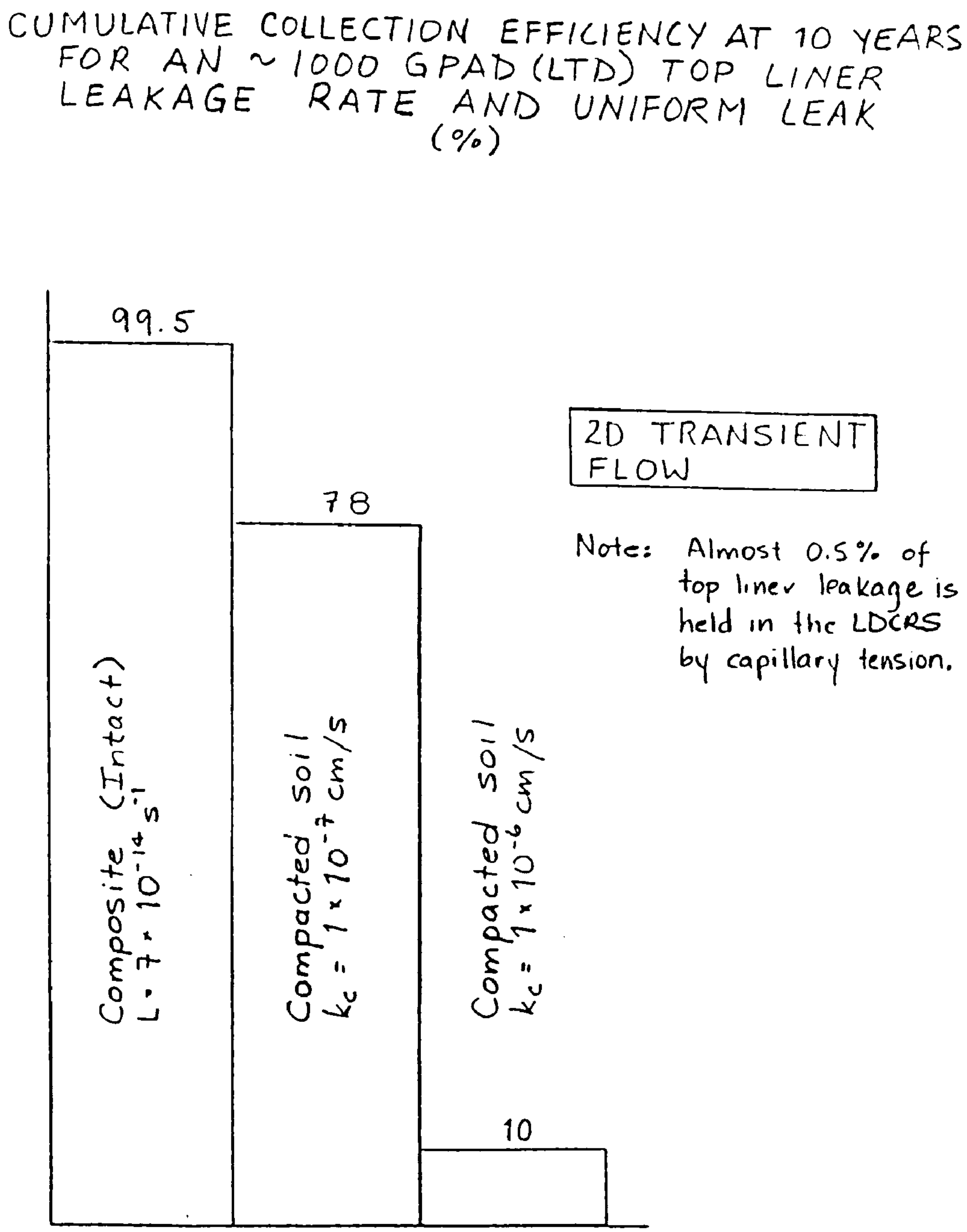


Figure 5-9. Comparison of cumulative leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

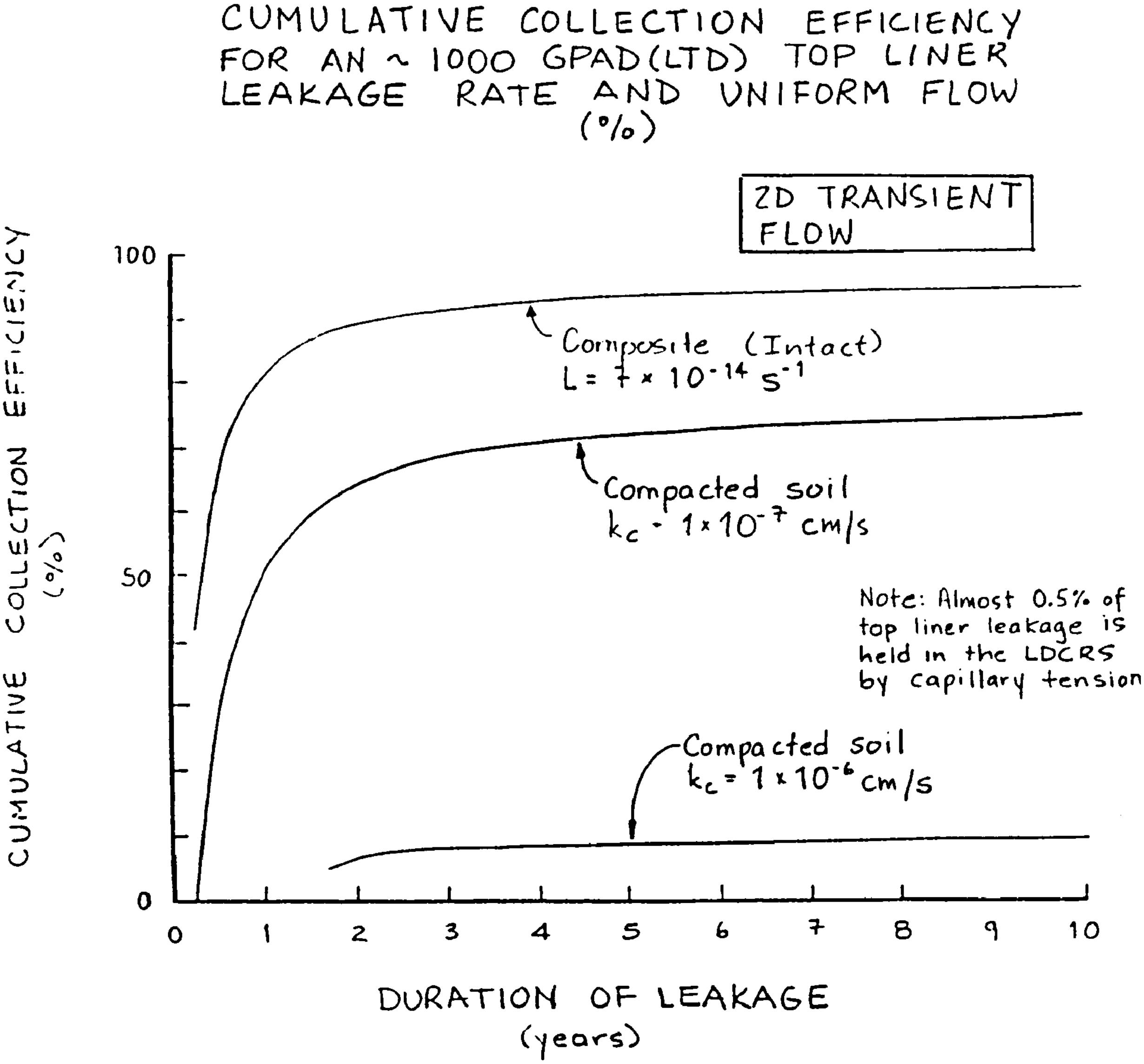


Figure 5-10. Comparison of cumulative leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

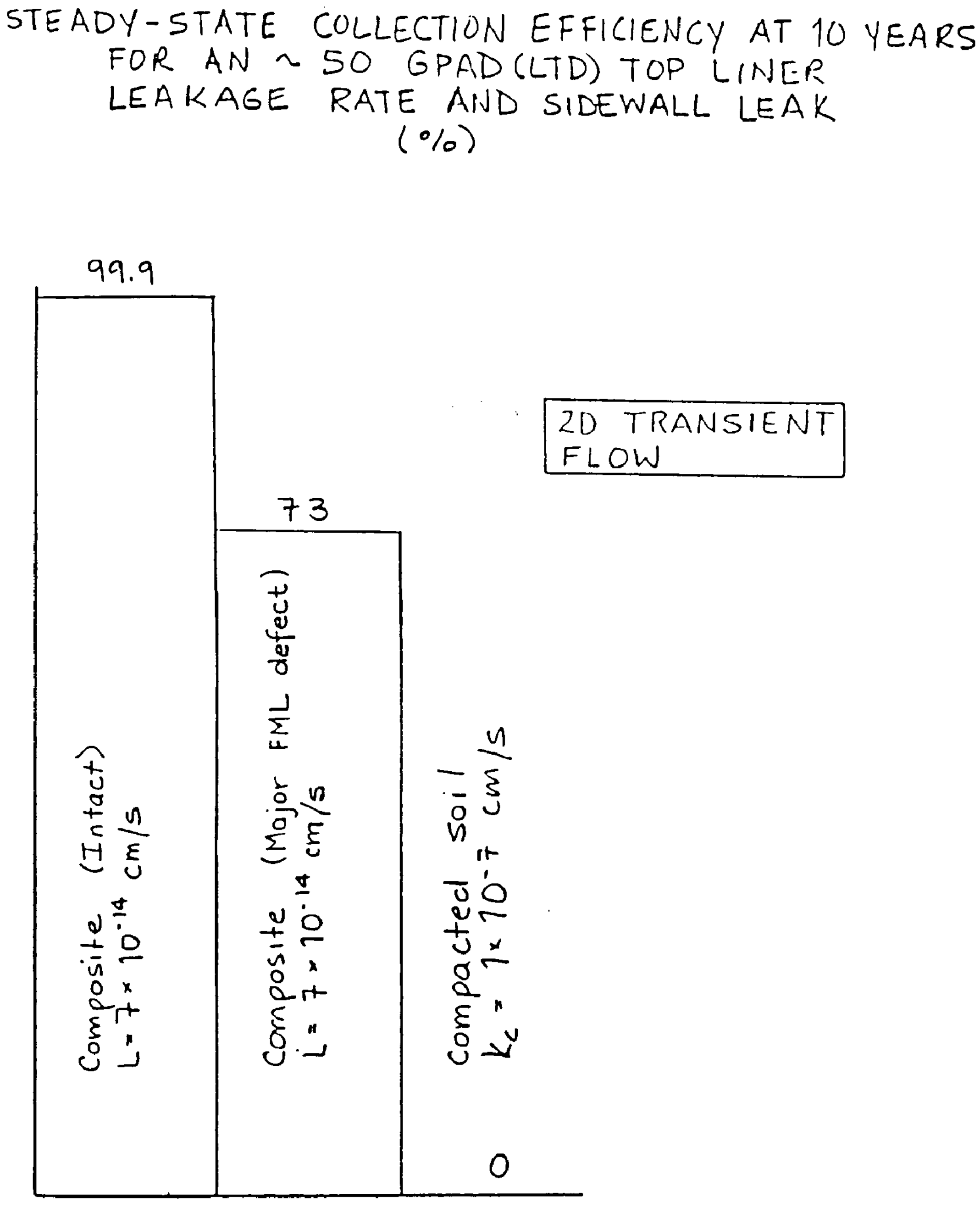


Figure 5-11. Comparison of steady-state leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

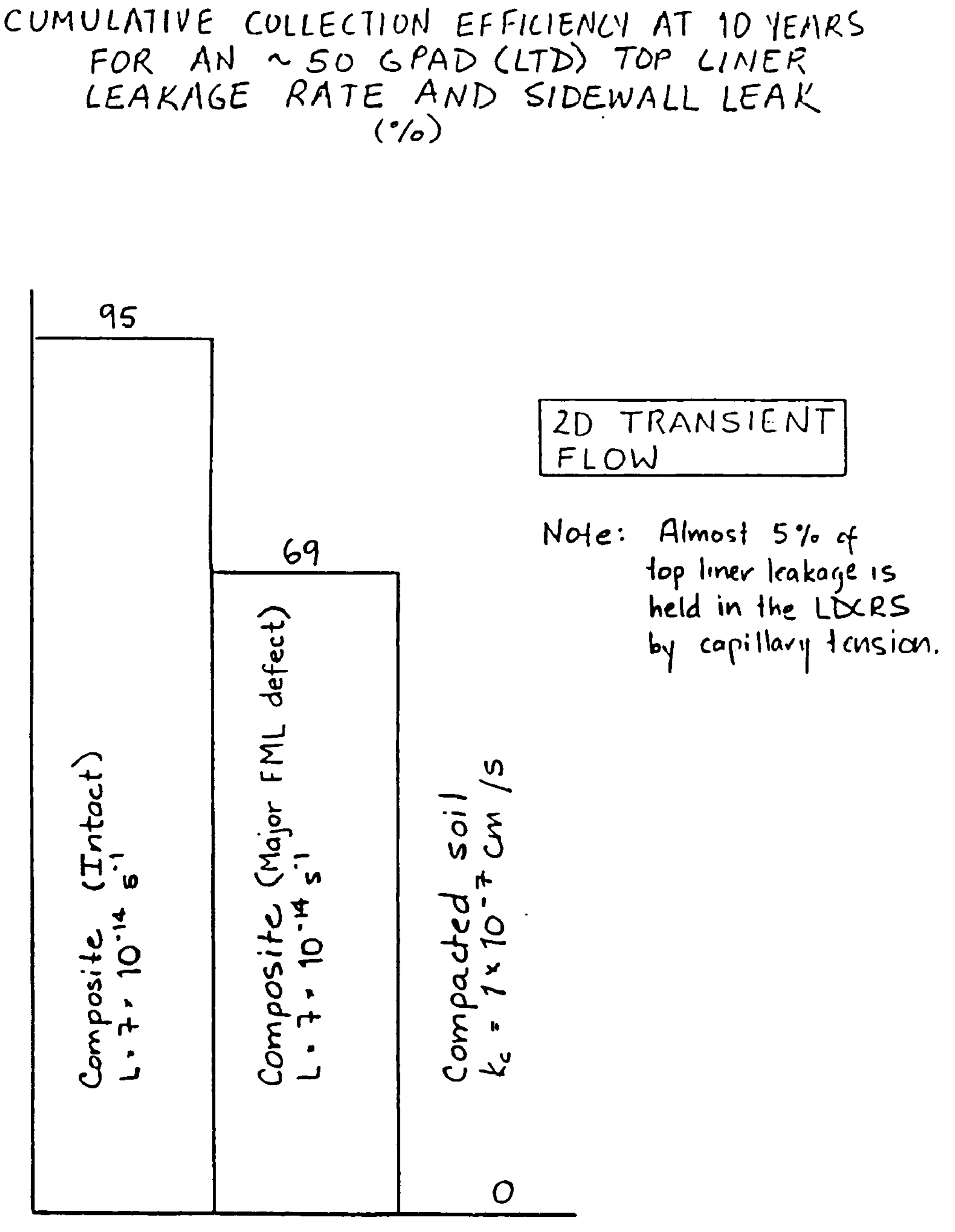


Figure 5-12. Comparison of cumulative leachate collection efficiencies of LDCRS with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

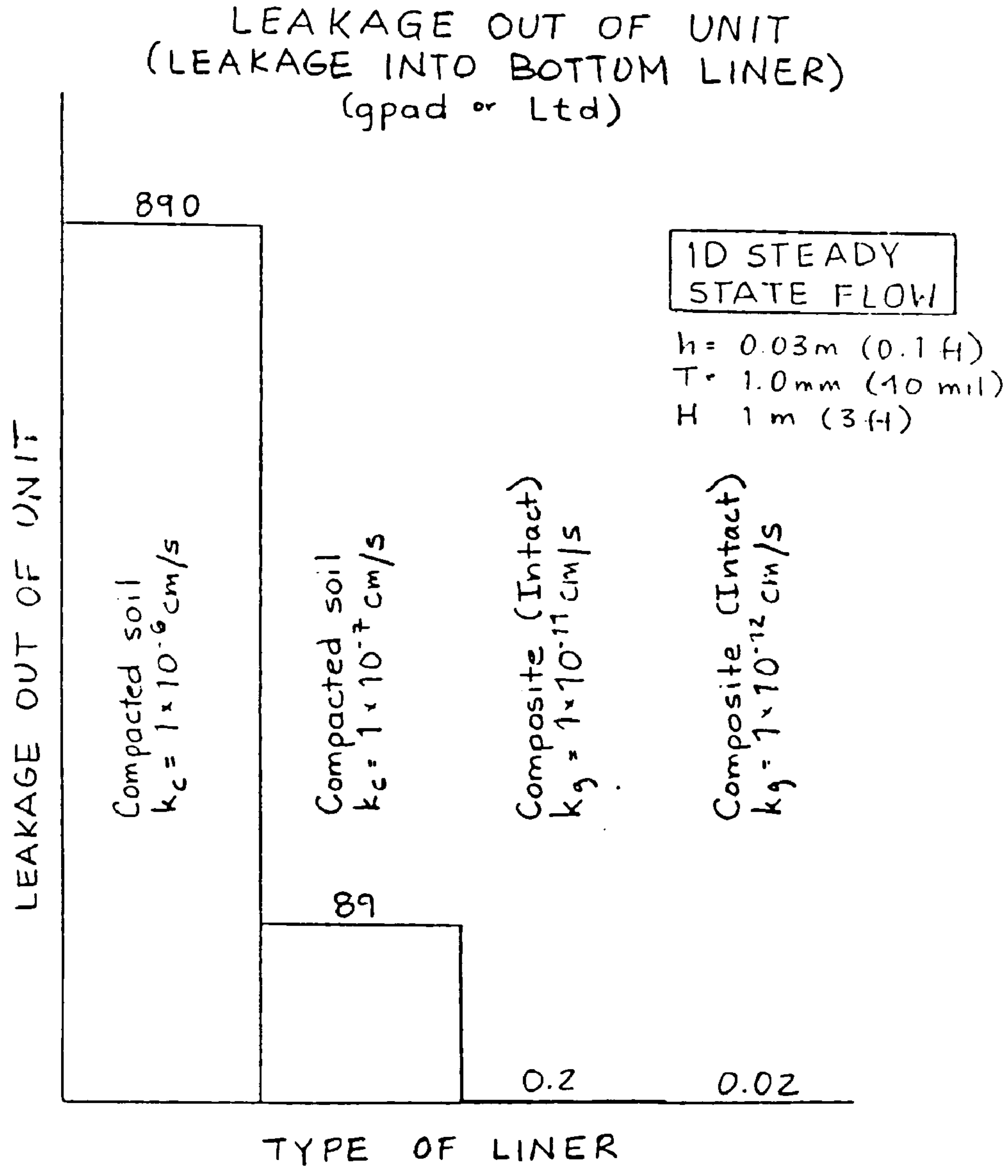


Figure 5-13. Comparison of leakage out of the unit (or leakage into the bottom liner) for units with compacted soil and composite bottom liners (1D steady-state analysis).

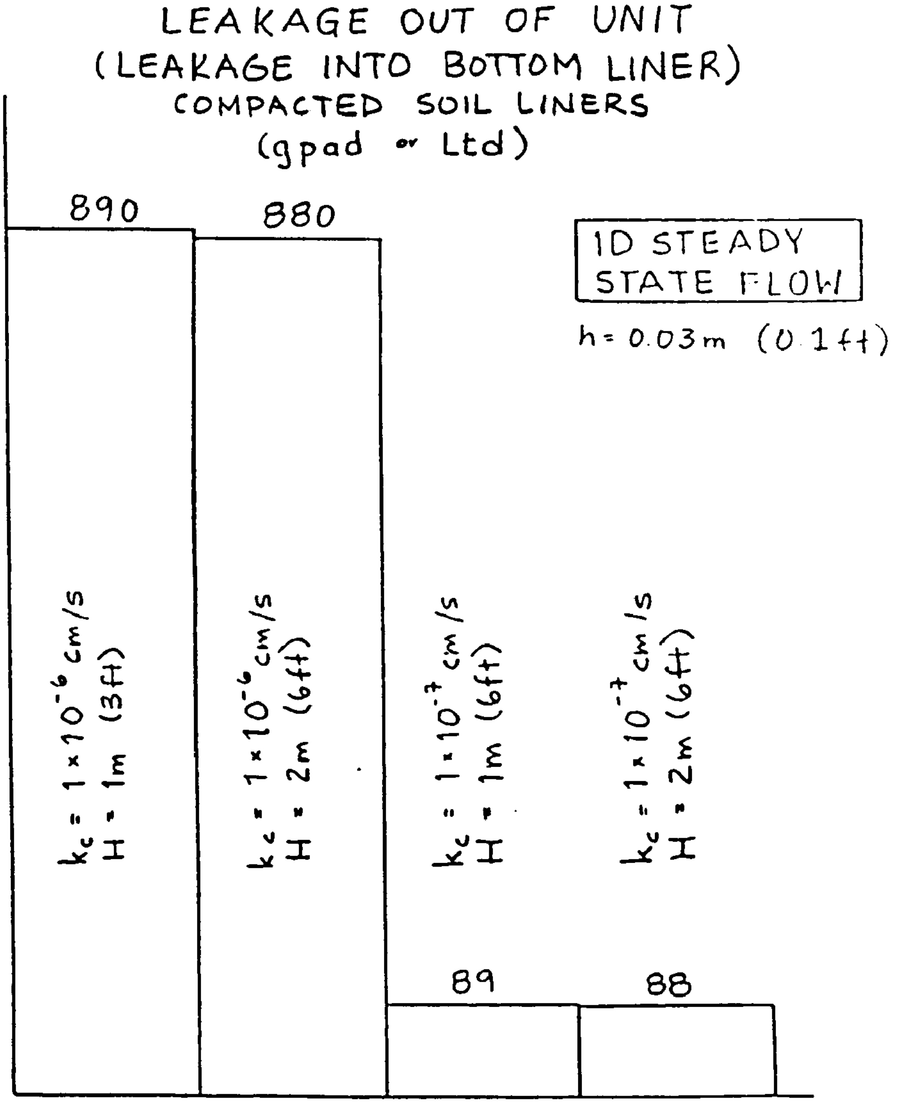


Figure 5-14. Comparison of leakage out of the unit (or leakage into the bottom liner) with various compacted soil bottom liners (1D steady-state analysis).

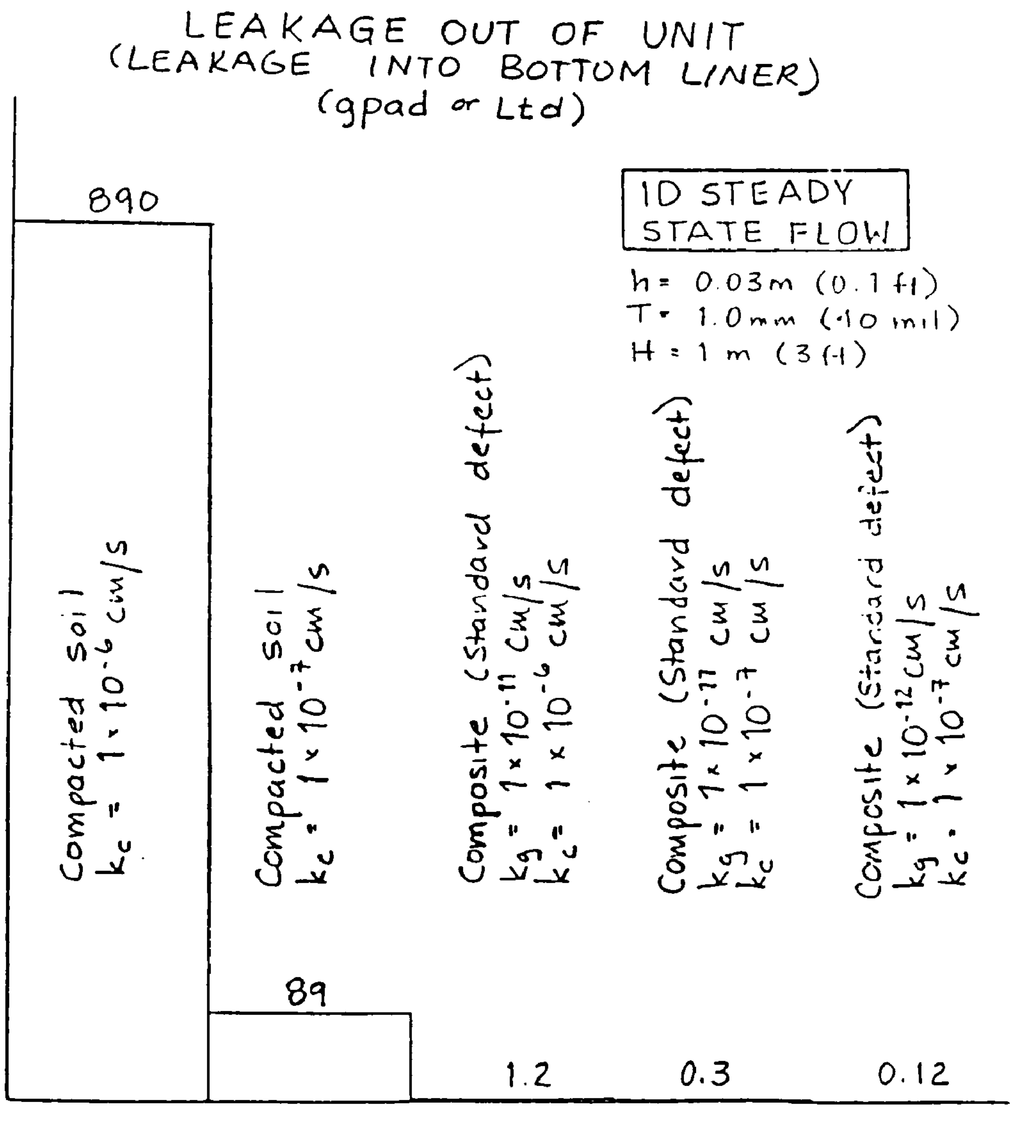


Figure 5-15. Comparison of leakage out of the unit with compacted soil and composite bottom liners. Composite bottom liners include FMLs with defects (1D steady-state analysis).

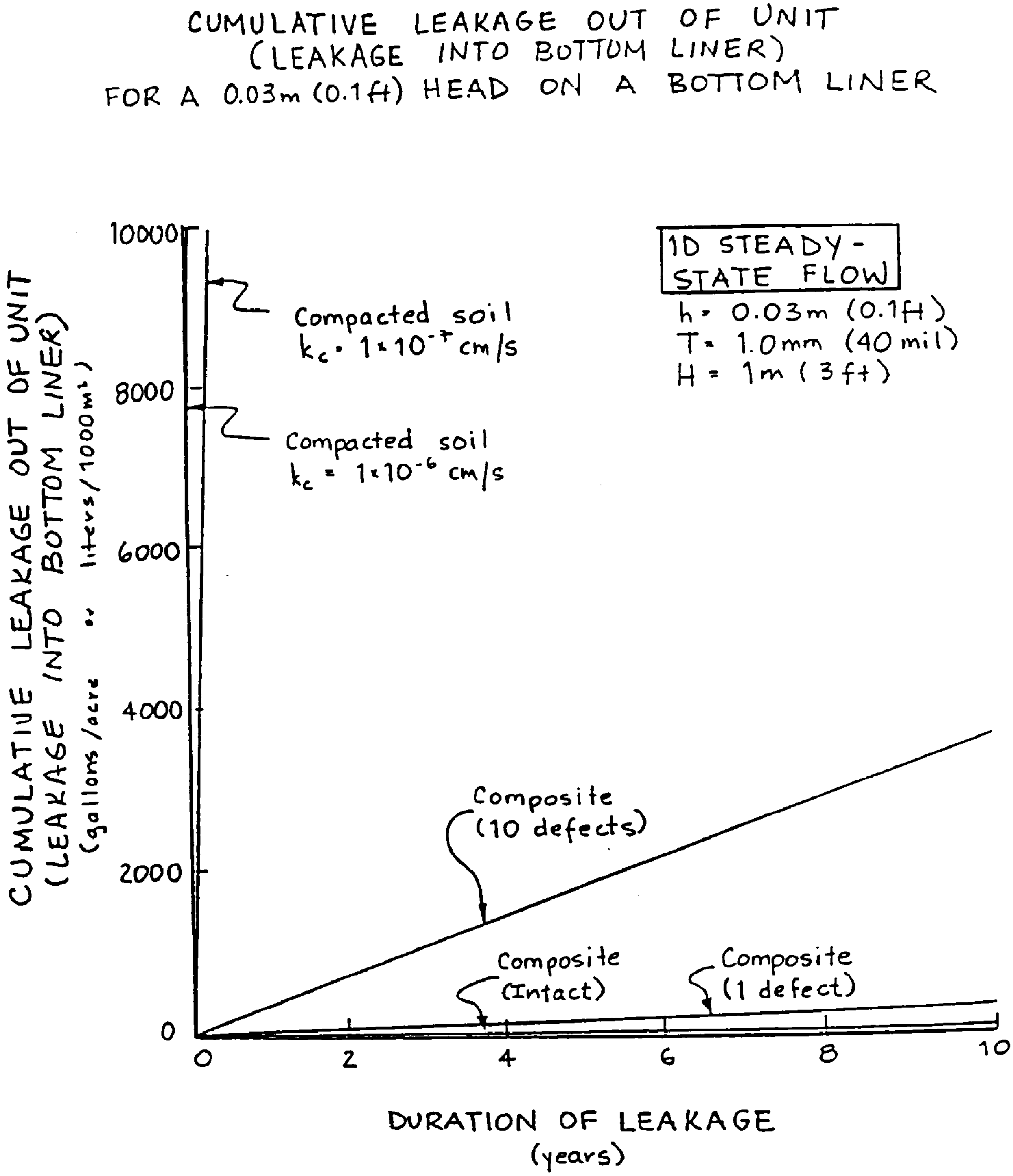


Figure 5-16. Comparison of cumulative leakage out of the unit (or leakage into the bottom liner) for units with compacted soil and composite bottom liners (1D steady-state analysis).

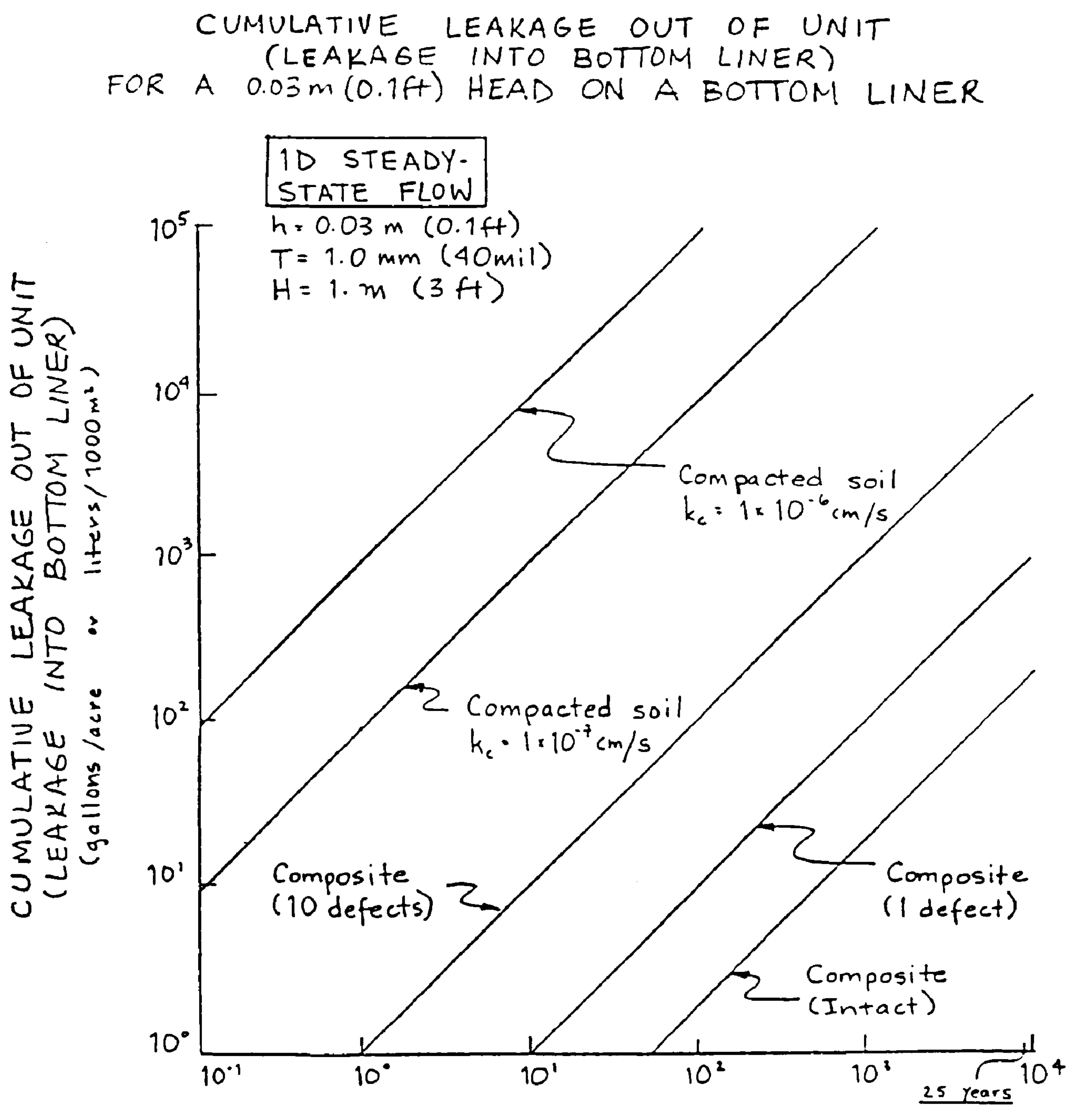


Figure 5-17. Comparison of cumulative leakage out of the unit (or leakage into the bottom liner) for units with compacted soil and composite bottom liners (1D steady-state analysis).

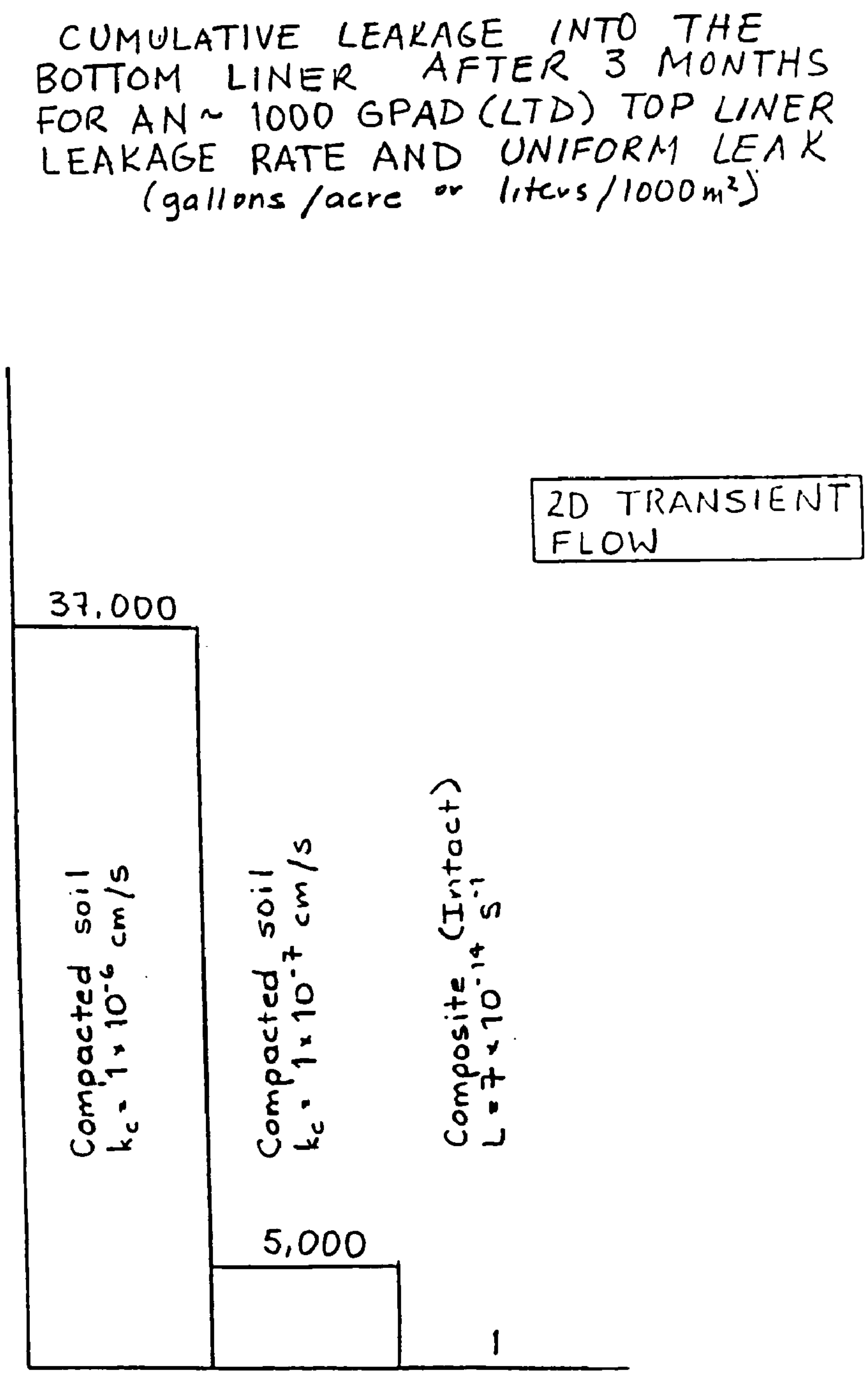


Figure 5-18. Comparison of leakage into the bottom liner after 3 months for units with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

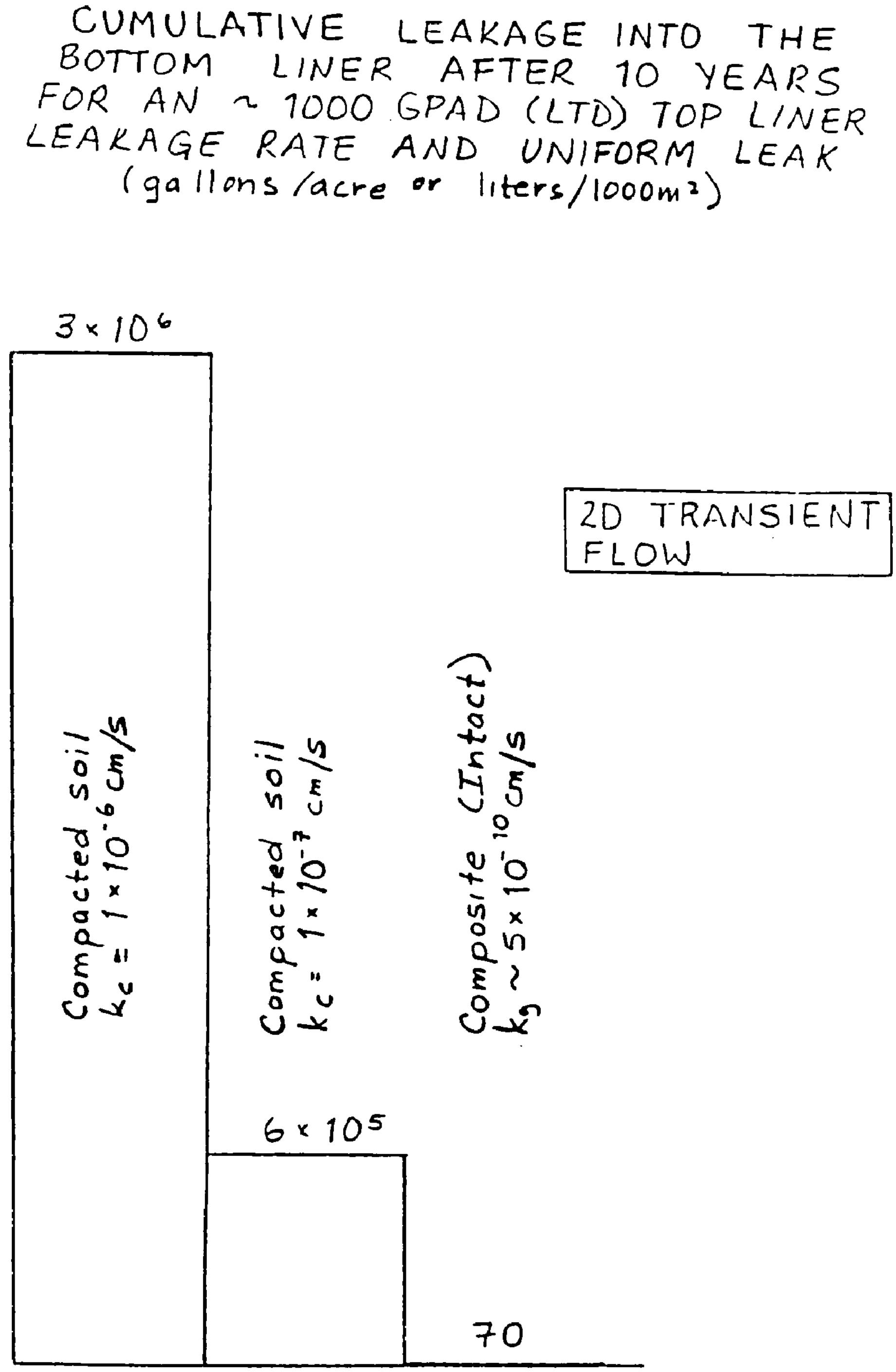


Figure 5-19. Comparison of leakage into the bottom liner after 10 years for units with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

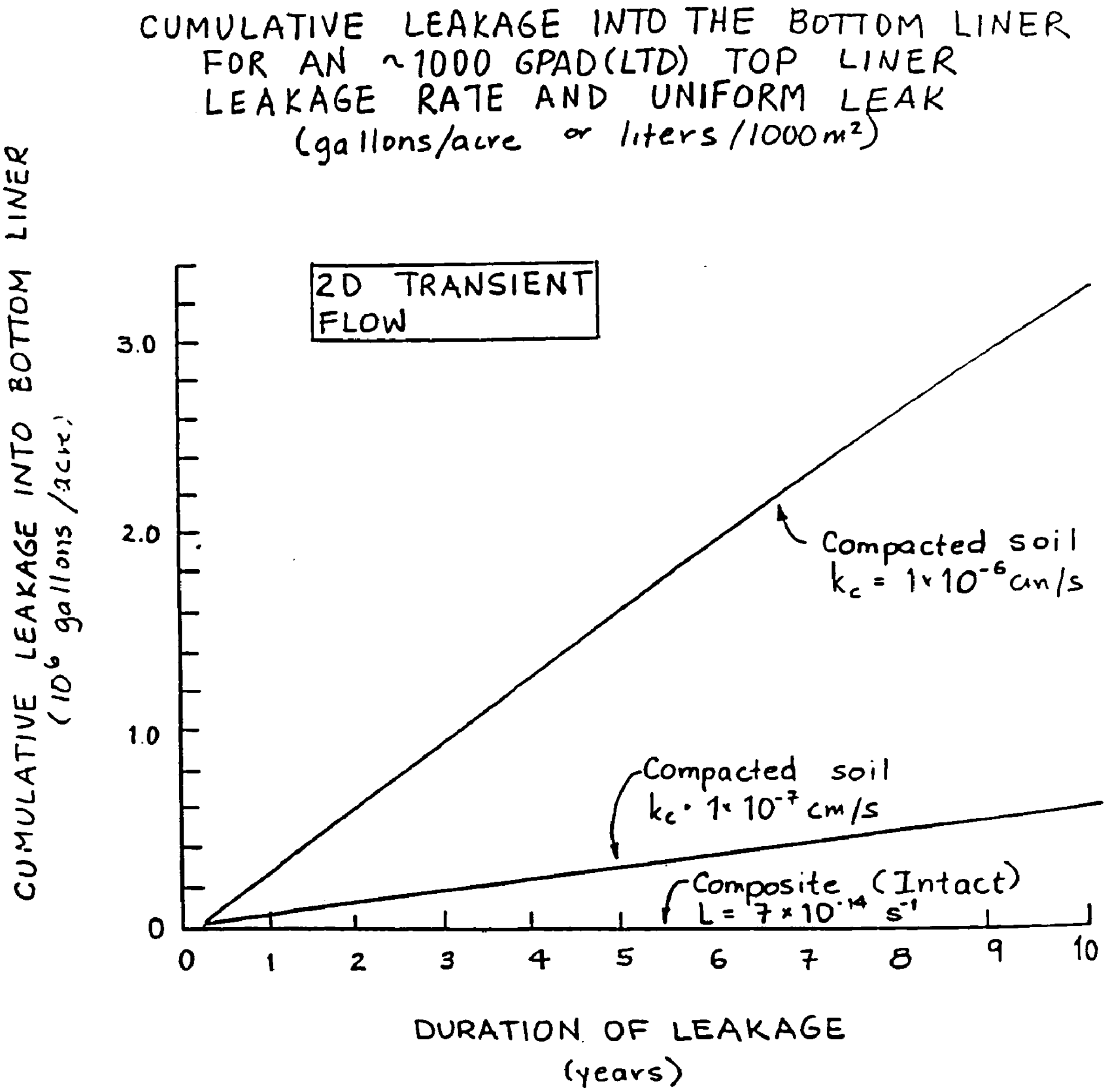


Figure 5-20. Comparison of leakage into the bottom liner out of the unit with compacted soil and composite bottom liners (2D transient analysis). [Data from Radian, 1987]

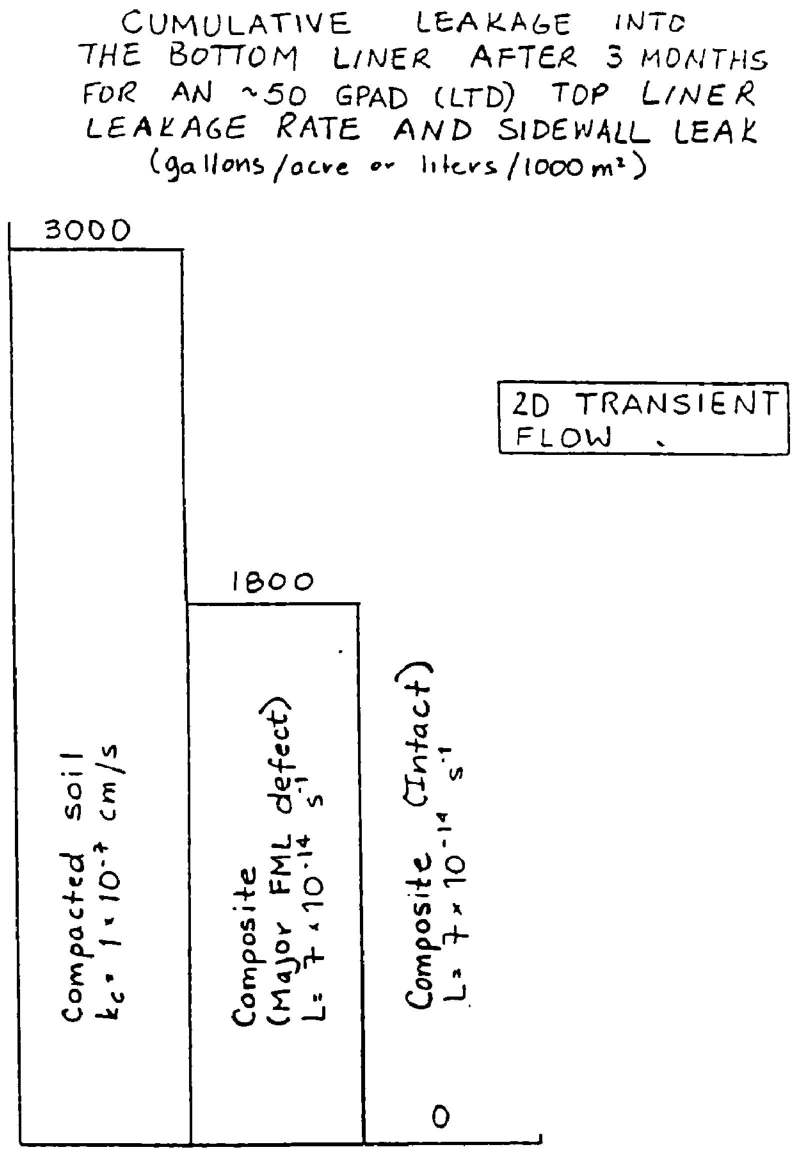


Figure 5-21. Comparison of cumulative leakage into the bottom liner for units with compacted soil and composite bottom liners. Composite bottom liners includes an FML with a major defect (2D transient analysis). [Data from Radian, 1987]

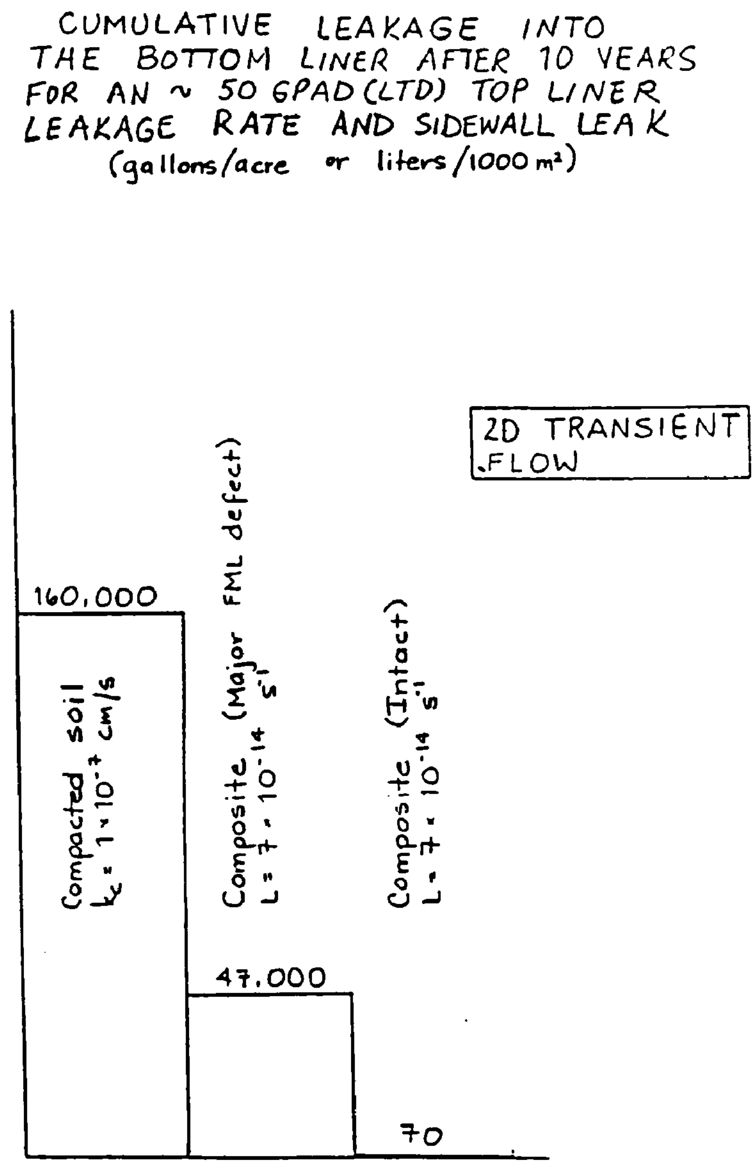


Figure 5-22. Comparison of cumulative leakage into the bottom liner for units with compacted soil and composite bottom liners. Composite bottom liners includes an FML with a major defect (2D transient analysis). [Data from Radian, 1987]

CHAPTER 6

CURRENT PRACTICE
IN LINING SYSTEM DESIGN

6.1 INTRODUCTION

This chapter presents a summary of current practice in lining system design of hazardous waste landfill and surface impoundment units regulated under RCRA (40 CFR Parts 264 and 265). This summary is from a survey conducted by EPA on the number of hazardous waste landfill and/or surface impoundment units for which permit applications were received since November 8, 1984, having either compacted soil bottom liners or composite bottom liners in their double liner system design. The survey was conducted in January and February 1987.

6.2 RESULTS OF EPA SURVEY

This section discusses the results of the survey of hazardous waste permit applications by EPA region. It includes the questions, the data and the assumptions.

6.2.1 Information on the Survey

6.2.1.1 Reason for the Survey

In developing the final rule for double liner and leachate collection systems for landfills and surface impoundments, the Land Disposal Branch of the Office of Solid Waste sought to determine whether eliminating the option of a compacted soil bottom liner in the double liner system design would have an adverse impact on the regulated community.

6.2.1.2 Questions in the Survey

Each of the EPA's ten regions were asked a set of questions in a memorandum from the Director of the Office of Solid Waste dated January 20, 1987. The questions were:

1. How many new landfill and surface impoundment <u>units</u> are included in permit applications submitted to your region?
2. How many new landfill and surface impoundment units have double liners where the lower liner is a compacted soil (clay) liner?
3. How many new landfill and surface impoundment units have double liners where the lower liner is a composite (a FML on top of a compacted soil) liner?
4. How many new landfill and surface impoundment units do not have detailed plans that provide enough information to make this determination?

6.2.1.3 Results of the Survey

The results of the survey are shown in Table 6-1. In the 10 EPA Regions, 183 applications for hazardous waste or surface impoundment units had been received. Of those applications:

- 7 units used compacted soil bottom liners in their designs;
- 152 units used composite bottom liners in their designs;
- there was not enough information on 24 units to make a determination on the type of bottom liner.

Therefore, of the 159 units for which permit applications have been filed since November 8, 1984 and for which sufficient information was provided:

- 95.6 percent of the units used composite bottom liners in the double liner system design;
- 4.4 percent of the units used compacted soil bottom liners in the double liner system design.

6.3 CONCLUSIONS

6.3.1 Owners or Operators Opted for Composite Bottom Liner

The survey conducted by EPA on current double liner system design practices, as indicated by permit applications for hazardous waste surface impoundment and landfill units, shows owners or operators at these units have overwhelmingly opted to utilize a composite bottom liner. The state of practice in double liner system design for hazardous waste management facilities today is to use composite bottom liners in double liner systems.

6.3.2 Assessment of Adverse Impact

The survey indicates there will be minimal impact on the regulated community if composite bottom liners are required in double liner system design. The total number of units for which permit applications have been submitted since November 8, 1984 which do not have composite bottom liners is estimated to be 7, or less than 4 percent (although this number may be slightly higher, depending on the determination of design for those units in the undetermined category).

Table 6-1. Summary of February 1987 EPA survey of current practice for design of bottom liners at hazardous waste management units for which permit applications have been submitted since November 8, 1984.

Region	No. of Units	Compacted Soil Bottom Liner	Composite Bottom Liner	Undetermined
Region I (Boston)	8	0	0	8
Region II (New York)	5	0	4	1
Region III (Philadelphia)	4	0	4	0
Region IV (Atlanta)	20	0	20	0
Region V (Chicago)	85	3	68	14
Region VI (Dallas)	15	3	12	0
Region VII (Kansas City)	11	0	11	0
Region VIII (Denver)	22	1	21	0
Region IX (San Francisco)	7	0	7	0
Region X (Seattle)	6	0	5	1
TOTALS	183	7	152	24

CHAPTER 7

SUMMARY

7.1 SUMMARY OF COMPARATIVE PERFORMANCE

Based on comparisons of performance of compacted soil and composite bottom liners, the following observations were drawn in Chapter 5.

- Leak detection sensitivity - The theoretical leak detection sensitivity of an LDCRS with a properly designed and constructed composite bottom liner is much less than one Ltd (gpad). A few "standard" FML defects have a negligible effect on the detection sensitivity of a lining system with a composite bottom liner. By comparison, the leak detection sensitivity of a compacted soil bottom liner is on the order of 100 Ltd (gpad) with $k_c = 1 \times 10^{-7}$ cm/s in all areas of the liner.

- Leachate collection efficiency - The theoretical steady-state leachate collection efficiency for a composite bottom liner with an intact FML is in excess of 99%, even for relatively small leakage rates such as 20 Ltd (gpad). Just as important, the collection efficiency remains high even when the FML component of a composite bottom liner has several "standard" defects (more defects than would be expected in a properly designed and constructed lining system). In contrast, the theoretical steady-state collection efficiency of a compacted soil bottom liner is zero for all rates of uniform top liner leakage up to approximately the leak detection sensitivity (on the order of 100 Ltd (gpad) for a compacted soil bottom liner with $k_c = 1 \times 10^{-7}$ cm/s, and on the order of 1000 Ltd (gpad) for a compacted soil bottom liner with $k_c = 1 \times 10^{-6}$ cm/s).

- Leakage into and out of the bottom liner - The theoretical steady-state leakage out of a unit with a composite bottom liner with an intact FML is much less than 1 Ltd (gpad). Just as important, the leakage out of the unit remains less than 1 Ltd (gpad) even when the FML component of a composite bottom liner has several "standard" defects (more defects than would be expected in a properly designed and constructed lining system). In contrast, for a uniform hydraulic head on the bottom liner of 0.03 m (0.1 ft), the leakage out of a unit with a compacted soil bottom liner with $k_C = 1 \times 10^{-7}$ cm/s is on the order of 100 Ltd (gpad).

Based on the above summary, it can be concluded that properly designed and constructed composite liners incorporating a FML upper component and a compacted soil lower component represent current best demonstrated available technology (BDAT). It is believed that a composite bottom liner, used in conjunction with a properly designed and constructed double liner <u>system</u>, can come very close to meeting the goal of Congress and EPA of preventing migration of hazardous constituents through the lining system and into the ground. In contrast, compacted soil bottom liners will significantly limit the migration of leakage through them, but they do not provide a level of performance comparable to, or even close to, composite bottom liners, and therefore do not represent the best demonstrated available technology (BDAT).

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APPENDIX A

CASE HISTORIES OF COMPACTED SOIL LINING SYSTEM PERFORMANCE

A.1 OVERVIEW OF CASE HISTORIES

This Appendix summarizes the documented performance of compacted soil lining systems for both landfills and surface impoundments. The landfill facilities reviewed were primarily for the containment of sanitary waste, however, one case history described the performance of a clay lining system at a hazardous waste landfill. Another case history reports the results from a large scale field test. The surface impoundment case histories describe facilities which were constructed to hold fresh water, salt water (brine), or contaminated liquid. The landfill case histories are summarized in Section A.2 and the surface impoundments are summarized in Section A.3.

A.2 LANDFILLS

A.2.1 Sanitary Landfill Sarnia, Ontario

Goodall and Quigley [1977] studied cation migration from two sanitary landfills near Sarnia, Ontario, Canada. These two sites are referred to as the Confederation Road site and the Blackwell Road site. Only the performance of the lining system at Confederation Road Site will be summarized here.

At the location of the Confederation Road landfill, approximately 41 m (135 ft) of water-laid glacial till overlie Devonian limestone and shale. The glacial till consist primarily of silty clay with 40-50% clay sized particles. The till deposit is slightly overconsolidated except for a desiccated crust above 7 m (23 ft). Fissuring has developed as a result of desiccation and the fissure spacing decreases with depth.

The landfill was excavated in the natural till to a depth of 5.6 m (18 ft) which corresponds to the upper boundary of the undesiccated soil. The landfill started operation in 1967 and was closed in 1971. Selected cation (calcium, magnesium, sodium, and potassium) concentrations were measured beneath the Confederation Road site and compared with background concentrations. From this comparison, it was estimated that the cations had migrated approximately 300 mm (1 ft) into the natural clay below the landfill.

Typical values of silty clay till hydraulic conductivity in the vicinity of the Sarnia landfills measured using a variety of test methods are shown in Table A-1. An exploration of the site revealed a downward hydraulic gradient of 0.16 to 0.25 beneath the landfill. Using this range of hydraulic gradient, hydraulic conductivities of 2 to 3 x 10^{-10} m/s (2 to 3 x 10^{-8} cm/s) which are based on the data in Table A-1, a porosity of 0.3, and a period of 6 years, Goodall and Quigley [1977] calculated an expected cation migration distance of 30 to 50 mm (1 to 2 in.), which is less than the estimated cation migration distance. Goodall and Quigley [1977] applied the concept of molecular diffusion to the Confederation Road site to explain the observed distance of 300 mm (1 ft) in 6 years.

If the calculations of Goodall and Quigley [1977] are repeated using hydraulic conductivities of 1 x 10^{-9} m/s (1 x 10^{-7} cm/s) and 1 x 10^{-8} m/s (1 x 10^{-6} cm/s) cation migration distances due to seepage of approximately 120 to 1200 mm (5 to 50 in.) are calculated, which bound the observed cation migration distance. These hydraulic conductivities are larger than those found in Table A-1. However, they may be attributable to fine desiccation cracks existing in the soil. Such cracks exist in a vertical direction and may not be accounted for in a borehole hydraulic conductivity test.

A.2.2 Four Compacted Clay Lined Landfills in Wisconsin

Gordon et al. [1984] documented the performance of four clay-lined landfills in Wisconsin, three of which are described here. The three facilities are for the containment of sanitary waste and all three lining systems were composed of a granular leachate collection system over a compacted clay liner. The compacted clay liners are on the order of 1.2 to 1.5 m (4 to 5 ft) thick. One of the landfills had been in operation for 8 years, the other two were in operation for 4 or 5 years. The landfill which was in operation for 8 years indicated leakage through the bottom of the clay liner after 8 years. The liners that had been in operation about 5 years showed no sign of leakage.

At the 8 year old site, the 1.2 to 1.5 m (4 to 5 ft) thick compacted clay liner has prevented the migration of pollutants for not more than 8 years. Back calculations based on saturated flow and a breakthrough time of 8 years give a clay liner hydraulic conductivity of approximately 5×10^{-9} m/s (5×10^{-7} cm/s).

A.2.3 Hazardous Waste Landfill in Illinois

Griffin et al. [1983] and Griffin et al. [1985] presented the results of a study of organic contaminants migration at a hazardous waste landfill. Hazardous waste was buried in 26 trenches. A compacted clay liner was used in at least one of the trenches, but for the most part the operation relied upon the natural clay tills at the site to contain the waste. Routine monitoring of wells revealed that organics had migrated as far as 15 m (50 ft) in a three year period, which is 100 times to a 1000 times faster than anticipated. These anticipated times were based on hydraulic conductivities measured in the laboratory. Subsequent field hydraulic conductivity tests indicated in situ permeabilities which were one to two orders of magnitude larger than those measured in the laboratory. The laboratory hydraulic conductivity of the soil layer with the highest degree of contamination ranged from 3.3×10^{-11} to 2.7×10^{-10} m/s (3.3×10^{-9} to 2.7×10^{-8} cm/s), while the field hydraulic conductivities ranged from 8.4×10^{-10} to 2.5×10^{-8} m/s (8.4×10^{-8} to 2.5×10^{-6} cm/s). The results show the types of variations between field and laboratory measured hydraulic conductivities and provide an indicator of the effect of scale on this parameter.

A.2.4 Field Scale Test Liner

Rogowski [1986] reported on results of a field scale research facility constructed to evaluate the hydraulic conductivity of compacted soil liners. The facility enables construction of a compacted soil liner 9.1 m (30 ft) by 22.9 m (75 ft) in area and 0.3-m (1-ft) thick. A set of collector drains are situated beneath the liner and a set of 250 infiltration cylinders are located on top of the liner. Compacted clay liners can be constructed in the facility using standard field equipment and procedures. Variables measured during testing include infiltration, exfiltration, and compacted soil density.

The soil used by Rogowski to construct the clay liner was defined as a cherty silt loam composed primarily of illite and kaolinite, with small amounts of montmorillonite. The laboratory hydraulic conductivity of this soil measured in a falling head permeameter is about 1 to 2 x 10^{-10} m/s (1 to 2 x 10^{-8} cm/s). Shortly after the start of the field test (which involved the ponding of water on top of the liner), exfiltration out of the bottom of the liner was observed. The rate of exfiltration increased steadily during the first 7 to 8 months after ponding and then began to decline. Based on infiltration rates after 9 months, and measured hydraulic gradients, hydraulic conductivity values were calculated. The results of this calculation are provided in Figure A-1. The conductivities of 10^{-7} m/s (10^{-5} cm/s) are believed to have been influenced by the proximity of the soil to the edge of the liner box. It can be seen that the remaining hydraulic conductivities range over several orders of magnitude, from about 10^{-8} to 10^{-10} m/s (10^{-6} to 10^{-8} cm/s). It is observed that this range of hydraulic conductivities has a lower limit corresponding to the hydraulic conductivity measured in the laboratory and an upper limit several orders of magnitude larger than the hydraulic conductivity measured in the lab. As of this date, no clear explanation has been obtained for the observed distribution of calculated hydraulic conductivities.

A.3 SURFACE IMPOUNDMENTS

A.3.1 Three Surface Impoundments in Texas

Daniel [1984] documented four case histories where laboratory hydraulic conductivity tests underpredicted the hydraulic conductivities back calculated from measurements of seepage through compacted soil liners. The surface impoundments were used to retain fresh water, salt water, or contaminated liquid. Three of the case histories are summarized here in this section, the fourth is summarized in Section A.3.2.

A.3.1.1 Two Ponds in Central Texas

Two ponds, each covering 0.8 ha (2 acres) and 1.5 m (5 ft) deep, were constructed at a manufacturing plant to hold fresh water. Each pond was lined with a 0.3 m (1 ft) clay liner compacted in two lifts with sheepsfoot rollers. A geotechnical consultant recommended, on the basis of laboratory results (standard Proctor compaction tests and triaxial permeability tests), that the clay liner be compacted wet of optimum. Several days after installation of the clay liner the geotechnical consultant was asked to inspect the liner. Moisture content measurements of the clay liner at the time of inspection revealed that it had either been compacted dry of optimum or it had dried since the time of placement. Attempts were made to fill the pond and the rate of leakage through the liner was several hundred times larger than anticipated. The hydraulic conductivities of the clay liners were back calculated from the observed rates of leakage and were found to be on the order of 2×10^{-8} to 5×10^{-9} m/s (2×10^{-6} to 5×10^{-8} cm/s). To reduce the leakage rate it was necessary to drain the pond, then remove and recompact the clay liner wet of optimum (field moisture content measurements were not taken). Water was pumped into the ponds within 30 minutes of recompaction to prevent desiccation. This procedure reduced the leakage rate enough so that the pond could be filled to the design depth and operated satisfactorily. The back calculated hydraulic conductivity of the recompacted liner was estimated to be 5×10^{-8} m/s (5×10^{-6} cm/s).

A.3.1.2 Evaporation Pond in North Texas

A 10 ha (25 acre) evaporation pond was constructed at a power plant by mixing bentonite into the upper 200 mm (8 in) of natural soil and recompacting this mixture. The pond went into operation in 1970 and by 1978 it was apparent that leakage from the pond had contaminated nearby wells. The average rate of leakage over the eight year period was back calculated to be approximately 40 000 liters/1000m^2/day (40,000 gallon/acre/day). The hydraulic conductivity was back-calculated to be approximately 3 x 10^{-8} m/s (3 x 10^{-6} cm/s). Samples of the soil were recompacted in the laboratory and the hydraulic conductivity was measured using water from the pond as the permeant. The laboratory measured hydraulic conductivities ranged from 2 x 10^{-8} to 2 x 10^{-7} m/s (2 x 10^{-7} to 2 x 10^{-9} cm/s).

The pond was taken out of service and a new pond was constructed with a compacted soil liner consisting of three 150 mm (6 in) thick lifts of a mixture of bentonite and local soil. The performance of the new lining system was not documented, however, collection wells were installed to recover the contaminated ground water.

A.3.1.3 <u>Brine Ponds in Southern Texas</u>

Two ponds (referred to as eastern and western ponds) were constructed at a chemical plant for the purpose of retaining a 25% brine solution. The ponds were constructed by excavating to a depth of 1.5 m (7 ft) below the ground surface, and then lining the excavations with 0.6 m (2 ft) of compacted clay. The construction procedure was poorly documented. The ponds were not put into service until two years after construction.

Contamination was detected in a nearby monitoring well within one month of putting the eastern pond into service. The brine was transferred to the western pond. The compacted clay liner in the eastern pond was removed and recompacted, however, this effort had no effect on the performance of the pond. During reconstruction of the eastern pond the western pond was found to be leaking. Monitoring of the western pond over a six month period provided data from which a hydraulic conductivity of 1 x 10^{-7} to 2 x 10^{-7} m/s (1 x 10^{-5} to 2 x 10^{-5} cm/s) was back calculated. This range of hydraulic conductivity is approximately two orders of magnitude larger than those measured on laboratory tests performed on undisturbed samples taken from the ponds just prior to filling with brine. The laboratory tests were permeated with the brine for two weeks and the measured hydraulic conductivity was on the order of 1 to 4 x 10^{-9} m/s (1 to 4 x 10^{-7} cm/s).

The leakage from the eastern pond was eventually minimized by installing a FML, while the use of the western pond was limited.

A.3.1.4 Conclusions

Several important conclusions can be drawn from the case histories summarized in Daniel [1984]. Drying of compacted soil liners can result in an increase in permeability and every effort should be taken to cover the compacted soil surface as soon as possible after construction. Construction quality assurance should be implemented to verify that the desired state of compaction is achieved. Drying and improper placement can increase a soil layer's hydraulic conductivity by up to one to two orders of magnitude.

A.3.2 Cooling Pond in Mexico

Auvinet and Espinosa [1981] summarized the results of field and laboratory hydraulic conductivity tests. The field tests included permeation of a 2 m by 2 m (6 ft by 6 ft) by 0.6 m (2 ft) thick clay liner, and a larger 50 m by 50 m (150 ft by 150 ft) test pond surrounded by 6 m (20 ft) dikes. These test sections were constructed as part of a study for a 300 hectare (740 acre) compacted clay lined cooling pond.

Great care was required in the construction of the lining system to achieve the desired hydraulic conductivity. The construction procedure used was to first thoroughly mix the soil while adding water (to a water content slightly greater than the optimum Proctor water content) and allowing it to cure for approximately one week. This was done to achieve a uniform water content throughout the soil, which is essential for obtaining a low-permeability soil. The compaction procedure was as follows:

" • The surface on which the lining was to rest was watered and recompacted with several passes of a crawler-type tractor. After that, the surface was smoothed and sealed with passes of a heavy (12 tonne) farm tractor.

- The homogenized and cured material for the first layer was brought in and spread by motorscrapers.

- A uniform 20-cm thickness was given to the loose layer with the blade of the crawler-type tractor.

- Water was added by sprinkling to raise the water content of the clay to about 5 percent above the Proctor optimum value.

- New passes of the crawler tractor helped to homogenize the material.

- The clay was remolded by passes of the heavy farm tractor (eight passes as an average).

- When the surface was sufficiently smooth to be traveled, the same process was repeated for the next layer."

Also, special attention was given to dry spots and areas which did not visually appear to be at the desired state of compaction.

The back-calculated hydraulic conductivity of the field test was slightly higher than 1×10^{-8}m/s (1×10^{-6} cm/s), while hydraulic conductivities obtained from laboratory triaxial permeability tests on undisturbed field samples were 10^{-10} m/s (10^{-8} cm/s) or lower.

The hydraulic conductivities achieved in the field tests were considered acceptable and the construction procedures used in the tests were adapted to construct the main cooling ponds.

It can be concluded that even with good control on the placement and compaction of a soil liner, the field permeability may be less than that achieved in the laboratory.

A.3.3 Two Prototype Compacted Clay Lining Systems

Day and Daniel [1985] present the results of two prototype clay liners which were designed, constructed, and tested to measure field hydraulic conductivity. A different clay type was used for each liner and their properties are summarized in Table A-2. Clay 1 classified as a low plasticity clay (CL) while Clay 2 classified as a high plasticity clay (CH). Each clay liner tested was approximately 6-m (20-ft) on a side and 150-mm (6-in.) thick. Underlying the compacted clay liner was a geotextile lateral drain. The geotextile drain was underlain by a FML. Any leakage through the compacted clay liner was transmitted by the geotextile drain to a monitoring station, where the outflow was measured. From the measured rate of outflow, the field hydraulic conductivities were calculated to be approximately 9×10^{-8} m/s (9×10^{-6} cm/s) and 4×10^{-8} m/s (4×10^{-6} cm/s) for Clays 1 and 2, respectively. However, it was noted by the authors that "Based on the average compaction water content and dry unit weight of each liner and the results of the permeability tests on the laboratory-compacted samples, the hydraulic conductivities that would be expected for the liners would be approximately 1×10^{-10} m/s (1×10^{-8} cm/s) for Clay 1 and 2×10^{-11} m/s (2×10^{-9}) cm/s) for Clay 2."

From the above results it can be observed that the hydraulic conductivities measured in the field were approximately 1000 times larger than that measured in the laboratory. Day and Daniel [1985] suggested several reasons for this large difference. First, clods of soil up to 100 mm (4 in.) were present in the field while the soil used in the laboratory tests contained clods smaller than 30 mm (1 in.). Second, it is possible that secondary structures such as cracks, fissures, joints, etc., were present in the field liner but not in the lab samples. Third, zones of poor compaction may have resulted in a clay liner of variable hydraulic conductivity.

Field hydraulic conductivity tests with the ring infiltrometer were also performed. These tests measured a hydraulic conductivity of the clay liner which was slightly larger but within an order of magnitude of the hydraulic conductivity back-calculated from ponding test.

It can be concluded that laboratory testing cannot account for all of the potential secondary structures which may exist in a compacted clay liner, and large scale in situ tests seem to provide a better indication of the actual field hydraulic conductivity.

A.4 SUMMARY

In all cases where field and laboratory data were available, it was found that the field measured hydraulic conductivity was up to an order of magnitude or more higher than the laboratory measured hydraulic conductivity. The range of values obtained and the probable cause of the difference between the laboratory and field measured values are summarized in Table A-3. Only the more conclusive case histories have been summarized in this table. It can be observed that many factors can have an affect on the performance of a compacted soil liner. Most of these factors relate to secondary structures (nonuniformities) in the compacted soil liner caused by:

- desiccation cracks;
- soil clods;
- spatial variation in compactive effort and compaction water content; and
- quality assurance of construction operation.

It should be realized that the above variables, which effect field performance, are seldom reproduced in standard laboratory tests. Therefore, achieving the desired hydraulic conductivity in the laboratory does not guarantee the same value will be obtained in the field. However, it is possible to achieve a hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) in the field and this is the design objective of the EPA. Achieving this goal requires the proper soils, compaction procedures, and construction conditions. Recognizing the number of factors which can affect the hydraulic conductivity, and that the design goal is not always achieved, the analyses presented in Chapter 3 of the background document should consider both a standard hydraulic conductivity of 10^{-9} m/s (10^{-7} cm/s) and a lower bound hydraulic conductivity of 10^{-8} m/s (10^{-6} cm/s). This lower value of conductivity might be representative of a compacted soil liner with some degree of secondary structure resulting from nonuniform compaction conditions, soil clods, drying or other factors. Therefore, these hydraulic conductivities will be used in the investigation of detection sensitivity, collection efficiency, leakage from the unit, and breakthrough time for compacted soil liners presented in Chapter 3.

Table A-1. Typical values of silty clay till hydraulic conductivities. [Goodall and Quigley, 1977]

Depth (m)	Method	Coefficient of permeability k (cm/s at 7°C)
1.5	Lab—direct, constant head	6.3×10^{-7}
1.5	Lab—direct, constant head	1.7×10^{-6}
1.5	Lab—Harvard miniature (remoulded)	1.0×10^{-7}
2.7	Field—uncased auger hole	1.8×10^{-7}
5.5	Lab—consolidation	2.2×10^{-8}
5.5	Lab—consolidation	2.4×10^{-8}
5.5	Lab—consolidation	2.4×10^{-8}
6.7	Lab—consolidation	2.3×10^{-8}
6.7	Lab—consolidation	1.5×10^{-8}
7.6	Field—Ogunbadejo piezometer	1.2×10^{-8}
8.2	Field—borehole 4, Confederation	1.3×10^{-8}
9.1	Lab—direct, falling head	1.7×10^{-8}
11.6	Field—borehole 1, Blackwell	1.6×10^{-8}
14.3	Field—borehole 8, Confederation	1.6×10^{-8}
17.1	Lab—direct, falling head	2.6×10^{-8}
18.3	Field—Ogunbadejo piezometer	5.2×10^{-8}
21.6	Lab—direct, falling head	2.9×10^{-8}
27.4	Field—Ogunbadejo piezometer	3.5×10^{-8}

Table A-2. Properties of clays used in construction of prototype compacted clay liner. [Day and Daniel, 1985]

Property (1)	Clay 1 (2)	Clay 2 (3)
Liquid limit, as a percentage	30	72
Plastic limit, as a percentage	19	27
Plasticity index, as a percentage	11	45
Percent passing No. 200 sieve	80	50
Soil classification	CL	CH

Table A-3. Comparison of field and laboratory hydraulic conductivities.

Field Hydraulic Conductivity (m/s)	Laboratory Hydraulic Conductivity (m/s)	Probable Cause for Difference	Reference
8.4×10^{-10} to 2.5×10^{-9} [a,c]	3.3×10^{-11} to 2.7×10^{-10}	joints and fissures in natural material	Griffin et al. [1985]
3×10^{-4} [b,d]	2×10^{-6} to 2×10^{-7} [b]	cracks caused by drying	Daniel [1984]
1×10^{-7} to 2×10^{-7} [b,d]	1×10^{-9} to 4×10^{-9} [b]	cracking caused by drying	Daniel [1984]
1×10^{-8} m/s	$< 10^{-10}$ m/s	limitations of field placement and compaction procedure (even with construction quality assurance)	Auvinet and Espinosa [1981]
9×10^{-8} m/s 4×10^{-8} m/s	1×10^{-10} m/s 2×10^{-11} m/s	variation in liner due to soil clods, cracks, or variation in compactive effort	Day and Daniel [1985]

[a] - natural soil

[b] - compacted soil liner

[c] - measured in field test

[d] - backcalculated

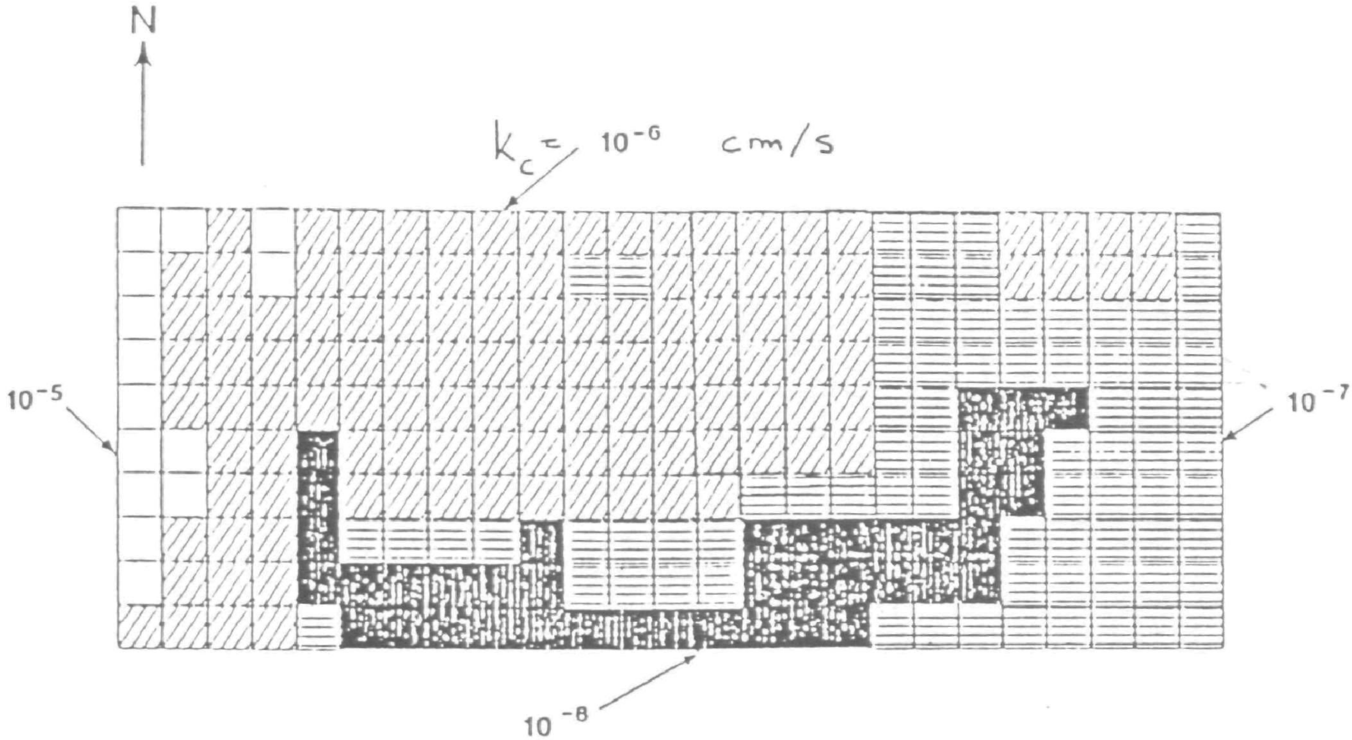

Figure A-1. Distribution of hydraulic conductivity in 0.3 m (1.0 ft) thick compacted clay liner after 9 months of ponding (liner dimensions, 9.1 x 22.9 m (30 x 75 ft)). [Rogowski, 1986]

APPENDIX B

ANALYSIS OF LEAKAGE THROUGH COMPOSITE BOTTOM LINERS

B.1 INTRODUCTION

B.1.1 Scope

Appendix B discusses leakage through composite liners with a view to evaluate leakage through bottom liners of hazardous waste management units.

Leakage through composite liners should first pass through the FML which is the upper component of the composite liner. Leakage through a FML is due to permeation through the FML and flow through holes in the FML. Evaluation of leakage through a composite liner due to holes in the FML is a complex matter and, accordingly, several sections of this appendix are devoted to this topic.

B.1.2 Organization

Appendix B is organized as follows:

- Section B.2: leakage due to permeation through the FML.
- Section B.3: discussion on frequency and size of FML defects.
- Section B.4: analytical studies related to leakage through composite liners due to holes in the FML.
- Section B.5: model tests on composite liners with a hole in the FML.
- Section B.6: conclusions on leakage through composite liners specific to bottom liners.

B.2 LEAKAGE DUE TO PERMEATION THROUGH FML

B.2.1 Permeameter Tests

Tests conducted at the University of Grenoble (France) by Giroud from 1973 to 1978 and, then, by Gourc and Faure using a permeameter similar to those used to measure clay permeability (Figure B-1) have shown that water flows through an FML.

Results of these tests have been published by Giroud [1984a, 1984c]. In these publications, Darcy's equation has been used to interpret the test results and calculate equivalent hydraulic conductivities which vary significantly with the hydraulic head (and, consequently, the hydraulic gradient).

B.2.2 The Concept of Coefficient of Migration

It is preferable to interpret the permeameter tests discussed above using the following equation proposed by Giroud et al. [1987]:

$$v = Q/A = \mu_g/T \qquad \text{(Equation B-1)}$$

where: Q = flow rate due to permeation through the FML; A = surface area of the considered FML; Q/A = flow rate per unit area; μ_g = coefficient of migration of the FML; and T = FML thickness. Recommended SI units are: Q (m^3/s), A (m^2), Q/A (m/s), μ_g (m^2/s), and T (m).

Values of the coefficient of migration for various FMLs are given in Table B-1. Although there are not enough test results to draw a firm conclusion, it appears that the coefficient of migration increases as the hydraulic head increases up to some maximum value, μ_{max}. For heads larger than approximately 10 meters (30 ft), $\mu = \mu_{max}$. The value of μ_{max} depends on the polymer used to make the FML. The value of μ is obviously zero for a hydraulic head equal to zero. Therefore, the typical shape of the curve of the coefficient of migration versus hydraulic head is given as shown in Figure B-2.

It is difficult to conduct water permeability tests on FMLs with a head of water smaller than 5 m (16 ft) because the flow rates are too small to be accurately measured. The hydraulic heads that are relevant to hazardous waste management units are usually smaller than 5 m (16 ft). Therefore it is useful to complement results from the permeameter tests cited above by results from water vapor transmission tests which are typically conducted with a pressure on the order of 1 to 10 kPa (0.15 to 1.5 psi), i.e., a hydraulic head on the order of 0.1 m to 1 m (4 in. to 40 in.).

B.2.3 Water Vapor Transmission Tests

Water vapor transmission tests are typically performed on thin membrane materials because the mechanism for fluid transport through membranes is believed to be one of molecular diffusion through a nonporous membrane [Haxo et al., 1984]. With this mechanism, transport through the membrane involves three steps: (i) dissolution of the fluid into the membrane; (ii) diffusion of the fluid through the membrane; and (iii) evaporation or dissolution of the fluid on the downstream side of the membrane. According to Haxo et al. [1984], the major driving force for the movement of a given fluid through a membrane is its concentration gradient across the membrane. In the case of water, the important concentration gradient is suggested to be the water vapor pressure, and moisture is thought to move through the membrane by water vapor diffusion. It is important to note that water vapor diffusion decreases when the thickness of the membrane increases, but is not dependent on the hydraulic head acting on the membrane.

Haxo et al. [1984] have described a water vapor transmission test (ASTM E96, Procedure BW) and have used it to measure water vapor transmission rates for the range of FML materials given in Table B-2. Values of water vapor transmission rates obtained from other sources are given in Table B-3.

Knowing the water vapor transmission rate of a given FML obtained in a given test, the quantity of vapor permeating through this FML can be calculated using Fick's equation:

$$M/(At) = (WVT)\ (T_o/T)\ (\Delta p/\Delta p_o) \qquad \text{(Equation B-2)}$$

where: M = mass of vapor migrating through the FML; A = FML surface area; t = time (i.e., duration of the permeation); WVT = water vapor transmission rate; T_o = FML thickness used in the water vapor transmission test; T = considered FML thickness; Δp = vapor pressure difference between the two sides of the considered FML; and Δp_o = vapor pressure difference between the two sides of the FML used in the water vapor transmission test. Recommended SI units are: M (kg), A (m^2), t (s), WVT ($kg/m^2.s$), T_o and T (m), and Δp and Δp_o (N/m^2). (Note: 1 g/m^2.day = 1.16×10^{-8} $kg/m^2.s$).

Vapor pressure is given by:

$$p = p_S H \qquad \text{(Equation B-3)}$$

where: p_S = vapor pressure at saturated point; and H = relative humidity.

Therefore, Equation B-2 can be written as follows:

$$M/(At) = (WVT)\ (T_o/T)\ (\Delta H/\Delta H_o) \qquad \text{(Equation B-4)}$$

where: ΔH = relative humidity difference between the two sides of the considered FML; ΔH_o = relative humidity difference between the two sides of the FML used in the water vapor transmission test; and other notation as for Equation B-2.

It should be pointed out that the use of Equations B-2 and B-4 should be restricted to pressures that are not too different from the pressures typically used to conduct the water vapor transmission test (e.g., pressures on the order of 1,000 to 10,000 Pa (0.15 to 1.5 psi), i.e., hydraulic heads on the order of 0.1 to 1 m (4 to 40 in.) of water).

According to Fick's equation (Equation B-2), there is no permeation through an FML if the relative humidity is the same on both sides of the FML. This is the case, in particular, if there is water on both sides, even if there is a pressure difference. This is in disagreement with results obtained using a permeameter, which were presented in Section B.2.1. More research is therefore needed on this subject.

B.2.4 Relationships between Various Expressions of Flow Rate

In order to use water vapor transmission test results to complement permeameter test results, it is necessary to establish relationships between the various coefficients used to express flow rate.

An equivalent hydraulic conductivity for FMLs can be obtained by expressing flow rate through a FML using Darcy's equation:

$$v = Q/A = k_g \, i \qquad \text{(Equation B-5)}$$

where: v = apparent velocity of the flow; Q = flow rate; A = area perpendicular to the flow; k_g = equivalent hydraulic conductivity of the FML; and i = hydraulic gradient.

By comparing Equation B-1 with Equation B-5, it appears that:

$$\mu_g = k_g \, h \qquad \text{(Equation B-6)}$$

where: μ_g = coefficient of migration of the FML; k_g = equivalent hydraulic conductivity of the FML; and h = hydraulic head. Recommended SI units are: μ_g (m^2/s), k_g (m/s), and h (m).

By comparing Equation B-5 (Darcy's equation) with Equation B-2 (Fick's equation), it appears that:

$$WVT = p \, k_g/g \, T = \rho \, k_g \, h/T \qquad \text{(Equation B-7)}$$

By combining Equations B-6 and B-7, it comes:

$$WVT = \rho \, \mu_g/T \qquad \text{(Equation B-8)}$$

where: k_g = FML equivalent hydraulic conductivity; g = acceleration of gravity; T = FML thickness; WVT = FML water vapor transmission rate; p = pressure; ρ = liquid density; h = hydraulic head; and μ_g =

coefficient of migration. The recommended SI units are: k_g (m/s), g (m/s^2), T (m), WVT ($kg/m^2.s$), p (Pa), ρ (kg/m^3), h (m), and μ_g (m^2/s). A useful conversion factor for WVT is:

$$1 g/m^2/day = 1.16 \times 10^{-8} \; kg/m^2/s$$

Using Equation B-8, the measured water vapor transmission (WVT) values given in Tables B-2 and B-3 have been converted into values of the coefficient of migration. It is interesting to see in Table B-2 that series of tests on a given product (e.g., series of four tests on PVC) with various thicknesses generally give consistent values of the coefficient of migration.

There are not enough values in Tables B-1, B-2 and B-3 to establish a complete table of values of coefficient of migration, μ_g, for FMLs. It is therefore necessary to draw curves such as those in Figure B-3 to make interpolations and extrapolations for small values of the hydraulic head. Also, Tables B-1, B-2 and B-3 contain discrepancies and apparently erratic results due to the difficulty of the tests and the sometimes great differences between FMLs of the same type. Therefore some averaging was necessary. Values of the coefficient of migration from Tables B-1, B-2 and B-3 are summarized in Table B-4. Figure B-3 was established using values of the coefficient of migration given in Table B-4.

The large discrepancy between water vapor transmission rates measured on PVC at 0.14 m head (Table B-2) and 0.6 m head (Table B-3) probably result from the fact that the PVC tested at 0.14 m head was a FML made of plasticized PVC and the PVC tested at 0.6 m was pure PVC. Plasticized PVC is swelled by the plasticizers and tends to be more permeable than pure PVC (such as the stiff PVC used to make bottles, which has a very low permeability).

B.2.5 Leakage Rate Evaluation

From Figure B-3, it is possible to establish Table B-5 which gives our best estimate of coefficient of migration values from the analyzed data. From Table B-5, it is possible, using Equation B-1, to establish Table B-6 which gives leakage rates due to permeation through FMLs, assuming an FML thickness of 1 mm (40 mils).

B.2.6 Migration of Chemicals

Many types of FMLs swell when placed in contact with chemicals. As a result, the distance between polymeric chains increases and permeability increases. Therefore, an FML can have a low permeability to water and a high permeability to some chemicals. Data regarding permeation of FMLs by chemicals can be found in [Haxo et al., 1984] and [Telles et al., 1986].

B.3 FREQUENCY AND SIZE OF FML DEFECTS

B.3.1 Purpose

The purpose of this section is to evaluate the size and frequency of defects which can occur in a FML. This information is necessary for making analytic calculations to evaluate leakage through top liners (FML alone as well as composite liners). Although this section is devoted to all types of defects, it focuses primarily on seam defects because forensic analyses have shown that leakage through FML liners is often due to defective seams, and the most complete documentation of FML defects is for seam defects.

This section is organized as follows: first, data from construction quality assurance and forensic analyses are reviewed, then conclusions are drawn from these data.

B.3.2 Data from Construction Quality Assurance

- Small Liquid Reservoir

This project, constructed in 1981, is described in detail by Giroud and Stone [1984], and Stone [1984]. Information regarding seam defects can be summarized as follows.

The double liner system includes two 2.5 mm (100 mil) thick HDPE FMLs which were welded using an automated extrusion welder. Ultrasonic testing, carried out as part of the quality control and quality assurance program, showed that approximately 0.5% of the seam length was defective. The detected defects were repaired and the reservoir was filled with water. Leakage occurred and an inspection showed that leakage was taking place through approximately 0.015% of the seam length. The ratio 0.5/0.015 shows that, in this project, intensive quality assurance divided the length of defects by approximately 30.

This project is particularly interesting because it provides an evaluation of the benefits from construction quality assurance.

- Large Landfill with Single Liner

Kastman [1984] indicates that in a carefully monitored landfill liner installation done in 1983, approximately one defect every 15 m (50 ft) of seam was detected and repaired, as part of the quality assurance process. The liner was a 1 mm (40 mil) thick HDPE FML and seaming was achieved with a fillet extrusion weld done using a hand welder.

- Large Landfill with Double Liner

Giroud and Fluet [1986] report the result of an analysis conducted on the basis of data collected during the quality assurance process of liner installation in a large landfill, lined in 1985 with an HDPE FML. The surface area of the liner is approximately 35 000 m^2 (350,000 ft^2) and seam length is approximately 5000 m (16,000 ft). During the quality assurance process, an average of approximately one seam defect every 9 m (30 ft) of seam length was discovered and repaired.

- Large Landfill with Single Liner

This case history presents the results of an analysis conducted on the basis of data available in GeoServices files. The data were collected during the installation of the lining system in a large landfill, in 1987, as part of the quality control provided by the FML installer and quality assurance provided by an independent firm. The surface area of the liner is approximately 53 000 m² (570,000 ft²) and seam length is approximately 8000 m (26,000 ft). The liner was a 1.5 mm (60 mil) thick HDPE FML. Half of the seam length was welded using a hand welder which made fillet extrusion welds; the other half was welded using an automated flat welder. An average of approximately one seam defect every 11.5 m (38 ft) of seam length was discovered by the FML installer and the independent quality assurance firm. All these defects were repaired. Seam inspection was performed first by the installer, and then by the independent firm after the installer had completed his inspection. The installer detected approximately one seam defect every 17 m (56 ft) of seam length. The independent firm detected approximately one seam defect every 35 m (115 ft) of seam length.

This project is interesting because it provides an evaluation of the benefits from construction quality assurance. The independent firm discovered additional seam defects, after the installer had completed his quality control inspection. The defects discovered by the independent firm totaled one third of the total seam defects. The benefits of quality assurance are probably greater than that: it is probable that, without the continuous presence at the site of the independent quality assurance firm, the FML installer would have found fewer defects than he did as part of his quality control effort.

B.3.3 Data from Forensic Analyses

- Small Indoor Tank

The following case history is reported by Giroud and Fluet [1986].

A power generating station required a small acid holding tank, which was constructed of concrete and lined in 1985 with a high density polyethylene (HDPE) FML which required approximately 100 m (300 ft) of field seaming. The seams were fillet welds done with a hand welder. The design and installation included no third party quality assurance, but careful quality control of seaming was provided by the installer, using visual inspection and vacuum box.

Upon completion of the liner installation, the tank was filled with water to check for leaks. The liner did leak, so the tank was emptied, repairs were made and the tank was filled again. This cycle was repeated several times, with leaks found on every filling. Leaks were found at 15 different locations, i.e. an average of one leak per 7 m (23 ft) of seam.

- Large Surface Impoundment

The following case history is reported by Giroud and Fluet [1986].

A large reservoir, lined with a single reinforced chlorosulfonated polyethylene (CSPE-R) FML, had been constructed to contain phosphoric acid. The reservoir was approximately 3 m (10 ft) deep and its surface area was approximately 20 000 m^2 (200,000 ft^2).

One year after the first filling, the reservoir suddenly emptied. The analysis of the failure indicated that phosphoric acid, leaking through several defective seams, attacked the ground, creating cavities. The largest cavity was one meter (three feet) in diameter and half a meter (20 inches) deep. Under the pressure of the impounded liquid, the FML spanning this largest cavity burst, releasing all of the impounded phosphoric acid into the ground.

Quality assurance during installation had consisted of only two one-day visits by an engineer who specialized in roofing membranes. Therefore, it is not surprising that defective seams were not detected prior to filling.

During the forensic analysis, visual observation showed that approximately 0.1% of the seam length was defective. It is probable that a higher percentage would have been obtained if a vacuum box had been used instead of the visual inspection.

B.3.4 Conclusions on Frequency of Defects

- Consistency of the Observations

Sections B.3.2 and B.3.3 present data related to frequency of seam defects. Some of these data are expressed as an average seam length exhibiting one defect (e.g., one defect per 7 m (23 ft) of seam), while other data are expressed as percentage of defective seam length (e.g., 0.5% of the total seam length was defective).

If an average length of seam defect (prior to quality assurance) of 25 mm (1 in.) is considered, a percentage of defective seam length of 0.5% is equivalent to one defect every 5 m (17 ft). Therefore, the above observations appear to be consistent.

- Conclusion Regarding Frequency of Seam Defects

It is not possible to draw general conclusions from only six cases. However, since the observations made in these six cases were consistent it is possible to draw the following tentative conclusions:

- An average of one defect per 10 m (30 ft) of seam can be expected without quality assurance.

- An average of one defect per 300 m (1,000 ft) of seam can be expected with reasonably good installation, adequate quality assurance, and repair of noted defects. (Quality assurance followed by adequate repair drastically decreases the number of seam defects but may not totally eliminate them.)

The average of one seam defect per 10 m (30 ft) without or before quality assurance will probably decrease in the future as a result of the increasing use of new, automated methods of seaming which are now available. However, the number of seam defects after quality assurance may not decrease significantly because, in the present state of practice for construction quality assurance, great emphasis is put on finding seam defects and repairing them. Nonetheless, the better seaming methods that are now available are highly beneficial for at least the following reasons: (i) less seam repair is required during installation; (ii) frequency of destructive seam testing may be decreased; (iii) quality assurance effort may shift toward other areas where improvement is sorely needed such as connections of FMLs with appurtenances and placement of drainage materials (which is essential for the functioning of leak detection systems); and (iv) stronger seams that are less likely to fail when subjected to stresses.

As a result of the above discussion, a frequency of one defect per 300 m (1,000 ft) of seam can be used as a working assumption. If FML panels 6 to 10 m (20 to 30 ft) wide are used, one defect per 300 m (1,000 ft) of seam is equivalent to 3 to 5 seam defects per hectare (1 to 2 seam defects per acre) of installed FML.

As soon as possible, these tentative conclusions must be supplanted and modified as required by conclusions established on a broader base of well documented case histories. In the meantime (and in the absence of better data), a frequency of one or two defects per 4000 m^2 (acre) will be used in calculations for estimating leakage rate in order to size leak detection drainage layers. This frequency is assumed to include all types of defects, not only seam defects.

B.3.5 Estimation of Size of Defects

The seam defect documentation reported above addressed primarily the frequency of seam defects. Extensive documentation of defect size does not exist. On the basis of interviews with quality assurance personnel it appears that the maximum size of defects which may still exist after intensive quality assurance is equivalent to hole diameters on the order of 1 to 3 mm (0.04 to 0.12 in.) for seam defects and maybe up to 5 mm (0.2 in.) for special areas such as connections of FML with appurtenances.

There are also defects that cannot be observed by the quality assurance personnel, such as: (i) puncture of the FML during installaticn of the protective earth cover; and (ii) puncture of the FML as a result of stresses due to the weight of waste or traffic related to the operation of the hazardous waste management unit.

Therefore, for design purposes it may be appropriate and conservative to consider a hole larger than the expected size of defects at the end of FML installation (which were estimated above as 5 mm (0.2 in.) maximum in diameter).

B.3.6 Standard Hole Size and Frequency

For the consistency of calculations and discussions supporting the Notice of Data Availability, it is recommended that a standard hole size and frequency be selected. The same standard hole size and frequency will also be useful as guidance for designers of leak detection systems.

As a result of the above discussions, a standard hole area of 1 cm^2 (10^{-4} m^2 or 0.16 in^2.) has been selected, and, on the basis of the discussion presented in Section B.3.4, a frequency of one standard hole per 4000 m^2 (acre) is considered. The standard hole area and frequency are used in this background document for calculations done to evaluate leakage rates, and they are recommended, as well, for design calculations.

It should be kept in mind that the standard hole size and frequency have been selected with the assumption that intensive quality assurance monitoring will be performed. Also, the standard hole size and frequency do not take into account cases where design flaws or poor construction practices would lead to many seam defects or a large tear in the FML.

B.4 ANALYTICAL STUDIES

B.4.1 Introduction

B.4.1.1 Purpose of the Section

This section discusses leakage through composite liners due to a hole in the FML. The purpose of this discussion is to draw practical conclusions regarding the evaluation of leakage rate through composite top liners.

B.4.1.2 Leakage Mechanisms

A composite liner is comprised of a FML (which is the upper component of the composite liner) and a low-permeability compacted soil layer (which is the lower component of the composite liner). If there is leakage through a composite liner, the leachate first migrates through the FML, then may travel laterally in the space, if any, between the FML and the low-permeability compacted soil, and, finally, migrates through the low permeability soil.

There are two mechanisms by which leakage can migrate through a FML:

- permeation through the FML (i.e., flow through a FML that has no defects); and

- flow through holes in the FML.

Leakage rate due to permeation through the FML should not be significantly affected by the presence of the low-permeability compacted soil layer under the FML because even a soil with a very low permeability is still very permeable as compared to a FML without holes and pinholes. The case of permeation through a FML without holes was discussed in Section B.2.

The leachate that has passed through the FML can flow laterally to a certain extent between the FML and the low-permeability compacted soil, before it migrates through the low permeability soil. This is possible if there is a space between the FML and the low permeability soil.

B.4.1.3 Organization of this Section

Two types of analytical studies can be found in the literature:

- analytical studies assuming that there is perfect contact between the FML and the low-permeability compacted soil, and, consequently, that the leachate does not flow laterally between the FML and the low-permeability compacted soil; and

- analytical studies assuming that leachate flows laterally between the FML and the low-permeability compacted soil before it migrates through the low permeability soil.

B.4.2 Analyses Assuming Perfect Contact

- Assumptions

Faure [1979] has made an extensive study of the leakage rate through a composite liner due to a hole in the FML, assuming perfect contact between the FML and the underlying low permeability soil. First, Faure considered two simple two-dimensional cases:

- flow net established by considering that the entire soil layer is saturated (Figure B-4 a); and

- radial flow (Figure B-4 b) which leads to a convenient close form solution for the leakage rate (the radial flow was thought to be a reasonable assumption for thick soil layers, but in fact is not, as shown by Faure (see Figure B-7)).

These two types of flow lead to absurd results (such as flow rate increasing when soil thickness increases). However, those cases are useful because Faure showed that they provide upper boundaries for the actual flow rate through the composite liner when the FML and the underlying soil are in perfect contact. Also the leakage rate in the case of the radial flow is expressed by a close form solution for the three-dimensional case (circular hole), which provides a convenient upper boundary for the three-dimensional case. This is very useful because the three-dimensional case is very difficult to analyze and this upper boundary is one of the few theoretical data available for the three-dimensional case.

A lower boundary of the leakage rate is obtained by assuming that the flow is vertical (Figure B-4 c).

The actual flow if the FML and the low-permeability compacted soil are in perfect contact is shown in Figure B-4 d. This has been demonstrated in the two-dimensional case by:

- Faure [1979] who used numerical methods; and
- Sherard [1985] who traced flow nets by trial and error.

Both Faure and Sherard have shown that, in a two-dimensional flow:

- there is horizontal flow in the soil along a portion of the interface (although there is no flow between the FML and the soil because there is no space between the FML and the soil when perfect contact is assumed); and
- there is a phreatic surface beyond which the soil is not saturated.

These qualitative characteristics of the flow are certainly also applicable to the three-dimensional case (circular hole). Typical flow nets for the two-dimensional case are given in Figure B-5 and a chart giving the location of the phreatic surface in the two-dimensional case is presented in Figure B-6.

- Leakage Rates for the Two-dimensional Case

Leakage rates obtained with the various assumptions discussed above are given in Figure B-7 adapted from Faure. This figure shows that:

- absurd results are obtained with the upper boundaries, cases (a) and (b), when the low-permeability compacted soil thickness, H, is large; and
- case (c) is a very low lower boundary when the low-permeability compacted soil thickness, H, is large.

A chart giving the actual leakage rate (i.e., the leakage rate obtained in case d) when the FML and the underlying soil are in perfect contact has been prepared by Faure [1979, 1984] for the two-dimensional case (Figure B-8). The results given by Sherard [1985] for a limited number of cases are consistent with Faure's. Faure's chart (Figure B-8) is used with the following equation:

$$Q/B = C\ k_c\ (H + h) \qquad \text{(Equation B-9)}$$

where: Q = leakage rate; B = length of the slot in the direction perpendicular to the figure; Q/B = leakage rate per unit length; C = dimensionless coefficient given by the chart; k_c = hydraulic conductivity of the low-permeability compacted soil underlying the FML; H = thickness of the low-permeability compacted soil; and h = hydraulic head on top of the FML.

The equation for the two-dimensional radial flow (case (b) in Figures B-4 and B-7) which gives an upper boundary for the actual leakage rate is obtained by integrating Darcy's equation for a circular domain:

$$Q/B = \pi\ k_c\ (h + H)/\text{Log}\ (2H/b) \qquad \text{(Equation B-10)}$$

where: Q = leakage rate; B = length of the slot in the direction perpendicular to the figure; Q/B = leakage rate per unit length; k_c = hydraulic conductivity of the low-permeability compacted soil; h = head on top of the FML; b = width of the slot; and H = thickness of the low permeability soil underlying the FML. Recommended SI units are : Q (m^3/s); Q/B ($m^3/s/m$, i.e., m^2/s); k_c (m/s); h (m); b (m); and H (m).

The equation for the vertical flow (case (c) in Figures B-4 and B-7), which gives a lower boundary for the flow rate, is obtained by writing Darcy's equation for a rectangular domain:

$$Q/B = k_c\ b\ (h + H)/H \qquad \text{(Equation B-11)}$$

where the notation is the same as above.

This lower boundary gives a good approximation of the actual leakage rate if the ratio between the width of the FML hole and the thickness of the low permeability soil is large, which is rare.

The upper boundary provided by the radial flow (Equation B-10) is excessively high in many cases and increases when H/h is large and increases, as shown in Figure B-5. Since the leakage rate cannot increase if the thickness of the soil layer increases, the upper boundary is increasingly far from the actual leakage rate when H/h increases and, therefore, cannot be used as an approximation for the actual leakage rate.

Equation B-10 can be arbitrarily transformed by replacing h + H by h, which gives:

$$Q/B = \pi k_c h/\text{Log}(2H/b) \qquad \text{(Equation B-12)}$$

As it turns out, this equation can be used for large values of H/h where it gives a lower boundary (case (b_2) in Figure B-7) of the actual leakage rate which is not too far from the actual value (case (d) in Figure B-7).

These considerations regarding boundaries will be useful to provide guidance for an approximate evaluation of the leakage rate in the three-dimensional case (circular hole) where the actual value of the leakage rate is not known.

- Leakage Rate for the Three-Dimensional Case

In the case of a three-dimensional flow (circular hole), the actual flow is certainly limited by a bell-shaped phreatic surface similar to the phreatic surface of the two-dimensional flow (case (d) in Figure B-4, and Figure B-5). However, no analytical or numerical study is presently available to the best of our knowledge. An upper boundary and a lower boundary are available and they are expressed by close-form solutions.

The equation related to the three-dimensional radial flow (similar to the two-dimensional case (b) in Figure B-7), which gives an upper boundary for the actual leakage rate, is obtained by integrating Darcy's equation for a spherical domain:

$$Q = \pi \, k_c \, (h + H) \, d/(1 - 0.5d/H) \qquad \text{(Equation B-13)}$$

where: Q = leakage rate; k_c = hydraulic conductivity of the low-permeability compacted soil; h = hydraulic head on top of the FML; d = diameter of the circular hole; and H = thickness of the low permeability soil. Recommended SI units are: Q (m^3/s), k_c (m/s), h (m), d (m), and H (m).

The equation related to the vertical flow (similar to the two-dimensional case (c) in Figure B-4), which gives a lower boundary for the actual leakage rate, is obtained by writing Darcy's equation for a cylindrical domain:

$$Q = k_c \, a \, (h + H)/H \qquad \text{(Equation B-14)}$$

where: a = surface area of the hole in the FML ($a = \pi \, d^2/4$ if the hole is circular); and other notation as above.

As discussed for the two-dimensional case, Equation B-13 can be rewritten as follows:

$$Q = \pi \, k_c \, h \, d/(1 - 0.5d/H) \qquad \text{(Equation B-15)}$$

It is possible that this equation gives a lower boundary of the actual leakage rate when d/H is small (like Equation B-12 for the two-dimensional case). It is interesting to note that Equation B-15 tends toward a very simple limit when d/H tends toward zero:

$$Q = \pi \, k_c \, h \, d \qquad \text{(Equation B-16)}$$

where: Q = leakage rate; k_c = hydraulic conductivity of the low-permeability compacted soil underlying the FML; h = hydraulic head on top of the FML; and d = diameter of the circular hole in the FML.

Due to the lack of any better solution, Equation B-16 will be used as an approximation for the actual leakage rate.

Another approach for evaluating leakage rate in the three-dimensional case is to use the chart established by Faure for the two-dimensional case (Figure B-8) and modify Equation B-9 by replacing the length B of the slot by the perimeter πd of the circular hole (and not half the perimeter, nor the diameter of the hole as one may be tempted to do):

$$Q = \pi C k_c (H + h) d \qquad \text{(Equation B-17)}$$

where: Q = leakage rate; C = dimensionless coefficient given by Faure's chart (Figure B-8); k_c = hydraulic conductivity of the low-permeability compacted soil; H = thickness of the low permeability soil layer; h = hydraulic head on top of the FML; and d = hole diameter.

B.4.3 Analyses Assuming Flow between FML and Soil

- Introduction

Analytical studies have been conducted by Fukuoka [1986] and Brown et al. [no date]:

- Fukuoka considers the case where there is a geotextile (without a hole) between the FML (with a hole) and the soil. The liquid leaking through the FML hole first flows horizontally in the geotextile, then vertically through the soil layer.

- Brown et al. consider that there is a space between the FML and the soil layer. The liquid leaking through the FML hole first flows horizontally in the space, then vertically through the soil layer.

- Flow in Geotextile between FML and Soil

Fukuoka [1986] considers that there is a geotextile between the FML and the low permeability soil, and that the leachate flows horizontally and radially within the geotextile before it flows vertically in the soil underlying the geotextile. Although geotextiles are not used in composite liners, the analysis made by Fukuoka is pertinent to composite liners because similar equations can be used for flow in the narrow space between a FML and the soil.

The following differential equation has been established by Fukuoka [1986]:

$$(1/r)\ (dh/dr) + d^2h/dr^2 = h\ k_c/(H\theta) \qquad \text{(Equation B-18)}$$

where: r = radius from center of hole; h = hydraulic head at radius r in the geotextile; k_c = hydraulic conductivity of the low-permeability compacted soil underlying the geotextile; H = thickness of the soil layer; and θ = hydraulic transmissivity of the geotextile.

The only assumption is that the flow in soil is vertical. No assumption is made regarding the hydraulic head in the geotextile. This head decreases from a maximum value at the FML hole, to zero at the periphery of the wetted portion of the geotextile. Consequently, flow through soil is faster at the center of the wetted area than at the periphery. Solving the above equation would give the radius of the wetted area and would allow to determine the leakage rate. Fukuoka did not solve the equation, but the solution proposed by Brown et al. for Equation B-24, which is similar, can be adapted to Equation B-18 if the thickness of the geotextile (and, therefore, its transmissivity) is assumed not to vary with the radius r (while, in fact it varies since the effective stress on the geotextile varies with the radius r).

Equation B-18 was established by combining Darcy's vertical flow in the soil with Darcy's radial flow in the geotextile, Q_r, which is governed by the classical differential equation:

$$Q_r = -2 \pi r k_p s \, dh/dr \qquad \text{(Equation B-19)}$$

where: k_p = hydraulic conductivity of the geotextile in the direction of its plane; s = thickness of the geotextile (i.e., spacing between FML and soil); and other notation as above.

This equation can also be written:

$$Q_r = -2 \pi r \theta \, dh/dr \qquad \text{(Equation B-20)}$$

where: θ = hydraulic transmissivity of the geotextile.

- Flow in Space between FML and Soil

This study was made by Brown et al. principally to extrapolate results obtained with their small diameter model to real situations where the flow may laterally extend over a large area.

The approach used by Brown et al. is similar to Fukuoka's. They combine vertical Darcy's flow in the low-permeability compacted soil with radial flow in the space between the FML and the underlying soil. Brown et al. integrated Newton's equation for viscous fluids in a circular domain and demonstrated that the radial flow is governed by:

$$Q_r = -[\pi r s^3 \rho g/(6 \eta)] (dh/dr) \qquad \text{(Equation B-21)}$$

where: r = radius from center of hole; s = spacing between FML and low permeability soil; ρ = density of leachate; g = acceleration of gravity; η = viscosity of leachate; and h = hydraulic head at radius r in the space between FML and soil.

By comparing Equations B-20 and B-21, it appears that a space s between the FML and the underlying soil is equivalent to a hydraulic transmissivity θ given by:

$$\theta = \rho\ g\ s^3/(12\ \eta) \qquad \text{(Equation B-22)}$$

For example, using the density ($\rho = 1000\ kg/m^3$) and the viscosity ($\eta = 10^{-3}\ kg/ms$) of water, this equation shows that a spacing s = 1 mm is equivalent to a hydraulic transmissivity of $8 \times 10^{-2}\ m^2/s$, and a spacing s = 0.1 mm is equivalent to a hydraulic transmissivity of $8 \times 10^{-5}\ m^2/s$. These transmissivity values are consistent with transmissivities of synthetic drainage layers.

The differential equation obtained by Brown et al. is:

$$d(r\ dh/dr)/d\ r = [12\ \eta\ k_C r/(\rho\ g\ s^3)]\ (1 + h/H) \qquad \text{(Equation B-23)}$$

which can be written:

$$(1/r)\ (dh/dr) + d^2h/dr^2 = [12\eta\ k_C/(\rho\ g\ s^3)]\ (1 + h/H) \qquad \text{(Equation B-24)}$$

Combining Equation B-22 and B-24, it appears that Equation B-24 [Brown et al.] is identical to Equation B-18 [Fukuoka, 1986] except for the last term, h/H for Fukuoka and (1 + h/H) for Brown et al. (This discrepancy must be elucidated.) Brown et al. solved this differential function using Bessel functions to interpret results from their laboratory model (see Section B.5.2). However, the charts they proposed for field conditions were established with a simplifying assumption: the hydraulic gradient for the vertical flow in soil is one. In other words, they assume that the hydraulic head on top of the low-permeability soil is zero. This assumption is valid only if the hydraulic head on top of the FML is much smaller than the thickness of the low-permeability soil layer. This assumption is:

- always acceptable for bottom liners;
- never acceptable for surface impoundment top liners; and

• probably acceptable in most cases of top liners for landfills.

With the simplifying assumption of a gradient of one in the soil, the differential equation governing the flow becomes, as indicated by Brown et al.:

$$\frac{dh}{dr} = \frac{6 \eta k_c}{\rho g s^3} (r - \pi R^2/r) \qquad \text{(Equation B-25)}$$

which gives the following relationship [Brown et al.]:

$$h + H = [3 \eta k_c d^2/(4 \rho g s^3)] \; [2 (2R/d)^2 \text{Log} (2R/d) - (2R/d)^2 + 1] \qquad \text{(Equation B-26)}$$

where: h = hydraulic head on top of the FML; H = thickness of the low-permeability soil layer; η = viscosity of the leachate; k_c = hydraulic conductivity of the low-permeability compacted soil; d = diameter of the hole in the FML; ρ = density of the leachate; g = acceleration of gravity; s = spacing between the FML and the low-permeability compacted soil; and R = radius of the wetted area.

Equation B-26 gives the radius of the wetted area if the spacing s between the FML and the low-permeability compacted soil is known. Guidance regarding selection of spacing values can be obtained through backcalculation of Brown et al.'s test results (see Section B.5.2).

When the radius R of the wetted area is known, the leakage rate can be determined by using the following equation which derives from Darcy's equation with the assumption that the hydraulic gradient is one in the low-permeability compacted soil:

$$Q = \pi R^2 k_c \qquad \text{(Equation B-27)}$$

The above equations were used by Brown et al. to establish charts giving the leakage rate and the radius of the wetted area (Figures B-9 through B-12). To summarize results presented in these charts and extrapolate or interpolate them, we propose the following equations:

$$Q = 0.7\ a^{0.1}\ k_C^{0.88}\ h \qquad \text{(Equation B-28)}$$

$$R = 0.5\ a^{0.05}\ k_C^{-0.06}\ h^{0.5} \qquad \text{(Equation B-29)}$$

These empirical equations are only valid with the units indicated: Q = leakage rate (m^3/s); a = surface area of FML hole (m^2); k_C = hydraulic conductivity of low-permeability compacted soil (m/s); h = hydraulic head on top of FML (m); and R = radius of wetted area between FML and soil (m).

B.4.4 Free Flow through Holes in the FML

- Purpose

The case of free flow through holes in the FML provides an upper boundary for the flow rate which could happen in the case of a large space between a FML with a hole and the underlying low-permeability compacted soil.

- Basic Equation for Leakage Rate

Assuming that there is a large empty space under a FML with a hole, Bernouilli's equation for free flow through orifices can be used to evaluate the leakage rate through the hole:

$$Q = C\ a \sqrt{2gh} \qquad \text{(Equation B-30)}$$

where: Q = leakage rate; h = hydraulic head on top of the FML; a = hole surface area; and g = acceleration of gravity. C is a dimensionless coefficient, valid for any Newtonian fluid, and is related to the shape of the edges of the aperture; for sharp edges, C = 0.6. Recommended SI units are: Q (m^3/s), h (m), a (m^2), and g (m/s^2).

- Radius of Wetted Area

The "wetted area" is the area where leakage flows between the FML and the underlying low-permeability compacted soil before it seeps into the soil.

By combining Equations B-27 and B-30, it appears that, if the spacing between the FML and the soil is large enough to ensure free flow, the radius of the wetted area is given by:

$$\pi R^2 k_c = 0.6 a \sqrt{2 g h} \qquad \text{(Equation B-31)}$$

hence:

$$R = 0.44 a^{0.5} (2 g h)^{0.25} k_c^{-0.5} \qquad \text{(Equation B-32)}$$

and, in the case of a circular hole:

$$R = 0.39 d (2 g h)^{0.25} k_c^{-0.5} \qquad \text{(Equation B-33)}$$

where: R = radius of the wetted area; a = hole area; d = hole diameter; g = acceleration of gravity; h = hydraulic head on top of FML; and k_c = hydraulic conductivity of the low-permeability compacted soil underlying the FML. Recommended SI units are: R (m), a (m^2), d (m), g (m/s^2), h (m), and k_c (m/s).

- Calculations

Equation B-30 has been used to calculate leakage rates for two typical holes:

- a 2 mm (0.08 in.) diameter hole which is typical of a small hole due to defective seaming (as discussed in Section B.3.5); and

- a 11.3 mm (0.445 in.) diameter hole which is the standard 1 cm^2 hole recommended for design, as indicated in Section B.3.6).

Results from these calculations are given in Table B-9. Hydraulic heads considered in these calculations are as follows:

- 0.03 m (0.1 ft) which is an average head that can normally be expected on the top liner of a landfill with a well designed and constructed leachate collection and removal system.
- 0.3 m (1 ft) which is the maximum head considered in the design of the leachate collection and removal system of a landfill.
- 3 m (10 ft) which is a typical head on the top liner of a surface impoundment.

B.5 LABORATORY MODELS

B.5.1 Introduction

Tests to evaluate leakage through composite liners due to a hole in the FML were conducted by Fukuoka [1985, 1986] and Brown et al. [no date]. It is important to recognize that neither the Brown et al. tests or Fukuoka tests were developed to model leakage through composite bottom liners under field conditions. The Brown et al. tests were preliminary and conceptual in nature. The Fukuoka tests did not even directly relate to field conditions existing at landfills and surface impoundments. However, both sets of tests (and in particular the Brown et al. tests) can be used to develop an understanding of the mechanics of flow through composite liners and to relate design equations to field condition.

In both cases, tests were conducted with a FML having a circular hole, and various hole diameters were used in both testing programs. Additional tests by Brown et al. included FML flaws that are not circular such as slits or seam defects. The tests were intended to be full-scale models of the reality since hole size, FML thickness, and (approximately) soil layer thickness were similar to what they are in the field. However, the permeameters used had a limited diameter (e.g., 0.6 m for Brown et al., and 1.5 m for Fukuoka) and the extension of lateral flow between the FML and soil was limited by the walls of the permeameter.

In the tests conducted by Brown et al., the FML was always covered by 0.15 m (6 in.) of gravel to ensure contact between FML and soil, and, in some tests, an additional load up to 160 kPa (3340 psf) (equivalent to 10 m of soil) was applied to evaluate the effect of overburden pressure. In many of the tests conducted by Fukuoka, the FML was not covered, and the only load applied on the FML was the water pressure.

Water heads in Brown et al. tests were up to 1 m, while in Fukuoka tests, they were up to 40 m. Tests by Brown et al. were conducted for landfill applications while Fukuoka was working on the design of a large dam and reservoir.

Fukuoka used only a PVC FML, while Brown et al. considered a variety of FMLs: HDPE, PVC, CSPE, and EPDM, with various thicknesses.

Tests by Fukuoka as well as tests by Brown et al. showed that there is flow between the FML and the soil. Some of the tests conducted by Fukuoka and by Brown et al. included a geotextile between the FML and the soil. With a geotextile, flow between the liners would be expected and the liners do not constitute a true composite liner.

B.5.2 Review of Tests by Brown et al.

These tests are presented in a report by Brown et al. [no date].

- Description of the Tests

Tests were conducted in a 0.6 m (24 in.) diameter permeameter. Hole diameters ranged between 0.8 mm (1/32 in.) and 13 mm (1/2 in.), and non-circular holes such as slits and seam defects were considered.

The FMLs were: HDPE (0.8 mm to 2.5 mm) (30 to 100 mils); PVC (0.5 to 0.8 mm) (20 to 30 mils); CSPE (0.9 to 1.15 mm) (36 to 45 mils); and EPDM (0.8 mm) (30 mils).

In some tests, geotextiles were included between the FML and the soil. The geotextiles were needlepunched nonwovens with a mass per unit area of 250 to 350 g/m^2 and a thickness (under no load) on the order of 2.5 to 4 mm.

The soils used were a silty sand ($k = 2 \times 10^{-6}$ m/s), and a clayey silt ($k = 2 \times 10^{-8}$ m/s).

- Approach

The diameter of the permeameter used by Brown et al. was small (0.6 m) and lateral flow could not extend beyond a radius of 0.3 m as it would have in most cases without the limitation imposed by the permeameter walls. Therefore, the calculations presented in Section B.4.3 were used to backcalculate the value of the spacing between the FML and soil from the test results. The value of the spacing thus obtained can then be used in similar equations to determine the radius of the wetted area and, therefore, the leakage rate in actual situations where lateral expansion of the flow is not impeded by permeameter walls. The backcalculated spacing values are as follows:

0.02 mm for clayey silt regardless of FML

0.08 mm for silty sand and flexible FML (PVC)

0.15 mm for silty sand and stiff FML (HDPE)

Spacing between the FML and the soil, and, therefore, the leakage rate, appears to increase if the FML stiffness increases (at least in the case of the more permeable soil). It also appears that spacing increases if the soil is coarse, which is illustrated by:

$$0.02 \text{ mm} = d_{10} \text{ of clayey silt}$$

$$0.08 \text{ mm} = d_{15} \text{ of silty sand}$$

The above spacing values are related to the case of a FML with 15 cm of gravel overburden. This is an unrealistically low overburden pressure in comparison to those typically encountered in the field.

Following is a review of the influence of various parameters on test results.

- Effect of Overburden Pressures

When a compressive stress of 160 kPa (equivalent to 10 m of soil) is applied on a 0.75 mm (30 mil) thick HDPE FML placed on a soil with a hydraulic conductivity of 2×10^{-6} m/s, the flow rate through a FML hole is divided by 200 and the backcalculated theoretical spacing between FML and soil is divided by 10 (there are no results for the soil with a hydraulic conductivity of 2×10^{-8} m/s).

- Effect of Flaw Shape

Erratic results were obtained with slits and seam defects on the soil with $k_c = 2 \times 10^{-6}$ m/s:

- Some tests showed that a 50 mm slit or seam defect is often equivalent to a 0.5 to 1 mm diameter circular hole (however other tests showed that a 50 mm seam defect can be equivalent to a 75 mm diameter hole).

- Tests showed that a 150 mm slit or seam is often equivalent to a 75 mm diameter circular hole (which is very different from the 0.5 to 1 mm diameter circular hole indicated above as equivalent to a 50 mm seam defect).

It was difficult to compare slits, seams and circular holes with the 2 x 10^{-8} m/s soil because for that soil there is more lateral flow and permeameter walls disturbed the flow.

- Conclusions from Brown et al.'s Tests

In order to extrapolate to field conditions, Brown et al. make the following recommendations regarding the values of the spacing between FML and soil to be used in the equations presented in Section B.4.3 to evaluate leakage rate and radius of wetted area in actual field conditions where lateral extension of flow is not impeded by wall permeameter:

soil hydraulic conductivity, k_c (m/s)	FML-soil spacing, s (mm)
10^{-6}	0.15
10^{-7}	0.08
10^{-8}	0.04
10^{-9}	0.02

These values are the upper boundary of (or even larger than) the backcalculated spacing values previously given in the discussion of the approach. Also, these spacing values are for the case when there is little or no overburden (e.g., 15 cm of gravel), and they are expected to be smaller than in the case when there is a large overburden. Therefore, for these two reasons, leakage rates calculated by Brown et al. are likely to be conservative. Results of the Brown et al. study indicate that there is a significant benefit of a composite liner design incorporating a FML upper component and a compacted soil lower component.

B.5.3 Review of Tests by Fukuoka

These tests are described in [Fukuoka, 1985; and Fukuoka, 1986]. They were conducted for the design of the lining system for a dam and a reservoir with a maximum water head of 40 m (130 ft). Although these conditions are not representative of hazardous waste management units, the study conducted by Fukuoka, when combined with the findings of Brown et al., provide a good understanding of the mechanisms governing leakage through composite liners.

- Description of the Test

All tests discussed below were conducted with the following equipment, conditions, and materials: permeameter diameter is 1.5 m (5 ft); water pressure is 200 or 400 kPa (4,000 or 8,000 psf); soil permeability is on the order of 10^{-7} to 10^{-8} m/s (10^{-5} to 10^{-6} cm/s); soil thickness is 0.45 m (1.5 ft) when no soil cover is placed on the FML and 0.225 m when a 0.225 m (0.75 ft) thick soil cover is placed on the FML; the FML is a 1 mm (40 mil) thick PVC; the geotextile is a needle-punched nonwoven geotextile (mass per unit area 450 g/m^2 (13 oz/sq. yd), 4 mm (160 mil) thick, permeability 0.001 m/s (0.1 cm/s) under no pressure and 0.0005 m/s (0.05 cm/s) under a 400 kPa (8,000 psf) pressure).

- Tests with FML Alone on Soil (no geotextile, no cover)

In this case, tests show that the diameter of the FML hole needs to be larger than 2 mm (0.08 in.) approximately in order to ensure that free flow through the hole (assuming there is nothing under the FML) is larger than flow rate through soil alone. This indicates that the soil layer has less influence in reducing leakage rate in the case of very small holes than in the case of large holes.

Tests showed that the leakage rate becomes equal to the leakage rate with no FML at all when the diameter of the FML hole is larger than approximately 20 mm (3/4 in.) (Figure B-13). This indicates that leakage flows laterally between the FML and the soil and reaches the walls of the permeameter (diameter 1.5 m (5 ft)) when the diameter of the hole is 20 mm (3/4 in.) or more. This also indicates that the pressure in the liquid located between the FML and soil is the same as the pressure on top of the FML.

Pressure measurements in the soil (Figure B-14a) showed that the full water pressure is applied on top of the soil, which confirms that there is a space between FML and soil where water flows freely. In other words the FML was slightly uplifted by water. (Note that pressure on top of the FML, plus the weight of the FML (specific gravity 1.2) exceeds the pressure under the FML by 2 Pa (0.04 psf). This is an extremely small pressure (i.e., of the order of the pressure exerted by a couple of sheets of paper in dry conditions) and it is easily overcome by the stiffness of the FML, even a FML as flexible as PVC - a PVC FML wrinkle can easily carry a couple of sheets of paper.)

- Tests with FML on Geotextile on Soil

The geotextile had no hole (only the FML had a hole). The geotextile and the FML were not glued together (i.e., the FML was simply laid on the geotextile). (This detail is important in the discussion presented hereafter.)

When FML hole was smaller than 30-50 mm (1-2 in.) approximately, flow rate was approximately 20 times smaller than flow rate through soil alone. In other words, when FML hole diameter was smaller than 30-50 mm (1-2 in.), using a geotextile under the FML decreased the flow rate by approximately one order of magnitude or more.

Pressure measurements in the soil in the case of a 20 mm (3/4 in.) diameter FML hole (Figure B-14 b) showed that the water pressure on the soil surface (i.e., under the geotextile) was roughly uniform and 15 times smaller than the uniform pressure in the case without geotextile between FML and soil. This indicates that the head and, consequently, flow rate was 15 times smaller with geotextile than without geotextile, which is consistent with the observations mentioned above.

Pressure measurement in the soil in the case of a 50 mm (2 in.) diameter FML hole (Figure B-15) showed that water pressure on the soil surface was less uniform than in the case of a 20 mm (3/4 in.) diameter FML hole. Pressures were larger in the vicinity of the hole which indicated that there was water flowing in the geotextile within a radius smaller than the radius of the test permeameter.

It may be concluded that FML, geotextile and soil stay in close contact when the FML hole is smaller than 50 mm (2 in.). This appears clearly because:

- if water were accumulating between FML and geotextile, the water pressure on the soil would be uniformly high, almost equal to the water pressure on the FML (i.e., 200 or 400 kPa) (4,000 or 8,000 psf) since geotextile permittivity (i.e., permeability/thickness) is much larger than soil permittivity and, therefore, head loss through geotextile would be small; and

- if water were accumulating between geotextile and soil, both geotextile and FML would be uplifted and the water pressure on the soil would be equal to the water pressure on the FML (i.e., 200 or 400 kPa (4,000 or 8,000 psf)).

FML, geotextile, and soil stay in close contact because the pressure on top of the FML (200 or 400 kPa) (4,000 or 8,000 psf) is much higher than the pressure below the geotextile. The same would happen with the FML alone (i.e., water pressure on top of the FML would be higher than water pressure under the FML) if the FML were in close contact with the soil. But, if the FML were not in close contact, because of small soil surface irregularities, and there were preferential channels for the flow of water between the FML and soil, water pressure between the FML and soil might become equal to water pressure on top of the FML. If the soil surface were perfectly smooth, and if the FML had no wrinkle, there would be no preferential path for the water: the FML and the soil would stay in close contact (the same way two pieces of polished steel stick to each other because there is no air or water pressure between them).

- Tests with Earth Cover on the FML, but no Geotextile

In this case, the tests (conducted with FML hole diameter of 10 and 20 mm (3/8 and 3/4 in.)) show a flow rate reduction of the order of 40% (i.e., a factor of 1.66) as compared to the case where there is no earth cover on the FML (Figure B-13). The thickness of the earth cover was 0.225 m (0.75 ft), and the thickness of the soil under the FML was 0.225 m (0.75 ft) (i.e., a total soil thickness of 0.45 m (1.5 ft) as in the tests discussed above).

More tests would be necessary to draw conclusions, such as tests with a permeable cover material and comparable tests with identical low-permeability compacted soil layer thickness under the FML. However, the tests by Fukuoka show that an earth cover, even on a flexible FML such as PVC, does not have a marked effect on leakage rate probably because it is not sufficient to force the FML into soil irregularities.

B.6 CONCLUSIONS ON LEAKAGE THROUGH COMPOSITE LINERS

B.6.1 Conclusions from Analytical Studies

It appears that the theoretical analyses involved in the apparently simple problem of leakage through a hole in a FML placed on a low permeability soil to form a composite liner are extremely complex.

If perfect contact between the FML and soil is considered, the two-dimensional problem has been solved but the three-dimensional problem still requires research. There is no satisfactory approximate solution and the analytical lower and upper boundaries are too far from the actual solution to give valuable information.

Differential equations have been proposed and some approximate numerical solutions are available for the case of imperfect contact between the FML and soil. To use these equations, it is necessary to know the spacing between the FML and the underlying low-permeability soil. Spacing values backcalculated from model tests are only preliminary and are probably smaller than actual spacing values in the field. Field conditions listed below will affect actual site-specific results. while the quality of FML - compacted soil contact is probably better in the laboratory than in the field, the laboratory tests to date have been carried out at unrealistically low overburden pressures.

- subgrade surface preparation is not as good as in the model tests; and

- FMLs have wrinkles and some of these wrinkles are probably not flattened by overburden pressures.

As a result, actual leakage rates in the field will likely vary from those calculated using equations incorporating FML-soil spacings backcalculated from model tests. Also, it is likely that there will be some spatial variation throughout the liner.

B.6.2 Conclusion from Model Tests

Tests show that, in all cases where a FML is placed in direct contact with a low permeability soil, some liquid that has passed through a hole in the FML flows laterally in the space between the FML and the underlying soil. Tests show that, as a result of lateral flow, leakage rates observed are higher than leakage rates which would be obtained if there was a perfect contact between the FML and the underlying soil. The degree of contact between the FML and soil in the model tests can be considered good (smooth soil surface, no cracks in clay) but not perfect since flow takes place between the FML and the soil.

From a construction standpoint, it is recommended to make every effort to ensure a good contact between FML and low permeability soil which includes: (i) having a low permeability soil with a smooth surface and no cracks; and (ii) minimizing or eliminating wrinkles in the FML. Ideally, the FML should be sprayed on the low permeability soil instead of being made in a plant and transported to the site: in this case, the contact may not only be "good" but "perfect".

From a design standpoint, it is necessary to take into account the flow of leachate between the FML and the soil for leakage evaluation as well as for any other appropriate design consideration such as damage caused to the soil layers by liquid flowing in the space between the FML and the underlying soil layer.

Although the tests provided a good understanding of the mechanisms involved, the diameter of the permeameter, the design parameters and test conditions used by Brown et al. and Fukuoka limit the usefulness of the test results when developing design recommendations. Although extrapolation of test data to field conditions was done by Brown et al. using a sound theoretical analysis, test conditions were too far from actual conditions to ensure that extrapolated values are adequate.

In spite of their limitations, the tests show that composite liners are significantly more effective than low-permeability compacted soil alone or FML alone.

B.6.3 Conclusions for Leakage Rate Evaluation

- Review of Methods for Leakage Rate Evaluation

A series of methods have been discussed to evaluate leakage rate through a composite liner due to a hole in the FML. These methods can be ranked as follows:

- An absolute minimum of the leakage rate is given by the vertical flow equation assuming perfect contact between the FML and the underlying soil (Equation B-14).

- An approximate value (possibly an underestimate) of the leakage rate in case of perfect contact between the FML and the underlying soil is given by Equation B-16. Since this equation has not been tested, it is appropriate to have the absolute minimum mentioned above to make sure that no absurd result is considered.

- Leakage rate obtained using charts prepared by Brown et al. on the basis of their tests (Figures B-9 through B-12) or the empirical equations we have proposed to summarize these charts (Equations B-28 and B-29) may be smaller than actual leakage rate because in the field FMLs have at least some wrinkles and subgrade preparation is not as good as in the model tests, thereby allowing more flow between the FML and the soil in the field than in the models. However, a counteracting influence is that the overburden pressure in the model tests was well below overburden pressures representative of field conditions.

- Finally, leakage through a hole in a FML alone (i.e., with nothing underneath it) is certainly much larger than leakage through a composite liner with the same FML hole, even in field conditions with a far from perfect contact between the FML and the underlying soil. This case, therefore, provides an absolute maximum of the leakage rate.

A summary of pertinent equations is presented in Table B-8.

- Leakage Rate and Radius Graphs

Because of the uncertainties in the analyses as well as the wide variety of contact conditions, it is appropriate in each given case to plot leakage rates obtained with all the methods described above in order to make interpolations. It is also appropriate to use a semi-logarithmic scale for the plot since leakage rates vary within a range of several orders of magnitude, as is usually the case in hydraulic problems. The graph in Figure B-16 has been established with a 1 cm^2 hole, which is the recommended standard hole for design as indicated in Section B.3.6. This graph has been established for a hydraulic head of 30 mm (0.1 ft) on top of the FML. Numerical values used to establish the graph in Figure B-16 are given in Table B-9.

Similarly, a graph can be established for the radii of wetted areas (i.e., the area covered by leakage flowing between the FML and the low-permeability compacted soil, before it flows into the compacted soil) obtained with all the methods described above and summarized in Table B-8. The radius graph related to a hydraulic head of 30 mm (0.1 ft) on top of the FML is given in Figure B-17.

- Use of Leakage Rate and Radius Graph

The leakage rate graph permits the determination of the leakage rate for any given field condition by interpolation between the best case and the worst case (this worst case is unlikely at a unit with CQA):

- In the best case: (i) the soil is well compacted, flat and smooth, has not been deformed by rutting due to construction equipment, and has no clods nor cracks; and (ii) the FML is flexible and has no wrinkles.

- In the worst case: (i) the soil is poorly compacted, has an irregular surface, and is cracked; and (ii) the FML is stiff and exhibits a pattern of large, connected wrinkles.

The conditions in the best case can be almost as good as the conditions in the tests by Brown et al. and Fukuoka discussed in Section B.5. Therefore, on the graphs, the best case for field conditions is represented by the vertical line corresponding to test results.

In order to locate the worst field case we have used the radius graph for a large head, i.e., 3 m (10 ft) (Figure B-21), and we have assumed that the radius of the wetted area cannot exceed a value on the order of 10-30 m (30-100 ft) for a value of the compacted soil hydraulic conductivity of 10^{-8} m/s (10^{-6} cm/s). The location of the worst case line thus obtained shows that the conditions in the worst case are still much better than the case of free flow through holes in the FML. Free flow is an extreme case which is possible only if the FML is very far from the low-permeability compacted soil over a very large area (radius of 10 to 100 m), which is practically impossible.

Between the best field case and the worst field case we have selected a vertical line representing good field conditions and a vertical line representing poor field conditions. As a result, it appears in Figure B-16 that, for a head of 30 mm (0.1 ft), a leakage rate of 0.8 liters/day (0.2 gallon/day) corresponds to good field conditions and a hydraulic conductivity of $k_C = 10^{-8}$ m/s (10^{-6} cm/s) for the low-permeability compacted soil underlying the FML. This value of the hydraulic conductivity is a conservative value to consider in design since the required value of 10^{-9} m/s (10^{-7} cm/s) may not always be reached at the site. A less conservative calculation could consider a compacted soil hydraulic conductivity of $k_C = 10^{-9}$ m/s (10^{-7} cm/s). In this case a leakage rate of 0.08 liters/day (0.02 gallon/day) is obtained. Poor field conditions would give a leakage rate value of 4 liters/day (1 gallon/day) for $k_C = 10^{-8}$ m/s (10^{-6} cm/s) and 0.4 liters/day (0.1 gallon/day) for $k_C = 10^{-9}$ m/s (10^{-7} cm/s).

- Leakage Rate due to Permeation and Holes

Leakage rates through composite liners due to a hole in the FML, obtained from Figure B-16 are summarized in Table B-10, which also gives leakage rate due to permeation obtained from Table B-6.

To the best of our knowledge, Table B-10 summarizes the best demonstrated available technology on leakage rate through bottom composite liners.

Table B-1. Values of the migration coefficient, μ, obtained from permeability tests conducted at the University of Grenoble (France) with the apparatus shown in Figure B-1.

	hydraulic head, h, in m					
FML Type	5	10	25	50	75	100
CSPE		3.8×10^{-12}		5.0×10^{-12}		5.5×10^{-12}
Butyl		7.7×10^{-12}		3.9×10^{-12}		3.1×10^{-12}
Butyl	3.5×10^{-15}	1.7×10^{-13}	1.9×10^{-12}	2.9×10^{-13}		3.0×10^{-13}
EPDM		1.1×10^{-12}		2.3×10^{-12}		2.2×10^{-12}
PVC		1.7×10^{-12}		2.5×10^{-12}		1.1×10^{-12}
PVC		1.6×10^{-12}		2.1×10^{-12}		4.4×10^{-13}
PVC		8.1×10^{-13}		2.0×10^{-12}		1.0×10^{-12}
Asphaltic	4.2×10^{-13}	7.4×10^{-13}	6.7×10^{-13}	6.5×10^{-13}	7.4×10^{-13}	
Asphaltic		1.6×10^{-13}	3.2×10^{-13}	6.5×10^{-13}	4.5×10^{-13}	
	Values of μ in m^2/s					

Table B-2. Water vapor transmission (WVT) rates of FMLs from [Haxo et. al., 1984] and values of the coefficient of migration derived from WVT values using Equation B-8 (See also Table B-3). All these tests were conducted at 23°C with a relative humidity difference of 50%, which is equivalent to a pressure of 1.4 kPa, i.e., a head of 0.14 m of water.

Polymer	Thickness, (mm)	Water Vapor Transmission WVT, (g/m^2.day)	Coefficient of migration μ (m^2/s)
Butyl rubber	0.85	0.384	3.8×10^{-15}
	0.85	0.020	2.0×10^{-16}
	1.85	0.097	2.1×10^{-15}
CPE	0.53	0.643	3.9×10^{-15}
	0.79	1.400	1.2×10^{-14}
	0.79	0.320	2.9×10^{-15}
	0.85	0.264	2.6×10^{-15}
	0.94	0.305	2.2×10^{-15}
	0.97	0.643	7.2×10^{-15}
CSPE	0.74	0.333	2.9×10^{-15}
	0.76	0.663	5.8×10^{-15}
	0.89	0.438	4.5×10^{-15}
	0.91	0.748	7.9×10^{-15}
	0.94	0.422	4.6×10^{-15}
	1.07	0.252	3.1×10^{-15}
ELPO	0.72	0.142	1.2×10^{-15}
CO	1.160	20.18	2.7×10^{-13}
	1.650	14.30	2.7×10^{-13}
EPDM	0.51	0.270	1.6×10^{-15}
	0.94	0.190	2.1×10^{-15}
	1.70	0.172	3.4×10^{-15}

Table B-2, continued

Neoprene	0.51	0.304	1.8×10^{-15}
	0.91	0.473	5.0×10^{-16}
	1.27	0.429	6.3×10^{-16}
	1.59	0.237	4.4×10^{-15}
Nitrile rubber	0.76	5.51	4.8×10^{-14}
PB	0.69	0.084	6.7×10^{-16}
PEEL	0.20	10.50	2.4×10^{-14}
LDPE	0.76	0.0573	5.0×10^{-16}
HDPE	0.80	0.0172	1.6×10^{-16}
	2.44	0.0062	1.8×10^{-16}
HDPE-A	0.86	0.0472	4.7×10^{-16}
PVC	0.28	4.42	1.4×10^{-14}
	0.51	2.97	1.7×10^{-14}
	0.76	1.94	1.7×10^{-14}
	0.79	1.85	1.7×10^{-14}
PVC-E	0.91	2.78	2.9×10^{-14}
PVC-OR	0.83	4.17	4.0×10^{-14}
Saran Film	0.013	0.563	8.5×10^{-17}

Abbreviations are defined in Table 4-1.

Table B-3. Water vapor transmission (WVT) rates of FMLs [Rogers, 1964] and values of the coefficient of migration derived from WVT values using Equation 2.2-9. (See also Table B-2.)

FML Type	Reference Pressure p (kPa)	Water Vapor Transmission WVT (g/m².day)	Reference Thickness T (mm)	Coefficient of Migration μ (m²/s)
Hypalon	6.4	161	0.025	4.6×10^{-14}
Butyl	6.4	26	0.025	7.5×10^{-15}
PVC	6.1	32	0.025	9.2×10^{-15}
HDPE 0.92	6.4	28	0.025	8.1×10^{-15}
0.94	5.8	14	0.025	4.1×10^{-15}
0.95	6.1	6.7	0.025	1.9×10^{-15}
0.96	5.8	4	0.025	1.1×10^{-15}

Notes: (i) the test pressure, p, is derived from the test relative humidity difference using Equation B-3; (ii) a 6 kPa pressure is equivalent to a water head of 0.6 m (2 ft).

Table B-4. Summary of values of the coefficient of migration, μ, from Tables B-1, B-2 and B-3.

Hydraulic head h	FML Type CSPE	FML Type PVC	FML Type HDPE
0.14 m	5×10^{-16}	1.7×10^{-14}	1.7×10^{-16}
0.6 m	4.6×10^{-14}	9.2×10^{-15}	4.1×10^{-15}
10 m	3.8×10^{-12}	1.6×10^{-12}	-
50 m	5.0×10^{-12}	2.0×10^{-12}	-
100 m	5.5×10^{-12}	1.0×10^{-12}	-
	Values of coefficient of migration, μ (m^2/s)		

Table B-5. Values of coefficient of migration resulting from extrapolations and interpolations in Figure B-3.

FML Type	Hydraulic head in m (ft): 0 m (0 ft)	0.03 m (0.1 ft)	0.3 m (1 ft)	3 m (10 ft)	> 10 m (> 30 ft)
CSPE	0	3.5×10^{-16}	1.5×10^{-14}	6×10^{-13}	6×10^{-12}
HDPE	0	1.5×10^{-17}	1×10^{-16}	7×10^{-14}	1×10^{-12}
	Values of coefficient of migration, μ, in m^2/s				μ_{max}

Table B-6. Values of rate of leakage due to permeation through FML derived from values of coefficient of migration given in Table B-5, using Equation B-1 and assuming an FML thickness of 1 mm (40 mils).

FML Type	Hydraulic head in m (ft): 0 m (0 ft)	0.03 m (0.1 ft)	0.3 m (1 ft)	3 m (10 ft)	> 10 m (> 30 ft)
CSPE	0	0.035	1.5	60	600
HDPE	0	0.0015	0.1	7	100
	Values of leakage rate in liters/1000m²/day (Ltd) or gallons/acre/day (gpad)				

Table B-7. Leakage rate due to holes in an FML placed on a very pervious medium such as a drainage layer. Note: the 11.3 mm diameter circular hole has a surface area of 1 cm^2.

	Hydraulic head		
Defect diameter	0.03 m (0.1 ft)	0.3 m (1 ft)	3 m (10 ft)
2 mm (0.08 in.)	125 (30)	400 (100)	1250 (300)
11.3 mm (0.445 in.)	1,260 (330)	4,000 (1,000)	12,600 (3,300)
	Values of leakage rate in liters/day (gallons/day)		

Table B-8. Summary of equations giving leakage rate, Q, and radius of wetted area, R, for composite liners when there is a hole in the FML.

ABSOLUTE MINIMUM (Vertical flow)	(MIN) in Figures B-16 and 17
$Q = k_c\ a\ (h + H)/H$	(Equation B-14)
$R = d/2$	
PERFECT CONTACT (Approximate value of Q given by radial flow)	(P.C.) in Figures B-16 and 17
$Q = \pi\ k_c\ h\ d$	(Equation B-16)
R = unknown	
EXCELLENT CONTACT (Empirical equations from model tests)	(TEST) in Figures B-16 and 17
$Q = 0.7\ a^{0.1}\ k_c^{0.88}\ h$	(Equation B-28)
$R = 0.5\ a^{0.05}\ k_c^{-0.06}\ h^{0.5}$	(Equation B-29)
LARGE SPACE BETWEEN FML AND SOIL (Q given by Bernouilli's equation)	(MAX) in Figures B-16 and 17
$Q = C\ a \sqrt{2gh} = 0.6\ a \sqrt{2gh}$	(Equation B-30)
$R = 0.39\ d\ (2\ g\ h)^{0.25}\ k_c^{-0.5}$	(Equation B-33)

where: k_c = hydraulic conductivity of low-permeability compacted soil underlying the FML; a = area of hole in FML; h = hydraulic head on FML; H = thickness of compacted soil layer; d = diameter of hole in FML; and g = acceleration of gravity. Recommended SI units: k_c (m/s), a (m^2), h, H, and (m); and g (m/s^2). These units are mandatory for the two empirical equations.

Table B-9. Numerical values used to establish the graphs presented in Figures B-16 and B-17. This table has been established for a hydraulic head of 30 mm (0.1 ft) on top of the FML, a hole area of 1 cm^2 (0.16 in^2.), and a low-permeability compacted soil thickness of 0.9 m (3 ft).

	Case	Equation	Hydraulic Conductivity of Compacted Soil Underlying the FML: 10^{-7} m/s	10^{-8} m/s	10^{-9} m/s
Leakage Rate g (m^3/s)	Absolute minimum	B-14	1.0×10^{-11}	1.0×10^{-12}	1.0×10^{-13}
	Perfect contact (approximate theory)	B-16	1.1×10^{-10}	1.1×10^{-11}	1.1×10^{-12}
	Good contact (model tests)	B-28	5.8×10^{-9}	7.6×10^{-10}	1.0×10^{-10}
	Free flow (Bernouilli's equation)	B-30	4.6×10^{-5}	4.6×10^{-5}	4.6×10^{-5}
Radius of Wetted Area R (m)	Absolute minimum (hole radius)	R = d/2	0.0056	0.0056	0.0056
	Perfect contact (unknown)		≈0.032(*)	≈0.032(*)	≈0.032(*)
	Good contact (model tests)	B-29	0.14	0.17	0.19
	Free flow	B-33	12	38	122

(*) Value obtained by interpolation in Figure B-17.

Table B-10. Leakage rates through composite liners. Leakage due to permeation is obtained from Table B-6 (rounding up the figures) and leakage due to holes is obtained from Figure B-16, as a function of the quality of contact between the FML component and the compacted soil component of the composite liner. This table has been established with: hole area = 1 cm^2 (0.16 in^2.); compacted soil thickness = 0.9 m (3 ft); FML thickness = 1 mm (40 mils); and frequency of holes = 1 per 4000 m^2 (1 per acre).

		Low-Permeability Compacted Soil Hydraulic Conductivity, k_C	
Quality of contact	Leakage mechanism	10^{-8} m/s (10^{-6} cm/s)	10^{-9} m/s (10^{-7} cm/s)
Good	Permeation	0.001	0.001
	Hole	0.2	0.02
	TOTAL	0.2	0.02
Poor	Permeation	0.001	0.001
	Hole	1	0.1
	TOTAL	1	0.1
		Values of leakage rate in Ltd or gpad	

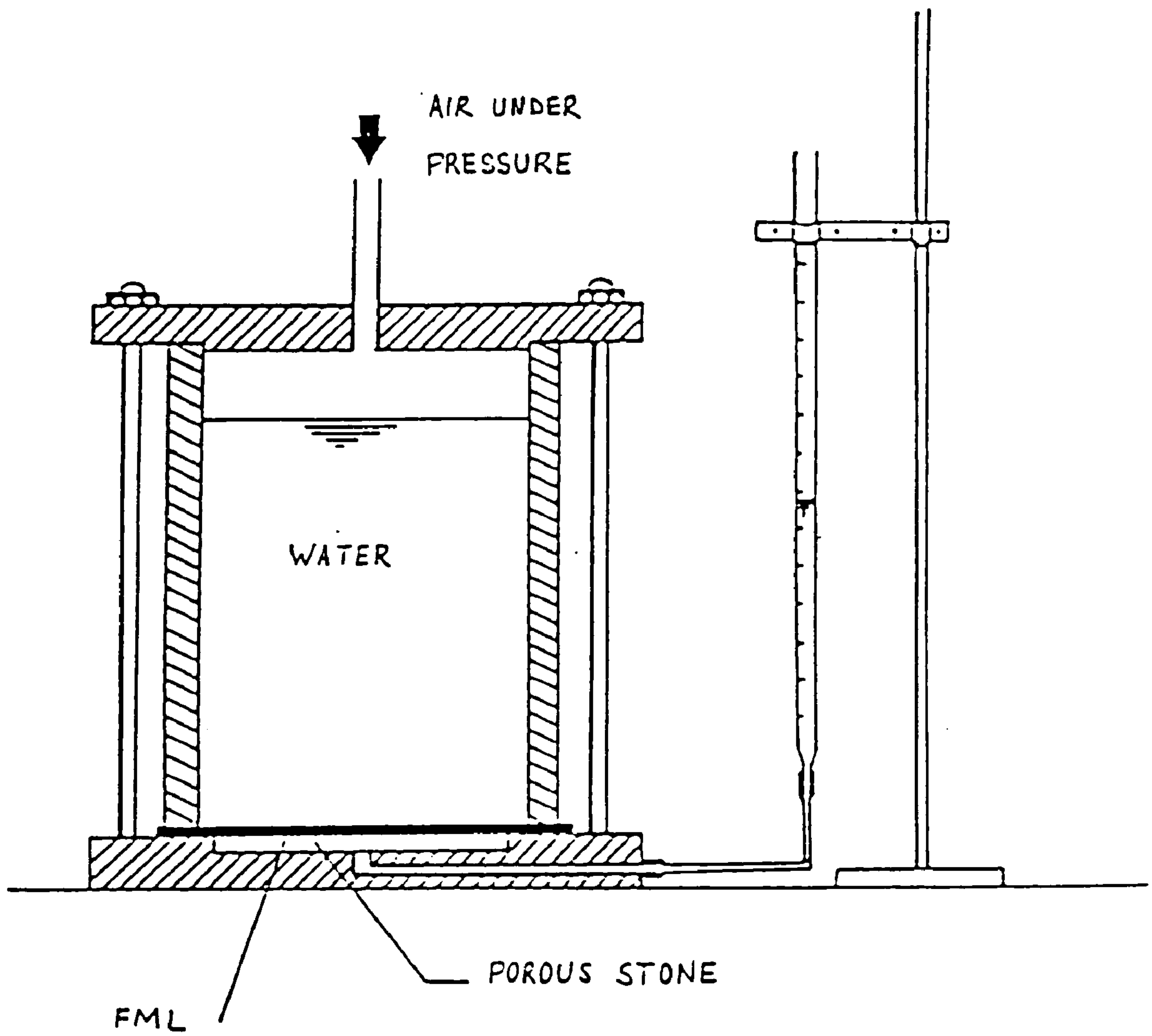

Figure B-1. Permeameter used to evaluate flow through intact FMLs at the University of Grenoble (France).

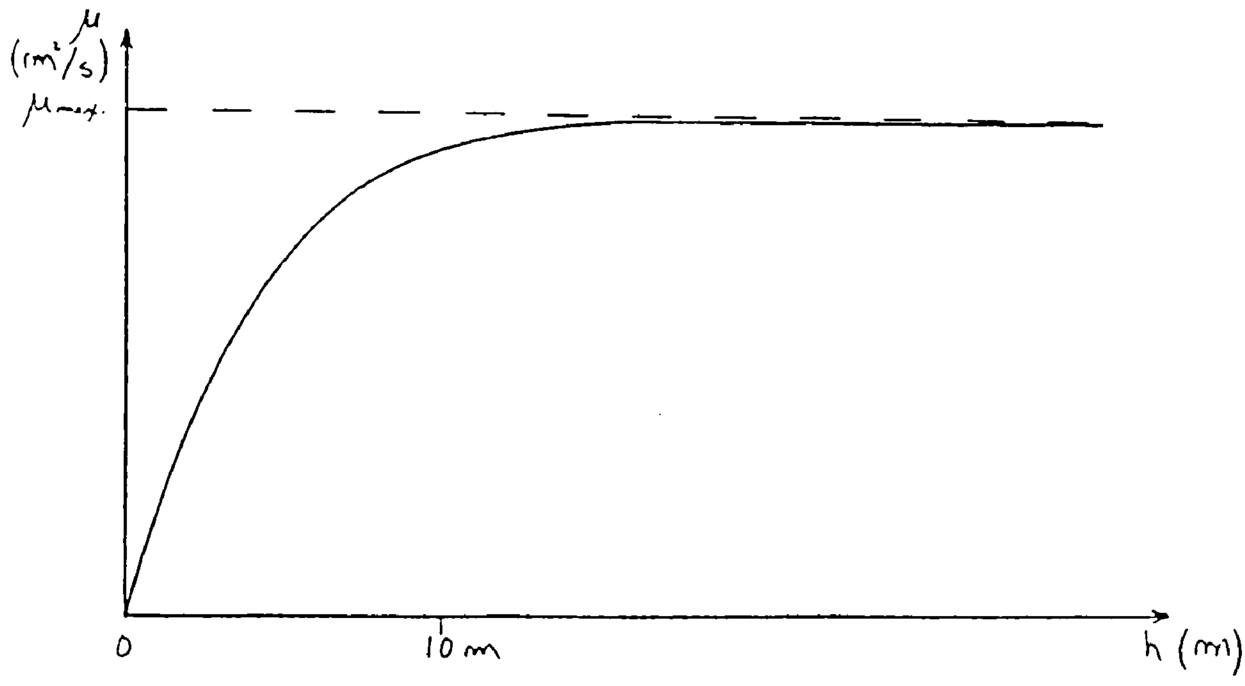

Figure B-2. Typical shape of the curve giving the coefficient of migration, μ_g, as a function of the hydraulic head, h.

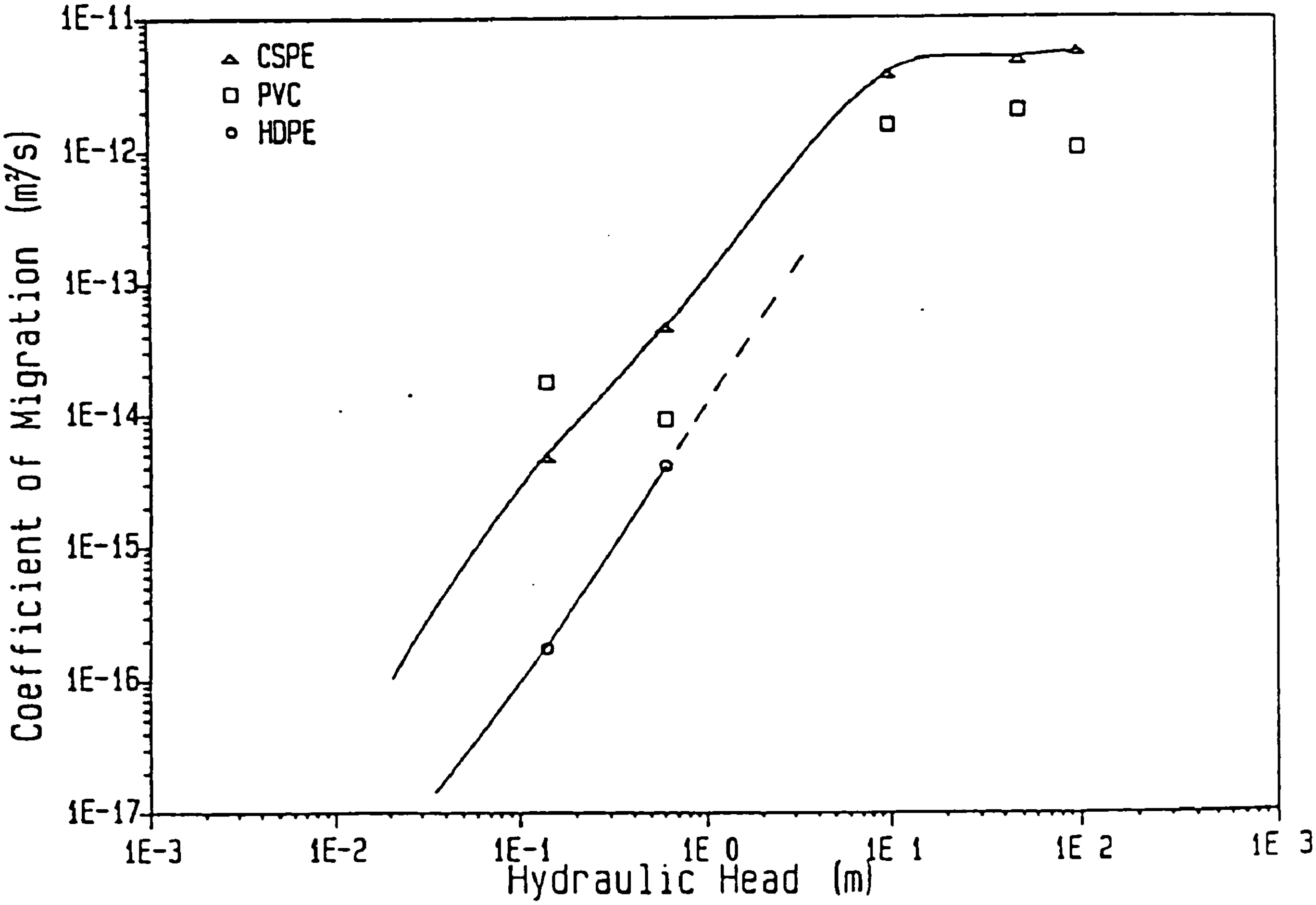

Figure B-3. Values of coefficient of migration, μ_g, for various FMLs from Table 2.2-6.

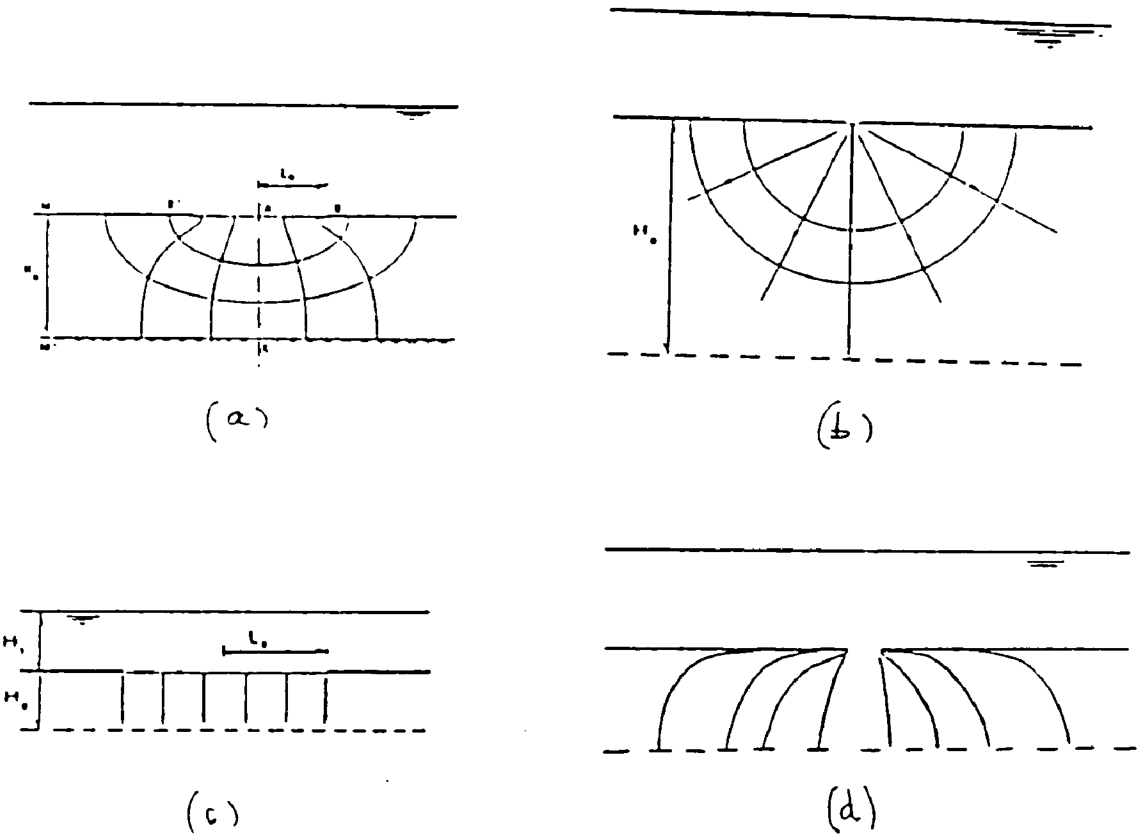

Figure B-4. Flow nets for the four cases considered in two-dimensional theoretical studies related to leakage through composite liners due to hole in FML, assuming perfect contact between FML and soil layer: (a) entire soil layer saturated; (b) radial flow; (c) vertical flow; (d) actual flow. As demonstrated by Faure [1979], the actual flow is limited laterally by a phreatic surface. Note that in cases (a), (b), and (d), there is flow in the soil along the interface, although there is no flow between the FML and the soil because there is no space between the FML and the soil in the considered cases since perfect contact is assumed.

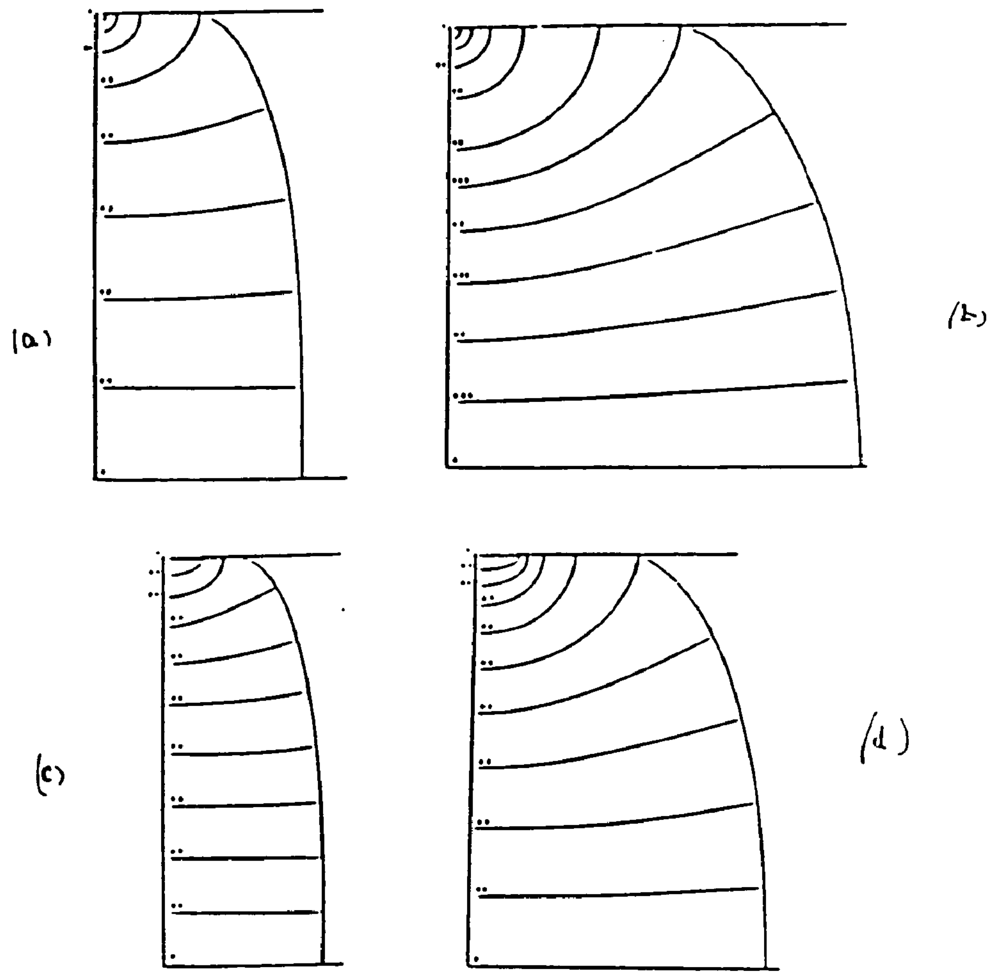

Figure B-5. Typical flow nets for leakage through a composite liner due to a FML hole (two-dimensional study assuming that the FML and the underlying soil are in perfect contact) (see case (d) in Figure B-4). The cases shown above are: (a) b/H = 0.005 and h/H = 1; (b) b/H = 0.005 and h/H = 3; (c) b/H = 0.05 and h/H = 1/3; and (d) b/H = 0.05 and h/H = 1. Notation: b = width of infinitely long hole (slot) in the FML; h = hydraulic head on top of the FML; and H = thickness of the soil layer underlying the FML [Faure, 1979].

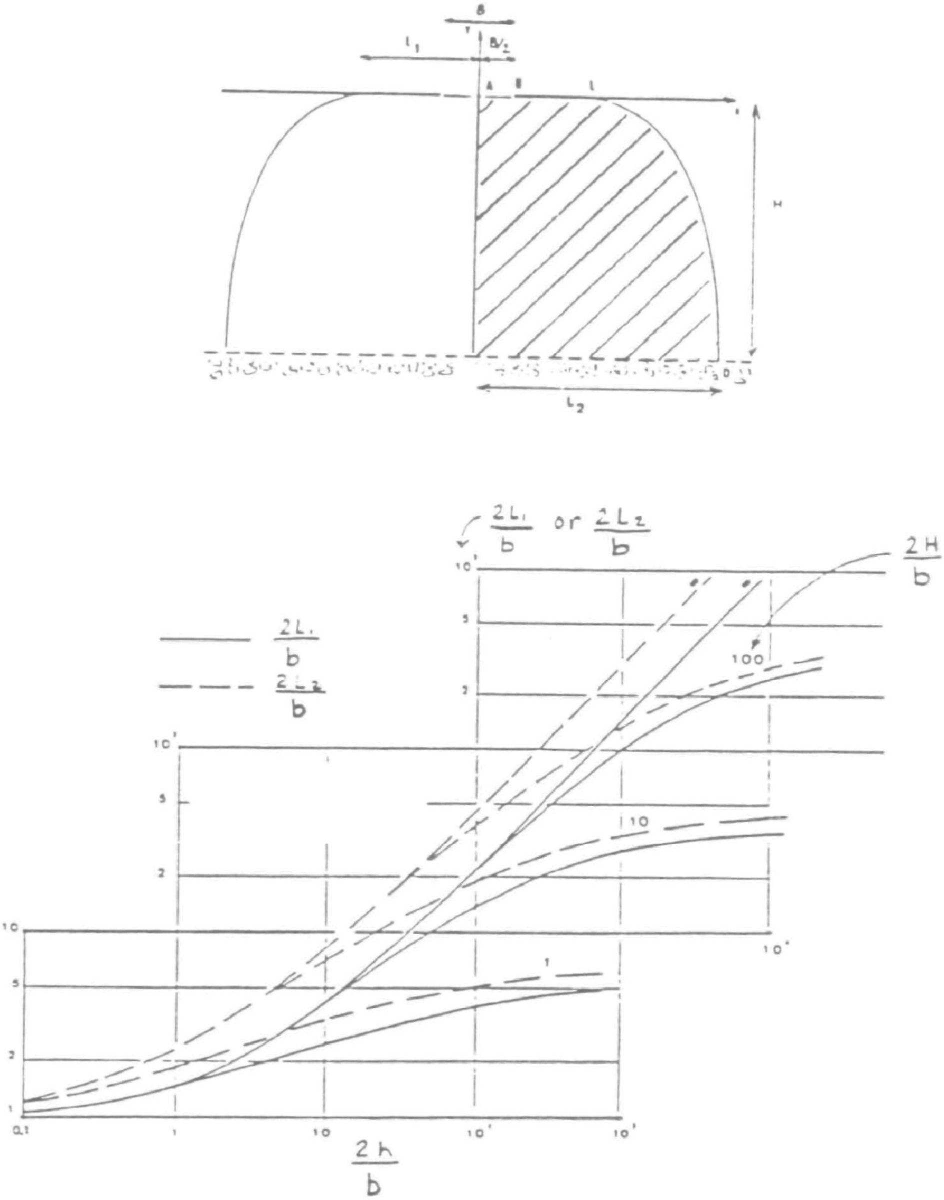

Figure B-6. Lateral extent of the phreatic surface limiting the flow in the soil layer due to a hole in the FML. This chart is related to the two-dimensional case (the hole is a slot of width b) and perfect contact is assumed between the FML and the soil layer [Faure, 1979].

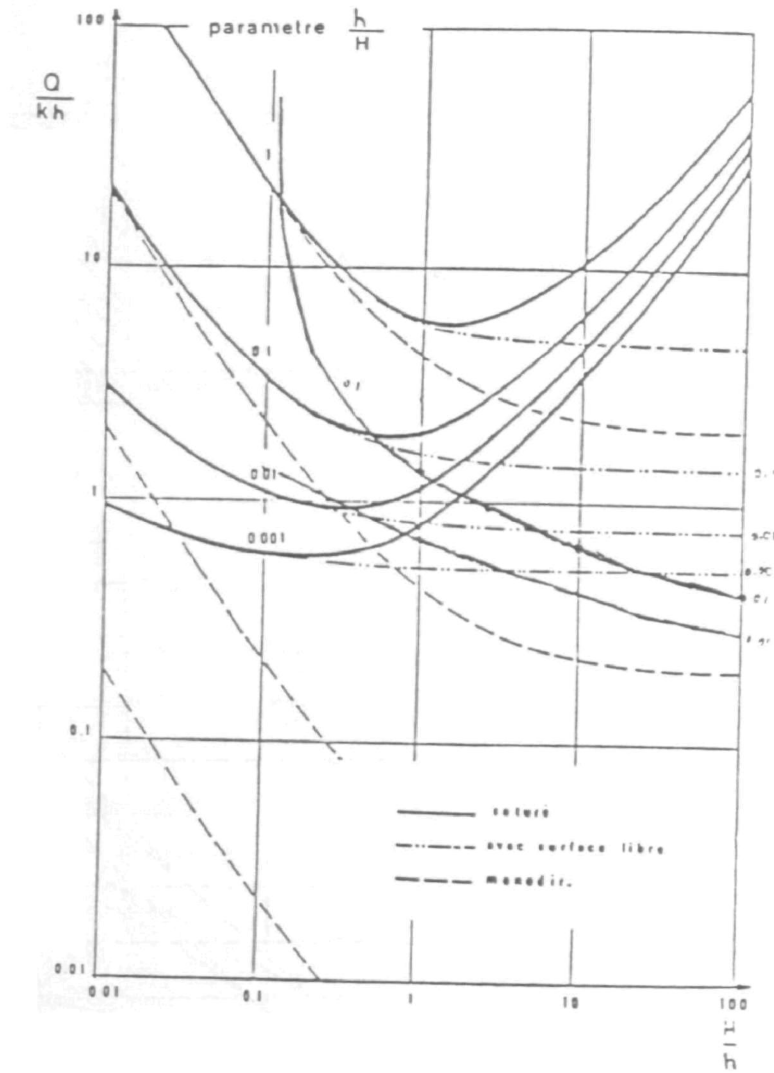

Figure B-7. Leakage rates through a composite liner due to a slot of width b in the FML (two-dimensional case), assuming perfect contact between the FML and the soil. Calculations were made with several assumptions regarding flow: (a) soil entirely saturated by the flow; (b_1) radial flow using Equation B-9; (b_2) radial flow using Equation B-11; (c) vertical flow; (d) actual flow. Cases (a) through (d) are illustrated in Figure B-4.

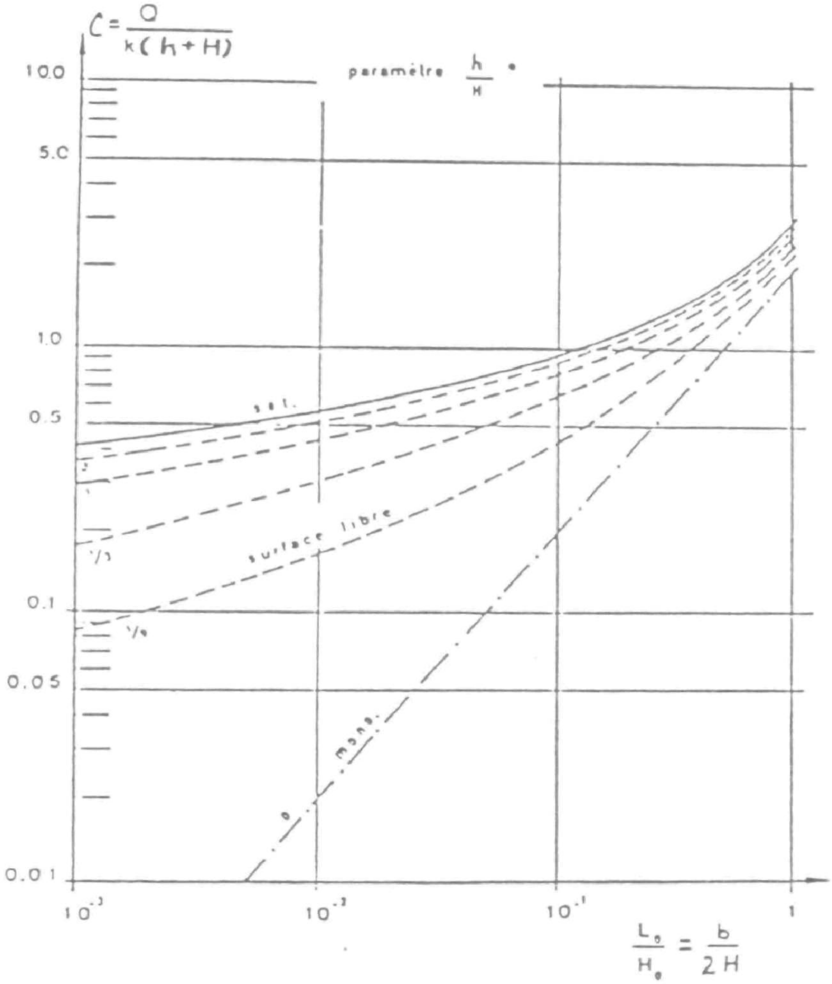

Figure B-8. Chart giving dimensionless coefficient C to be used in Equation B-9 which gives the leakage rate through a composite liner due to a slot in the FML (two-dimensional case). Coefficient C can also be used in Equation B-17 to make an approximate evaluation of the leakage through a composite liner due to a circular hole in the FML (three-dimensional case). Notation: h = hydraulic head on top of the FML; b = width of the slot (to be replaced by the diameter d of a circular hole when the chart is used for the three-dimensional case); and H = thickness of soil layer.

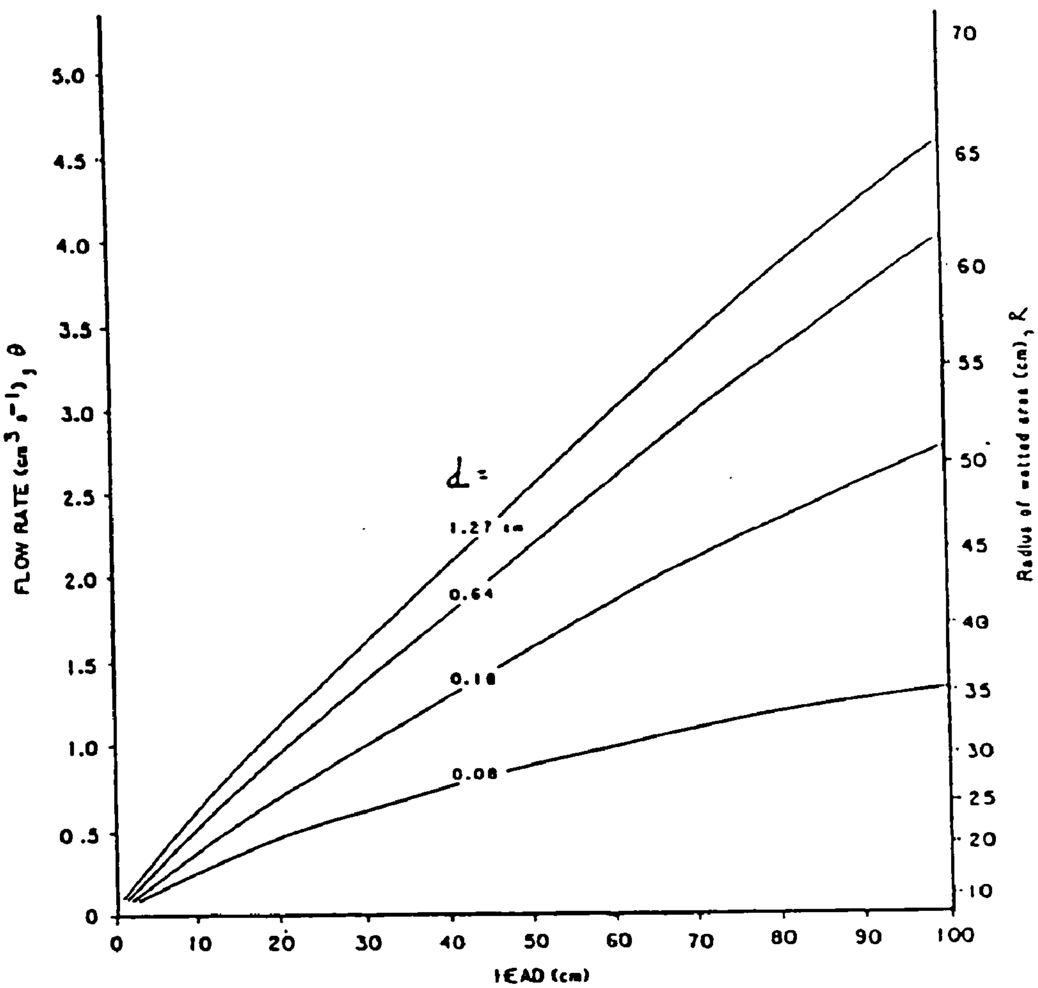

Figure B-9. Leakage through a composite liner due to a hole in the FML [Brown et al.]. Chart giving the leakage rate, Q, and radius, R, of the wetted area as a function of the hydraulic head on the FML, for a compacted soil hydraulic conductivity $k_c = 3.4 \times 10^{-6}$ m/s (3.4×10^{-4} cm/s). Notation: d = diameter of the FML hole; and h = hydraulic head on the FML. Note: although the chart in [Brown et al.] is labeled "$k_c = 10^{-4}$ cm/s", it seems to us that it was established for 3.4×10^{-4} cm/s.

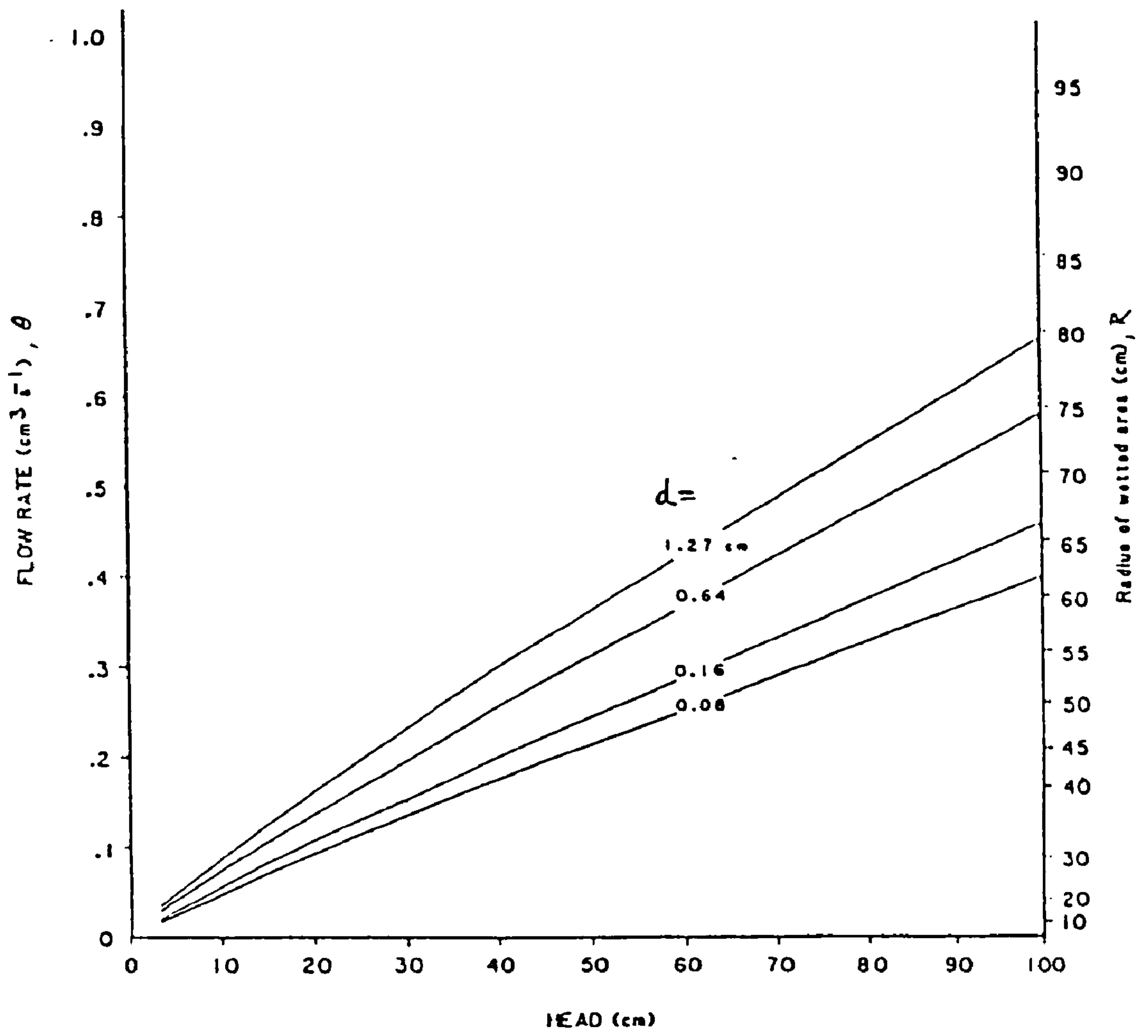

Figure B-10. Leakage through a composite liner due to a hole in the FML [Brown et al.]. Chart giving the leakage rate, Q, and radius, R, of the wetted area as a function of the hydraulic head on the FML, for a compacted soil hydraulic conductivity $k_c = 3.4 \times 10^{-7}$ m/s (3.4×10^{-5} cm/s). Notation: d = diameter of the FML hole; and h = hydraulic head on the FML. Note: although the chart in [Brown et al.] is labeled "$k_c = 10^{-6}$ cm/s", it seems to us that it was established for 3.4×10^{-5} cm/s.

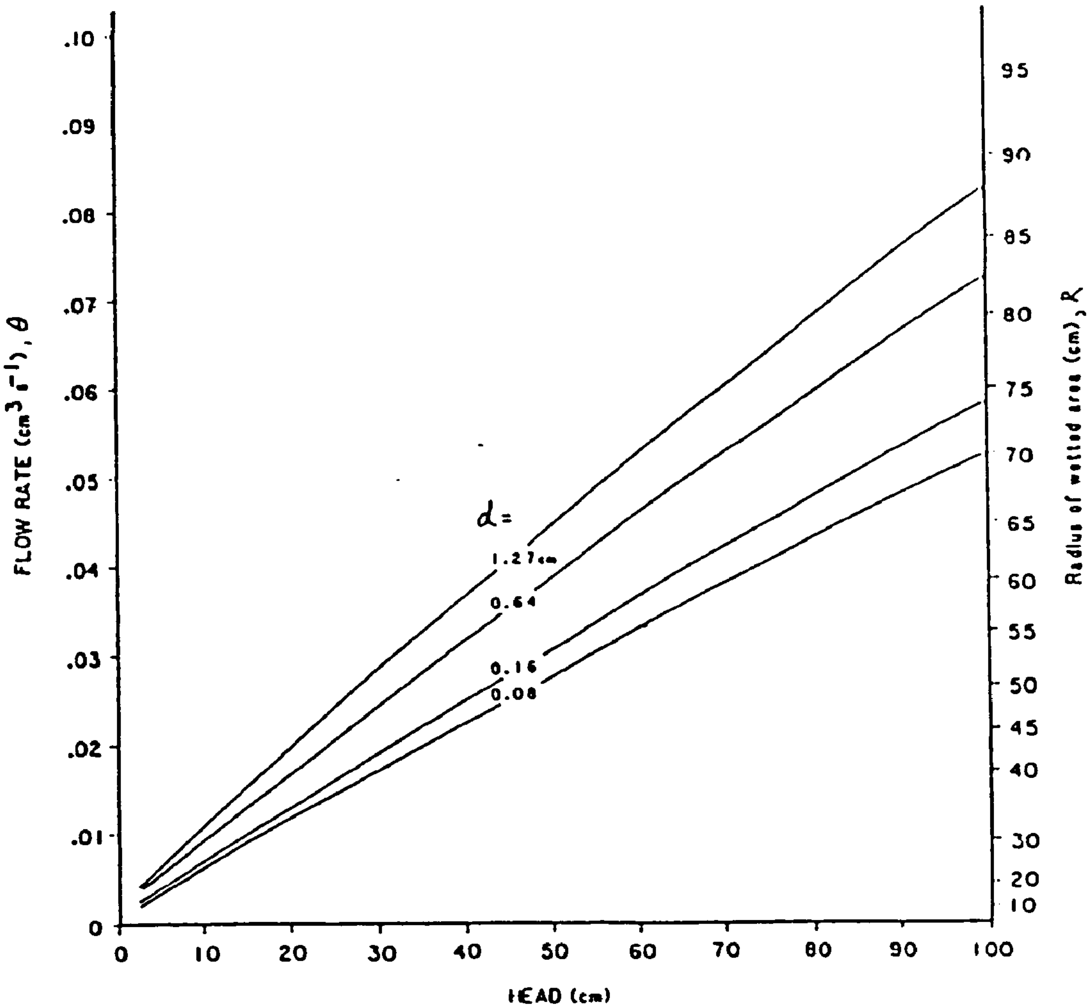

Figure B-11. Leakage through a composite liner due to a hole in the FML [Brown et al.]. Chart giving the leakage rate, Q, and radius, R, of the wetted area as a function of the hydraulic head on the FML for a compacted soil hydraulic conductivity $k_c = 3.4 \times 10^{-8}$ m/s (3.4×10^{-6} cm/s). Notation: d = diameter of the FML hole; and h = hydraulic head on the FML. Note: although the chart in [Brown et al.] is labeled "$k_c = 10^{-6}$ cm/s", it seems to us that it was established for 3.4×10^{-6} cm/s.

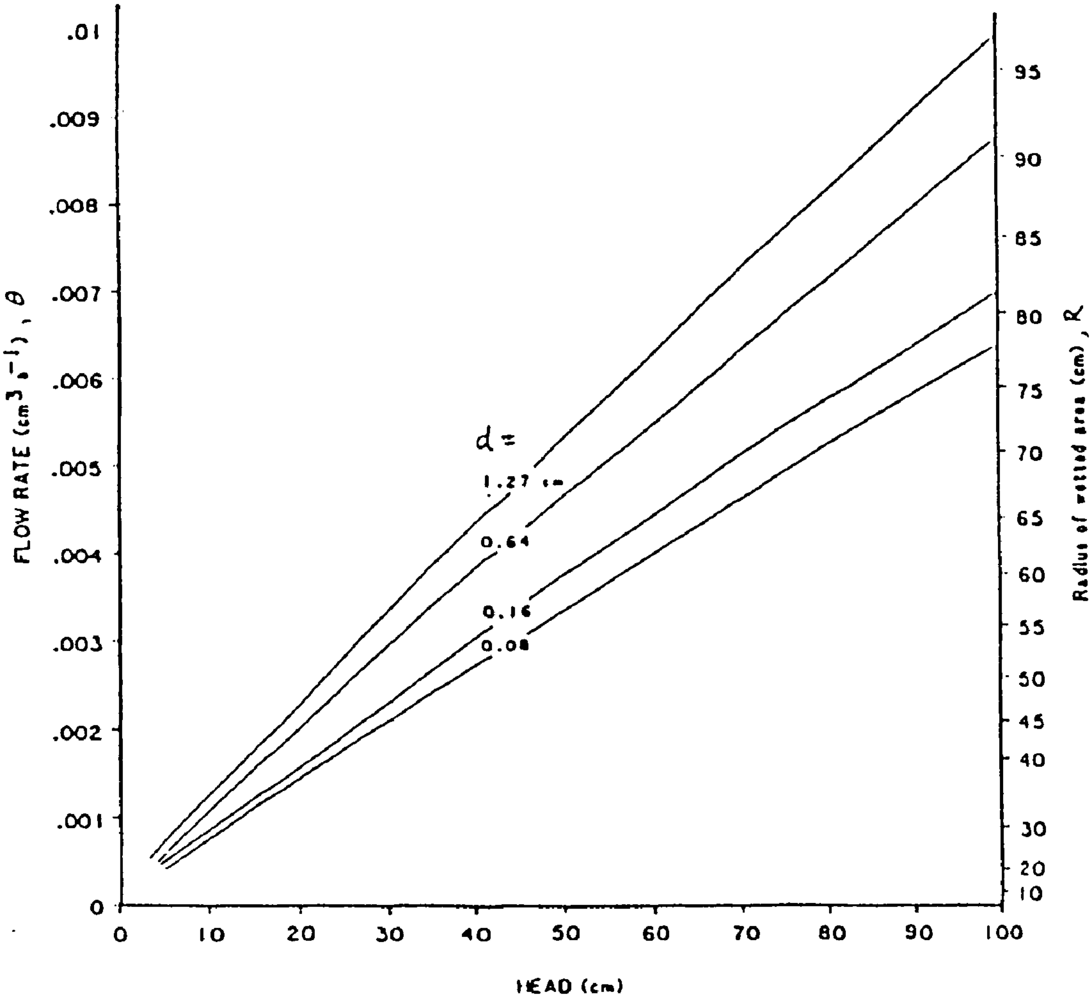

Figure B-12. Leakage through a composite liner due to a hole in the FML [Brown et al.]. Chart giving the leakage rate, Q, and radius, R, of the wetted area as a function of the hydraulic head on the FML, for a compacted soil hydraulic conductivity $k_c = 3.4 \times 10^{-9}$ m/s (3.4×10^{-7} cm/s). Notation: d = diameter of the FML hole; and h = hydraulic head on the FML. Note: although the chart in [Brown et al.] is labeled "$k_c = 10^{-7}$ cm/s", it seems to us that it was established for 3.4×10^{-7} cm/s.

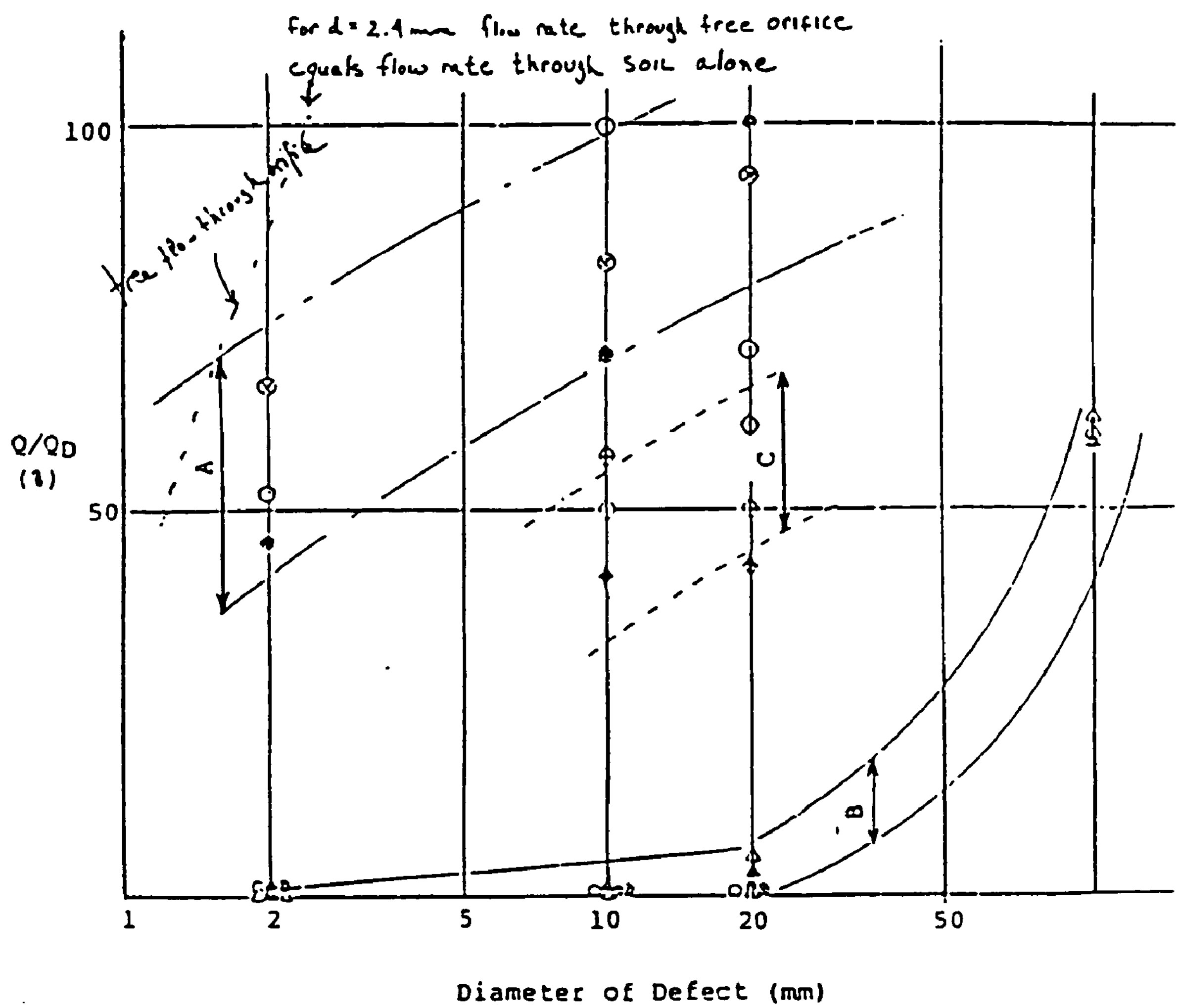

Figure B-13. Leakage rates measured in tests conducted with a FML having a circular hole [Fukuoka, 1985]: (A) no soil cover on the FML, no geotextile between the FML and the soil; (B) there is a geotextile between the FML and the soil, but there is no soil cover on the FML; and (C) there is a soil cover on the FML and no geotextile between the FML and the soil. Notation: Q = leakage rate measured in the tests; and Q_D = leakage rate when there is no FML (i.e., leakage rate governed by Darcy's flow through the soil).

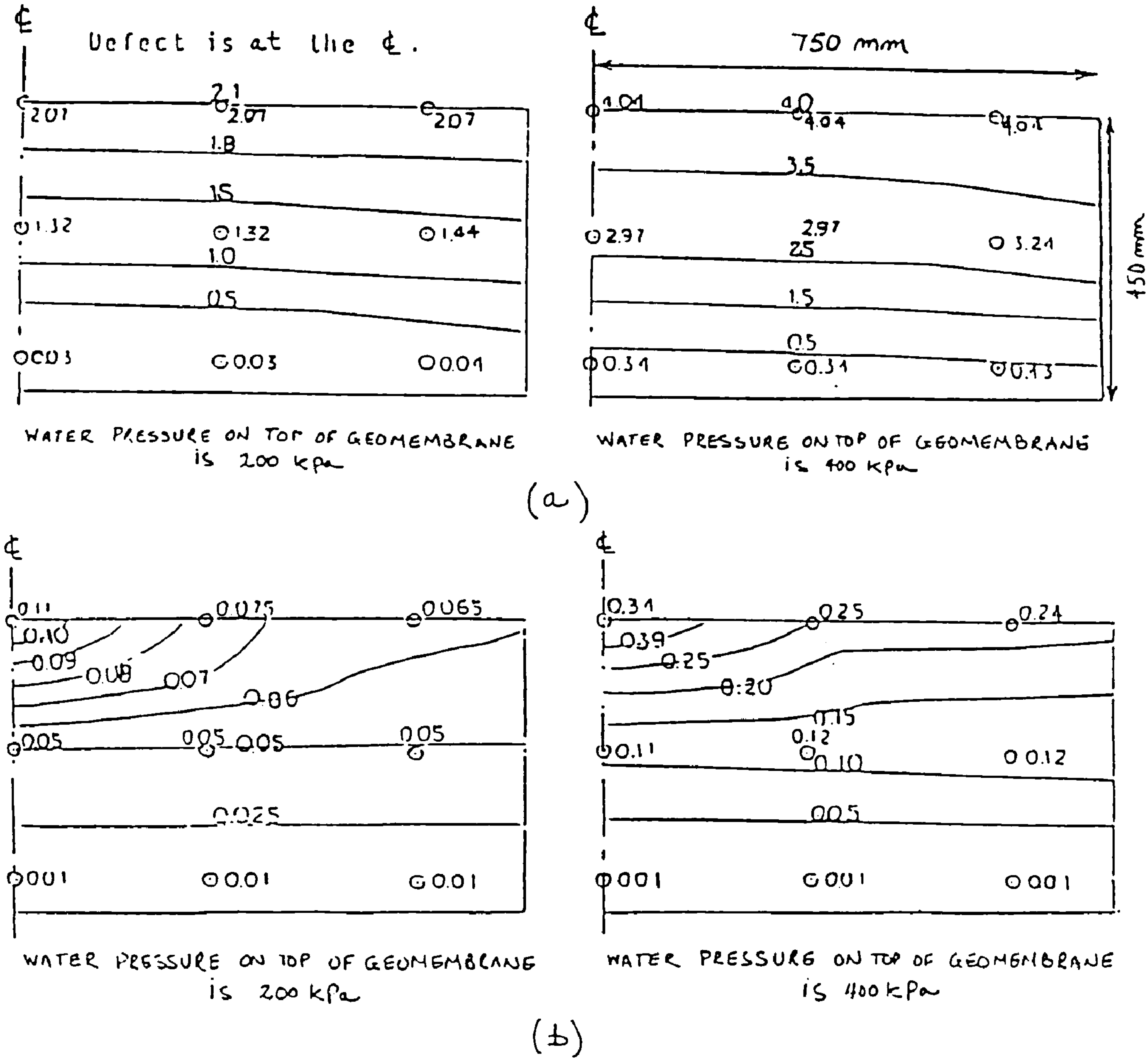

Figure B-14. Water pressure in the soil under the FML in the case of a 20 mm (3/4 in.) diameter hole in a 1 mm (40 mil) thick PVC FML; (a) the FML is placed directly on the soil; and (b) there is a geotextile between the FML and the soil [Fukuoka, 1985].

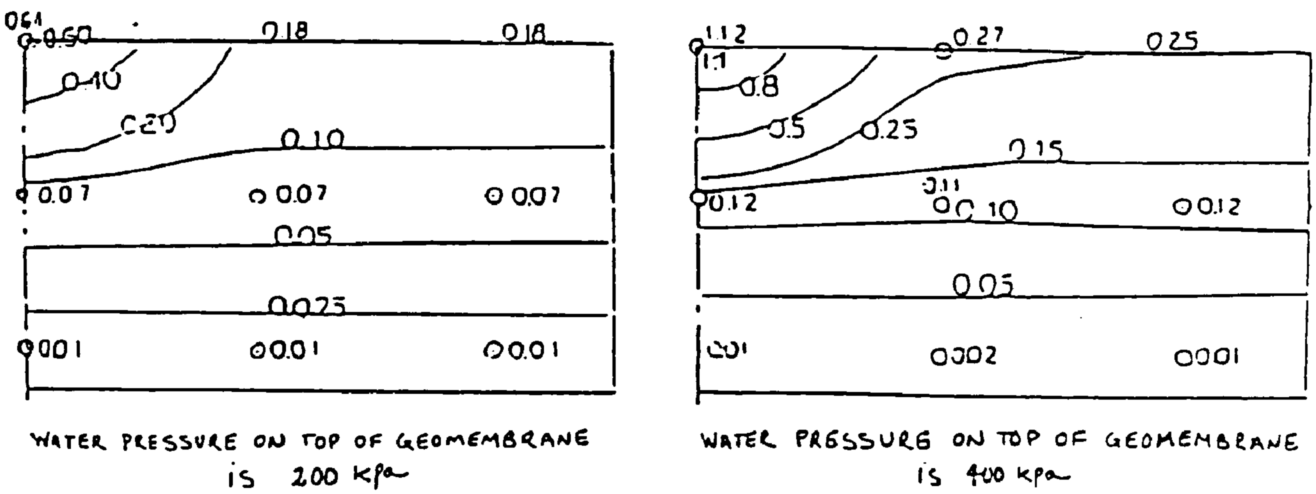

Figure B-15. Water pressure in the soil under the FML in the case of a 50 mm (2 in.) diameter hole in a 1 mm (40 mil) thick PVC FML placed on a needlepunched nonwoven geotextile (mass per unit area 450 g/m² (13 oz/sq. yd)) resting on the soil [Fukuoka, 1985].

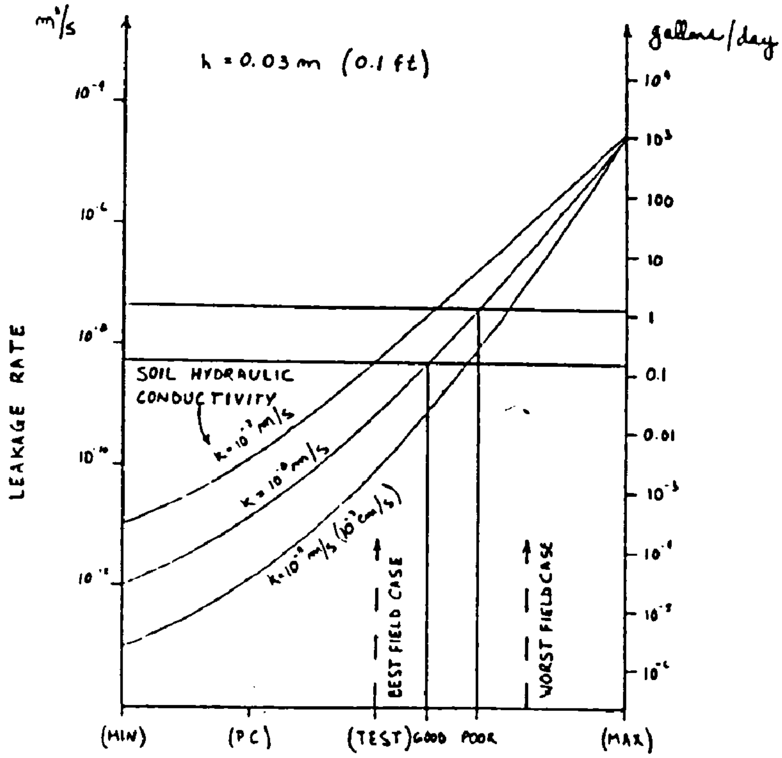

Figure B-16. Graph giving the leakage rate in case of leakage through a FML hole in a composite liner. The hydraulic head is 30 mm (0.1 ft) and the hole area is 1 cm^2 (i.e., diameter of 11.3 mm). Because of uncertainties in the analytical analyses as well as the large influence of soil conditions and contact between the FML and the soil, only a range of values can be given. Field conditions can be anywhere between the two extremes: (1) best, i.e., the soil is well compacted, flat and smooth, has not been deformed by rutting during construction, and has no clods and cracks, and the FML is flexible and has no wrinkles; and (2) the soil is poorly compacted, has an irregular surface and is cracked, and the FML is stiff and exhibits a pattern of large, connected wrinkles. Abbreviations: GOOD and POOR = good and poor field conditions; MIN, P.C., TEST, and MAX are defined in Table B-8.

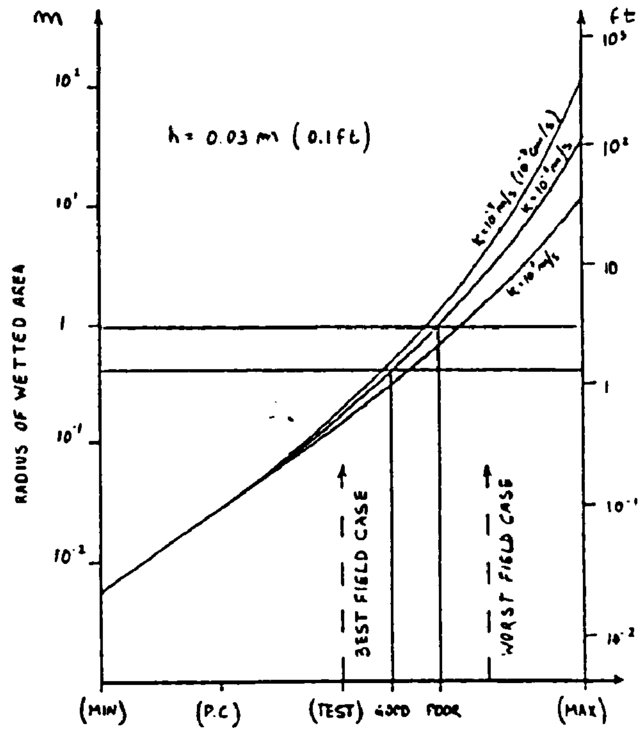

Figure B-17. Graph giving the radius of the wetted area in case of leakage through a FML hole in a composite liner. The hydraulic head is 30 mm (0.1 ft) and the hole area is 1 cm^2 (i.e., diameter of 11.3 mm). Because of uncertainties in the analytical analyses as well as the large influence of soil conditions and contact between the FML and the soil, only a range of values can be given. Field conditions can be anywhere between the two extremes: (1) best, i.e., the soil is well compacted, flat and smooth, has not been deformed by rutting during construction, and has no clods and cracks, and the FML is flexible and has no wrinkles; and (2) the soil is poorly compacted, has an irregular surface and is cracked, and the FML is stiff and exhibits a pattern of large, connected wrinkles. Abbreviations: GOOD and POOR = good and poor field conditions; MIN, P.C., TEST, and MAX are defined in Table B-8.

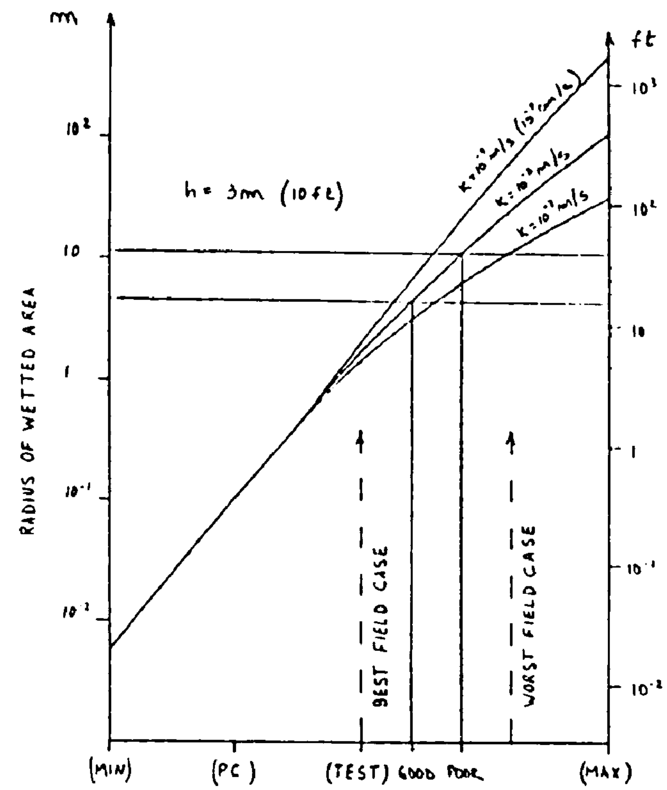

Figure B-18. Graph giving the radius of the wetted area in case of leakage through a FML hole in a composite liner. The hydraulic head is 3 m (10 ft) and the hole area is 1 cm^2 (i.e., diameter of 11.3 mm). Because of uncertainties in the analytical analyses as well as the large influence of soil conditions and contact between the FML and the soil, only a range of values can be given. Field conditions can be anywhere between the two extremes: (1) best, i.e., the soil is well compacted, flat and smooth, has not been deformed by rutting during construction, and has no clods and cracks, and the FML is flexible and has no wrinkles; and (2) the soil is poorly compacted, has an irregular surface and is cracked, and the FML is stiff and exhibits a pattern of large, connected wrinkles. Abbreviations: GOOD and POOR = good and poor field conditions; MIN, P.C., TEST, and MAX are defined in Table B-8.

APPENDIX C

Summary of Two-Dimensional Partially Saturated Flow Analysis Results [Data from Radian, 1987]

C.1 DESCRIPTION OF RESULTS

The two-dimensional partially saturated flow analyses results employed in the body of the report were developed by the Radian Corporation [Radian, 1987]. These results are summarized in this appendix by the following categories:

- compacted soil liners;
- composite soil liners with FML leakance, L = 7×10^{-14} s^{-1};
- composite soil liners with FML leakance, L = 3×10^{-12} s^{-1}; and
- composite soil liners with FML leakance, L = 3×10^{-11} s^{-1}.

Two tables are presented for each lining system simulated: (i) the first table describes the lining system and gives details of the various design variables, and (ii) the second table summarizes the various leakages (or fluxes) calculated as a function of time.

It was noted by Radian that the calculated cumulative drainage quantities provided in the second table include significant roundoff error. Radian suggested that the best way to calculate the cumulative drainage is as follows:

Cumulative Drainage = Cumulative Leakage - Cumulative Flux into Bottom Liner - Liquid Stored in LDCRS

Therefore, in the following tables the reported cumulative drainage at 40 years is reported using the above equation.

Compacted Soil Liners

TABLE A2-21. DESIGN VARIABLES FOR SIMULATION AH-1

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	800 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	14.0 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Compacted soil
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	127.9 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A2-22. EXPERIMENT AH-1--SIMULATION SUMMARY

Elapsed Time (weeks)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
2	1145.53	16,800	0.00	0	142.95	1,610	42.59	548
4	1069.45	32,200	0.00	0	148.92	3,660	47.29	1,180
6	1016.05	46,700	0.00	0	151.00	5,770	53.17	1,880
8	975.10	60,600	0.00	0	151.93	7,890	62.96	2,690
10	939.71	74,000	0.00	0	154.43	10,000	75.16	3,660
12	904.42	86,900	0.00	0	160.84	12,200	88.94	4,810
(drain flux begins)								
13.40	874.28	95,600	0.00	0	171.92	13,900	99.69	5,740
14	861.48	99,200	114.42	385	175.23	14,600	103.85	6,170
18	795.40	122,000	586.93	10,500	185.81	19,900	146.59	9,680
22	794.68	144,000	638.19	27,900	175.53	24,900	170.12	14,200
26	794.59	167,000	622.56	45,400	174.31	29,800	173.10	19,100
(approximate time to steady-state)								
26.45	794.57	169,000	622.56	47,400	174.29	30,300	173.18	19,600
40 Years	794.52	11,600,000	622.56	9,054,000 ~~9,010,000~~	173.94	2,540,000	173.94	2,530,000

Liquid [illegible] after 40 years = 9120 gallons/acre

TABLE A2-23. DESIGN VARIABLES FOR SIMULATION AH-2

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	101 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	11.7 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Compacted soil
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	127.9 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A2-24. EXPERIMENT AH-2--SIMULATION SUMMARY

Elapsed Time (years)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	111.17	43,600	0.00	0	59.50	18,700	53.25	13,700
2	104.72	82,800	0.00	0	70.01	42,400	67.61	36,100
3	101.26	120,000	0.00	0	77.43	69,400	76.04	62,400
4	99.00	157,000	0.00	0	83.13	98,800	82.21	91,400
5	97.45	193,000	0.00	0	87.35	130,000	86.75	122,000
6	96.45	228,000	0.00	0	90.22	162,000	89.84	155,000
(approximate time to steady-state)								
6.44	96.15	243,000	0.00	0	91.11	177,000	90.80	169,000
40 Years	95.16	1,410,000	0.00	~~0~~ [illegible]700	94.05	1,330,000	94.00	1,320,000

Liquid stored in LCRS after 40 years = [illegible]8,300 gallons/acre

TABLE A4-5. DESIGN VARIABLES FOR SIMULATION AH-6

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	62 gallons/acre-day
Leak location	Sidewall
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	14.0 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Compacted soil
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	127.9 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A4-6. EXPERIMENT AH-6--SIMULATION SUMMARY

Elapsed Time (years)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	61.10	23,000	0.00	0	32.96	11,000	30.66	8,870
2	61.37	45,400	0.00	0	40.25	24,400	38.08	21,500
3	61.38	67,800	0.00	0	46.21	40,200	44.18	36,500
4	61.38	90,200	0.00	0	50.66	58,000	49.01	53,600
5	61.38	113,000	0.00	0	53.93	77,100	52.65	72,200
6	61.38	135,000	0.00	0	56.28	97,300	55.31	92,000
7	61.38	157,000	0.00	0	57.91	118,000	57.23	113,000
(approximate time to steady-state)								
7.38	61.38	166,000	0.00	0	58.40	126,000	57.79	121,000
40 Years	61.38	897,000	0.00	~~0~~ 15,300	60.24	843,000	59.98	834,000

Liquid stored in LCRS after 40 years = 32,100 gallons/acre

TABLE A2-15. DESIGN VARIABLES FOR SIMULATION AG-2

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	74 feet
Sideslope grade	25%
Lower slope length	76 feet
Lower slope grade	2%
Impounded liquid depth	20 feet at centerline
Top Liner	
Type	FML
Average leak rate	1,406 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	11.5 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	38 feet
Bottom Liner	
Type	Compacted soil
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.9 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A2-16. EXPERIMENT AG-2--SIMULATION SUMMARY

Elapsed Time (weeks)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	1,801	13,300	0.00	0	119.21	594	32.44	254
2	1,697	25,400	0.00	0	189.72	1,770	33.16	483
3	1,648	37,100	0.00	0	193.41	3,130	39.95	732
4	1,607	48,400	0.00	0	196.16	4,490	45.49	1,030
5	1,570	59,500	0.00	0	200.32	5,880	48.38	1,360
6	1,534	70,300	0.00	0	206.23	7,310	53.20	1,710
7	1,491	80,900	0.00	0	223.52	8,810	62.46	2,110
(drain flux begins)								
7.16	1,481	82,600	0.00	0	229.99	9,080	64.34	2,190
8	1,448	91,100	618.38	2,410	227.73	10,500	57.62	2,560
12	1,428	131,000	733.74	22,700	190.92	16,100	127.99	5,370
16	1,420	171,000	800.43	44,400	184.06	21,400	149.67	9,310
20	1,417	211,000	863.14	67,200	180.49	26,400	160.82	13,700
24	1,416	251,000	889.38	91,200	178.28	31,500	167.45	18,300
28	1,416	290,000	889.38	116,000	177.02	36,400	171.25	23,000
32	1,416	330,000	889.38	141,000	176.36	41,400	173.28	27,900
(approximate time to steady-state)								
34.17	1,416	351,000	889.38	154,000	176.14	44,100	173.99	30,500
40 Years	1,415	20,700,000	873.81	~~12,700,000~~ 18,050,000	175.61	2,570,000	175.61	2,550,000

Liquid stored in LCRS after 40 years = 80,000 gallons/acre

TABLE A2-35. DESIGN VARIABLES FOR SIMULATION BA-5

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	800 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	14.7 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Compacted soil
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	6 feet
Initial moisture storage	261.1 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A2-36. EXPERIMENT BA-5--SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	1039.30	33,800	0.00	0	127.77	3,330	50.27	1,290
2	949.11	63,900	0.00	0	143.15	7,470	61.46	3,000
(drain flux begins)								
2.83	877.69	87,000	0.00	0	164.15	11,300	68.22	4,640
3	861.46	91,400	126.25	556	168.04	12,200	69.18	4,990
4	796.19	116,000	631.91	12,700	167.64	17,500	74.82	7,170
5	795.24	140,000	631.45	31,900	153.54	22,400	98.40	9,790
6	794.98	165,000	631.45	51,800	147.97	26,900	120.92	13,200
7	794.84	189,000	631.45	71,800	145.34	31,400	132.32	17,100
8	794.77	213,000	631.45	91,900	144.33	35,800	136.93	21,200
9	794.72	237,000	631.45	112,000	143.84	40,200	138.95	25,400
(approximate time to steady-state)								
9.75	794.72	255,000	631.45	127,000	143.60	43,400	139.80	28,600
40 Years	794.62	11,600,000	631.45	~~9,190,000~~ 9,425,000	142.76	2,090,000	142.76	2,070,000

Liquid stored in LCRS after 40 years = 25,400 gallons/acre

TABLE A2-37. DESIGN VARIABLES FOR SIMULATION BB-1A

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	928 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	7.9 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Compacted soil
Soil	Clay
Saturated hydraulic conductivity	10^{-6} cm/s
Thickness	3 feet
Initial moisture storage	125.5 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A2-38. EXPERIMENT BB-1A--SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
2	1,059	70,800	0.00	0	606	29,100	555	18,000
4	986	133,000	0.00	0	746	70,800	731	58,100
6	953	192,000	0.00	0	826	119,000	819	106,000
8	936	249,000	0.00	0	873	171,000	869	157,000
10	928	306,000	0.00	0	897	225,000	896	211,000
12	924	362,000	0.00	0	909	280,000	908	266,000
14	922	418,000	0.00	0	914	335,000	914	321,000
16	921	474,000	0.00	0	916	391,000	916	377,000
18	921	530,000	0.00	0	917	447,000	917	433,000
20	921	586,000	0.00	0	917	502,000	917	489,000
22	921	642,000	0.00	0	917	558,000	917	544,000
24	921	698,000	0.00	0	918	614,000	917	600,000
26	921	754,000	0.00	0	918	670,000	918	656,000
(approximate time to steady-state)								
26.71	921	774,000	0.00	0	918	690,000	918	676,000
40 Years	921	13,500,000	0.00	~~0~~ 120,000	918	13,300,000	918	13,300,000

Liquid stored in LDCRS after 40 years = 79,700 gallons/acre

Composite Soil Liners

With

FML Leakance = $7 \times 10^{-14}\ s^{-1}$

TABLE DESIGN VARIABLES FOR SIMULATION AM-4

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	60 gallons/acre-day
Leak location	Sidewall
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	37.0 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	7×10^{-14} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.7 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE EXPERIMENT AM-4—SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
2	61.11	4,100	0.00	0	0.016	1	-0.0394	-11
4	60.44	7,770	0.00	0	0.017	2	0.0231	-10
6	60.56	11,500	0.00	0	0.017	3	0.0236	-8
8	60.50	15,100	0.00	0	0.017	4	0.0363	-6
10	60.42	18,800	0.00	0	0.017	5	0.0418	-4
12	60.34	22,500	0.00	0	0.018	6	0.0369	-1
14	60.27	26,200	0.00	0	0.018	7	0.0410	1
16	60.19	29,800	0.00	0	0.018	8	0.0391	4
(drain flux begins)								
16.52	60.17	30,800	0.00	0	0.018	9	0.0304	4
17	60.15	31,700	22.23	323	0.019	9	0.0362	5
19	60.02	35,300	44.47	2,880	0.019	10	0.0289	7
21	59.89	39,000	44.47	5,590	0.019	11	0.0415	10
23	59.81	42,600	44.47	8,300	0.019	12	0.0396	12
(approximate time to steady-state)								
23.79	59.79	44,000	44.47	9,360	0.019	13	0.025	13
40 Years	59.71	873,000	44.47	837,000 ~~638,300~~	0.019	277	0.019	285

Liquid stored in LDCRS after 40 years = 35,400 gallons/acre

TABLE DESIGN VARIABLES FOR SIMULATION CB-5

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	780 gallons/acre-day
Leak location	uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	35.4 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	7×10^{-14} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.2 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE EXPERIMENT CB-5--SIMULATION SUMMARY

Elapsed Time (weeks)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	970	6,870	0	0	0.017	0.12	-2.29	-15
2	943	13,500	0	0	0.018	0.24	-2.24	-31
3	918	20,000	0	0	0.018	0.36	-2.20	-46
4	891	26,300	0	0	0.019	0.49	-2.08	-61
(drain flux begins)								
4.33	881	28,400	0	0	0.019	0.54	-2.12	-66
5	863	32,500	133	553	0.019	0.63	-2.01	-76
8	791	49,700	543	8,070	0.021	1.06	-1.85	-117
11	779	66,100	745	22,600	0.021	1.50	-1.69	-154
14	778	82,400	726	38,200	0.021	1.95	-1.49	-187
17	778	98,700	757	54,100	0.021	2.40	-1.37	-217
20	777	115,000	761	69,900	0.021	2.84	-1.22	-244
23	777	131,000	765	85,800	0.021	3.29	-1.12	-269
26	777	148,000	752	101,000	0.021	3.73	-1.00	-291
(approximate time to steady-state)								
28.93	777	164,000	745	117,000	0.021	4.17	-0.90	-311
40 Years	777	11,400,000	747	~~10,900,000~~ 11,358,000	0.021	307	0.02	-126

Liquid stored in [illegible] after 40 years = 41,400 gallons/acre

TABLE DESIGN VARIABLES FOR SIMULATION OSE-4

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section ~~width~~	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	49 gallons/acre-day
Leak location	Sidewall
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	35.4 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	7×10^{-14} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.2 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

Comment: Tear in upper liner directly above tear in bottom liner.

TABLE EXPERIMENT OSE-4--SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
3	52.87	4,900	0.00	0	11.42	1,760	5.79	-6
6	52.15	9,690	0.00	0	10.98	2,770	8.60	685
9	51.67	14,400	0.00	0	11.15	3,780	9.74	1,530
12	51.28	19,100	0.00	0	11.35	4,810	10.47	2,450
15	50.89	23,800	0.00	0	11.56	5,860	10.99	3,440
18	50.43	28,400	0.00	0	11.86	6,920	11.43	4,460
(drain flux begins)								
20	50.04	31,500	0.00	0	12.12	7,650	11.71	5,160
22	49.62	34,500	22.23	1,350	12.38	8,400	12.01	5,890
24	49.31	37,500	44.47	2,850	12.56	9,160	12.29	6,630
26	49.08	40,500	44.47	4,950	12.68	9,920	12.48	7,380
28	48.91	43,500	44.47	7,520	12.78	10,700	12.64	8,140
30	48.79	46,400	44.47	9,820	12.85	11,500	12.75	8,920
(approximate time to steady-state)								
30.94	48.74	47,800	44.47	11,100	12.88	11,800	12.78	9,280
40 Years	48.47	710,000	44.47	~~618,000~~ 491,500	13.03	190,000	13.03	187,000

Liquid stored in LDCRS after 40 years = 23,500 gallons/acre

Composite Soil Liners

With

FML Leakance = $3 \times 10^{-12}\ s^{-1}$

TABLE A3-5. DESIGN VARIABLES FOR SIMULATION CZ-1

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	92 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Coarse Sand
Saturated hydraulic conductivity	10^{-2} cm/s
Thickness	1 foot
Initial moisture storage	4.6 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	3×10^{-12} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.4 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A3-6. EXPERIMENT CZ-1--SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
2	97.46	6,020	0.00	0	0.82	47	0.03	3
4	95.36	11,900	0.00	0	0.85	98	0.17	9
6	94.33	17,600	0.00	0	0.86	150	0.31	24
8	93.33	23,400	0.00	0	0.87	202	0.42	46
10	92.52	29,000	0.00	0	0.87	255	0.45	74
(drain flux begins)								
11.12	92.14	32,200	0.00	0	0.87	285	0.54	93
12	91.97	34,600	53.64	993	0.88	308	0.60	108
13	91.88	37,400	74.20	3,000	0.88	335	0.62	126
14	91.83	40,200	83.85	5,440	0.88	362	0.65	146
15	91.81	43,000	87.56	8,050	0.88	388	0.68	166
(approximate time to steady-state)								
15.45	91.81	44,300	88.74	9,260	0.88	400	0.68	175
40 Years	91.77	1,340,000	90.54	~~1,290,000~~ 1,291,000	0.87	12,800	0.80	11,400

Liquid stored in LDCRS after 40 years = 35,800 gallons/acre

TABLE A3-7. DESIGN VARIABLES FOR SIMULATION CZ-2

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	1238 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Coarse Sand
Saturated hydraulic conductivity	10^{-2} cm/s
Thickness	1 foot
Initial moisture storage	4.6 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	3×10^{-12} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.4 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A3-8. EXPERIMENT CZ-2--SIMULATION SUMMARY

Elapsed Time (weeks)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	1,316	9,330	0.00	0	0.82	5	-0.25	0.7
2	1,311	18,500	0.00	0	0.87	11	-0.07	0.9
3	1,305	27,700	0.00	0	0.89	17	-0.08	1.1
4	1,299	36,800	0.00	0	0.90	24	0.01	1.4
(drain flux begins)								
4.94	1,287	45,300	0.00	0	0.90	30	0.07	1.6
5	1,286	45,800	24.63	9	0.90	30	0.03	1.6
7	1,264	63,700	332.85	2,740	0.92	43	-0.02	1.9
9	1,250	81,300	826.00	11,200	0.92	56	-0.03	2.6
11	1,242	98,700	1,075.61	24,800	0.93	69	-0.02	3.4
13	1,240	116,000	1,172.79	40,700	0.93	82	0.19	4.8
15	1,237	133,000	1,209.31	57,400	0.93	95	0.17	6.6
17	1,237	151,000	1,224.67	74,500	0.93	108	0.29	8.9
(approximate time to steady-state)								
17.92	1,237	159,000	1,226.87	82,400	0.93	114	0.11	10
40 Years	1,237	18,100,000	1,235.09	18,000,000	0.93	13,500	0.32	4,650

Liquid stored in LDCRS after 40 years = 79,100 gallons/acre

Composite Soil Liners

With

FML Leakance = 3×10^{-11} s^{-1}

TABLE A5-1. DESIGN VARIABLES FOR SIMULATION AM-2

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	60 gallons/acre-day
Leak location	Sidewall
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	37.6 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	3×10^{-11} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.2 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A5-2. EXPERIMENT AM-2--SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
2	61.24	4,100	0.00	0	6.48	398	-0.03	-2
4	60.53	7,790	0.00	0	6.40	789	1.03	26
6	60.66	11,500	0.00	0	6.37	1,180	2.14	125
8	60.62	15,200	0.00	0	6.37	1,570	3.08	285
10	60.55	18,900	0.00	0	6.39	1,950	3.78	494
12	60.48	22,500	0.00	0	6.43	2,340	4.35	742
14	60.41	26,200	0.00	0	6.49	2,740	4.80	1,020
16	60.35	29,900	0.00	0	6.58	3,130	5.17	1,320
18	60.29	33,600	0.00	0	6.69	3,540	5.47	1,650
(drain flux begins)								
18.35	60.27	34,200	0.00	0	6.72	3,610	5.54	1,710
20	60.19	37,200	44.47	1,520	6.77	3,950	5.74	1,990
22	60.07	40,900	44.47	4,120	6.80	4,360	5.97	2,350
24	59.99	44,500	44.47	6,830	6.82	4,780	6.15	2,720
(approximate time to steady-state)								
25.21	59.95	46,700	44.47	8,470	6.82	5,030	6.25	2,940
40 Years	59.86	875,000	44.47	~~624,000~~ 741,000	6.80	99,100	6.80	96,900

Liquid stored in LDCRS after 40 years = 34,800 gallons/acre

TABLE A3-3. DESIGN VARIABLES FOR SIMULATION CB-3

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leak rate	92 gallons/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-2} cm/s
Thickness	1 foot
Initial moisture storage	4.6 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	3×10^{-11} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.4 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE A3-4. EXPERIMENT CB-3--SIMULATION SUMMARY

Elapsed Time (months)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	98.60	3,040	0.00	0	7.41	219	0.13	14
2	97.63	6,020	0.00	0	7.65	449	0.27	19
3	96.57	8,980	0.00	0	7.72	683	0.89	36
4	95.67	11,900	0.00	0	7.75	919	1.50	71
5	95.15	14,800	0.00	0	7.74	1,150	2.12	127
6	94.68	17,700	0.00	0	7.71	1,390	2.80	202
7	94.17	20,600	0.00	0	7.70	1,620	3.46	295
8	93.70	23,400	0.00	0	7.69	1,860	3.87	405
9	93.28	26,300	0.00	0	7.68	2,090	4.32	530
10	92.91	29,100	0.00	0	7.67	2,320	4.74	667
11	92.57	31,900	0.00	0	7.66	2,560	5.06	816
(drain flux begins)								
11.69	92.36	33,800	0.00	0	7.66	2,720	5.29	925
12	92.28	34,700	25.91	176	7.65	2,790	5.37	975
14	92.07	40,300	71.11	3,590	7.62	3,250	5.90	1,320
16	92.02	45,900	81.71	8,350	7.58	3,720	6.30	1,690
18	92.00	51,500	83.46	13,400	7.56	4,180	6.59	2,080
(approximate time to steady-state)								
18.46	92.00	52,800	83.72	14,600	7.55	4,280	6.64	2,180
40 Years	91.98	1,340,000	84.10	1,195,000 ~~1,200,000~~	7.51	110,000	7.05	101,000

Liquid stored in LDCRS after 40 years = 35,000 gallons/acre

TABLE A3-27. DESIGN VARIABLES FOR SIMULATION CB-4A

Description	Value
General Design Parameters	
Facility Type	Surface Impoundment
Plan Area	2.0 acres
Half-section width	150 feet
Sideslope length	30 feet
Sideslope grade	25%
Lower slope length	120 feet
Lower slope grade	2%
Impounded liquid depth	10 feet at centerline
Top Liner	
Type	FML
Average leal rate	778 gallon/acre-day
Leak location	Uniform
Drainage Layer	
Soil type	Sand
Saturated hydraulic conductivity	10^{-3} cm/s
Thickness	1 foot
Initial moisture storage	35.4 cubic feet
Drain System	
Number of drains	3
Drain locations	Evenly spaced along lower slope
Drain spacing	60 feet
Bottom Liner	
Type	Composite
Bottom FML Leakance	3×10^{-11} s^{-1}
Soil	Clay
Saturated hydraulic conductivity	10^{-7} cm/s
Thickness	3 feet
Initial moisture storage	125.2 cubic feet
Native Soil	
Soil Type	Loam
Saturated hydraulic conductivity	10^{-4} cm/s
Initial moisture condition	Hydrostatic from water table
Water Table	
Elevation	10 feet below top FML at centerline

TABLE - EXPERIMENT CB-4A--SIMULATION SUMMARY

Elapsed Time (weeks)	Leak Rate (gpad)	Cumulative Leakage (gal/acre)	Drain Flux (gpad)	Cumulative Drainage (gal/acre)	Flux into Bottom Liner (gpad)	Cumulative Flux into Bottom Liner (gal/acre)	Flux from Unit (gpad)	Cumulative Flux from Unit (gal/acre)
1	970	6,870	0	0	7.19	50	-6.78	-36
2	944	13,500	0	0	7.38	101	-6.21	-81
3	918	20,000	0	0	7.56	153	-5.69	-123
4	892	26,400	0	* 0	7.76	207	-5.13	-161
(drain flux begins)								
4.33	882	28,400	0	0	7.84	225	-4.97	-173
5	864	32,500	129	446	7.97	262	-4.60	-195
25	778	142,000	745	95,400	8.16	1,430	1.78	-297
45	778	251,000	767	200,000	7.88	2,550	4.71	177
65	778	360,000	756	305,000	7.75	3,650	6.18	952
85	778	469,000	756	409,000	7.68	4,730	6.91	1,880
105	778	578,000	723	513,000	7.65	5,800	7.27	2,870
125	778	687,000	762	617,000	7.63	6,870	7.45	3,900
(approximate time to steady-state)								
133.53	778	733,000	745	662,000	7.63	7,320	7.48	4,350
40 Years	778	11,400,000	745	~~10,900,000~~ 11,245,000	7.62	111,000	7.62	108,000

Liquid stored in LDCRS after 40 years = 41,200 gallons/acre