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# DRAFT FINAL

# INTERIM REPORT 2

# SYNTHETIC CAP AND LINER SYSTEMS

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# 1.0 EXECUTIVE SUMMARY

## 1.1 INTRODUCTION

The Environmental Protection Agency, Office of Solid Waste, initiated broad technical investigations of current land disposal technology in response to comments received following publication of the Interim Final Land Disposal Regulations. The project was divided into the five principal tasks identified below:

- o Clay Cap and Liner Systems
- o Synthetic Cap and Liner Systems
- o Leachate Quality
- o Fate and Transport Modeling
- o Review of Existing Facilities Which Have Failed

The following report provides a summary of available information regarding the design, installation and operation of synthetic cap and liner systems.

### 1.1.1 Objectives

The synthetic liner investigation was designed to evaluate the advantages and disadvantages of using synthetic liner systems to contain hazardous waste materials. Secondary objectives of the project included: the consolidation of available information on the performance of existing synthetic liner facilities; the development of analysis tools to aid in the evaluation of liner designs; and, the identification of information gaps which will require further research. Essentially, the objective of the project was to establish a data base defining the "state of the art" in synthetic liner technology, and utilizing this base, provide recommendations for further research, the need for additional technical guidance materials, and areas requiring regulatory action.

### 1.1.2 Approach

The Environmental Protection Agency recognized the importance of synthetic liner materials to the field of hazardous waste disposal and designed this project to consolidate the available information in this area. Data was obtained from existing facilities using synthetic liners, current research efforts and from an evaluation of current facility design alternatives. Field data was obtained through interviews with regulatory personnel, facility operators and liner construction specialists. A literature survey was conducted to identify current research efforts, and the individuals involved were contacted to provide research results and professional perspective for incorporation into the synthetic liner data base. Finally, a research tool, the HELP model, was developed and used to assess the relative merits of various facility design alternatives. Overall, the approach selected was geared to consolidate available theoretical, field, and design information to build a scientific data base to assess the advantages and disadvantages of synthetic liners for containment of hazardous waste.

## 1.2 AREAS OF INVESTIGATION

### 1.2.1 Chemical Resistance

The chemical and physical properties of synthetic liner materials are based primarily on the type of polymer and the particular formulation used in the liner manufacturing process. An almost unlimited number of material variations can be achieved by changing material additives, pigments and reinforcing materials. Similarly, the specific components of leachate generated from a fairly simple waste stream may exceed several hundred individual components. Specific resistance testing of particular liner materials with each leachate component would represent a monumental task and is impractical. The alternative, which is widely used in the synthetic liner field, uses a representative multi-component leachate to test the resistance of a specific liner material. Liner material resistance is inferred based on the rate of change of the physical and chemical properties of the liner material with exposure time. Several testing methods have been proposed and all suffer from a basic lack of standardization, either in the parameters used, the testing protocol or the level of parameter change which indicates a lack of liner resistance. In general, the chemical resistance testing is largely a subjective evaluation at the present time depending on the specific experience and motivation of the principal investigators.

The EPA has recently taken the first step toward meaningful standardization and quantification of chemical resistance testing with the development of EPA Method 9090. The EPA Method 9090 defines a basic protocol for conducting immersion testing of liner materials. The standard defines exposample leachate selection, testing temperatures and bath level maintenance procedures. Further development of standard testing procedures is warranted to establish chemical resistance criteria on a more quantitative basis.

At present, the existing base of chemical resistance testing results is limited. Based on the evaluation of existing facilities conducted under this program, it appears that the resistance procedures used have accurately assessed short-term liner performance. Extrapolation of test results to project long-term performance cannot be verified, since the base of actual synthetic material field data extends over the past 10 years only. However, the existing 10 year data base indicates that selected synthetic liners are sufficiently resistant to specific types of leachate. Generally, the results of resistance testing and available field data indicate that different liner material types exhibit varying resistance to different leachate types. Efforts to identify a single class of synthetic materials resistant to all leachate types have not been successful. In summary, specific liner materials can be effectively tested for resistance to particular leachates with a high degree of reliability in the short-term. Extrapolation of short-term resistance test results to long-term performance cannot be verified using current techniques. Further research in chemical resistance testing is warranted to resolve these problems.

### 1.2.2 Synthetic Liner and Cap Installation

The installation of synthetic cap and liner systems is performed using the construction and preparation techniques developed for the installation of soil liner systems. Generally, liner installation requires completion of a detailed geotechnical investigation of the site and the preparation of a foundation design to accomodate anticipated loads during the life of the facility. Due to the importance of the facility foundation design a quality assurance program should be required to verify attainment of design specifications for proper commpaction of all soil liners, subgrade materials, waste materials and the final cap system.

In addition to the general problems associated with waste facility design and construction, proper installation of synthetic materials pose several unique problems which should be avoided. Synthetic liners are relatively thin polymer barriers. Therefore they are more susceptible to puncture, tearing and stress than thicker soil liners. Special precautions must be taken in the selection of liner bedding material to avoid induced stress. Generally, any fine sand or filtered soil can be used to provide a six inch buffer layer above and below the liner to add the required protection. Also, as a result of liner and cap thickness, penetration by vegetation and burrowing animals can occur if the liner is not adequately protected. The use of a layer of gravel or cobbles above the liner cover bed has been used successfully to minimize animal damage. All soils and subgrade materials must be sterilized to prevent vegetative damage. Shallow rooted cover vegetation should be selected and properly maintained to prevent cap damage. These problems can be adequately resolved using the techniques specified. However, a comprehensive quality assurance program is required to insure proper application of the techniques identified during the liner and cap installation process.

The most significant problem encountered during the evaluation of existing facilities was that of cap subsidence. All waste materials can be expected to consolidate to some extent as material decay progresses. Studies have shown that most consolidation occurs during the first 5 years after facility closure. Proper waste compaction during facility operation and the placement of soil cover materials during all filling should reduce the overall subsidence problem, but some subsidence can be expected. Cap liners can be designed to support the facility cover, if suitable reinforcing materials are incorporated into the liner. However, the effect of the induced long-term stress may result in the eventual weakening of the cap material. An alternative approach would allow the facility to install a temporary soil cap during the period of maximum subsidence, followed by the installation of a final cap after the rate of subsidence diminished. This would require an extension of the normal closure period and would require continued leachate removal during this period.

The final installation problem which is peculiar to synthetic liners is the proper seaming of liner panels. Liner seaming techniques vary depending on the liner material selected. However, the basic procedure for all liner types is the same. The liner panels are cleaned, the solvent or adhesive is applied, the panels are pressed together and allowed to cure. Major problems associated with field seaming are presented by adverse weather conditions, including wind, rain, and cold temperatures. Proper scheduling of installation activities, and adequate storage of materials should prevent most of these problems. The review of existing facilities indicated that most faulty seams were attributed to the use of the wrong seaming adhesives and cleaners. The results of this study indicate that reliable field seams can be made if proper precautions are observed. A comprehensive quality ing operation it is recommended that 100 percent field testing of seams be included in the quality assurance plan. Further, sample liner seam patches should be prepared and subjected to laboratory testing to insure proper strength and bonding of the seamed materials. Special precautions are required when seaming old and new liner materials. However, suitable techniques have been developed and should produce reliable seams if correctly applied.

### 1.2.3 Performance and Service Life

This investigation has identified a basic flaw in the current regulatory concept with respect to the use of synthetic liners. Synthetic liners cannot strictly prevent leakage of volatile leachate. Leakage occurs through the liner via a gaseous diffusion mechanism referred to as vapor transport. Essentially, volatized waste material is absorbed by the liner, passed through the liner membrane due to the presence of a concentration gradient, and is desorbed on the outer side of the liner. Proper selection of liner material can effectively minimize the effective leakage, but minute amounts of volatile leachate components will escape. Therefore, synthetic liners cannot, in general, meet the performance objective of preventing leachate escape during the active life of the facility. The regulations should be modified to incorporate a clause allowing "de minimus" leakage during the facility life. The significance of the vapor transsport mechanism is relatively minor if liner material selection is accomplished recognizing the need to minimize vapor transport through the liner. Synthetic liner materials can be selected using available testing techniques to minimize leakage due to vapor transport.

The projection of liner service life represents a more difficult problem. The regulations refer to liner "service life" and "long term" effects without providing a working definition of these terms. Precise definitions would provide a basis for comparison of liner performance which is presently unavailable. The lack of clearly defined performance goals is complicated by the extremely short experience base available for synthetic liners in hazardous waste applications (10) years.

Current liner service life projections are based on exposure tests which provide a measure of the rate of change of liner properties as a function of exposure time. Results available to date indicate that synthetic liners with suitable resistance to chemical leachate attack can be expected to meet performance objectives for a period of 40 to 45 years. This result is based on a subjective evaluation of projected liner service life estimates which ranged from 3 to 200 years. Existing facility data have shown that synthetic materials are reliable, but data exists for very short periods (10 years for hazardous waste and 25 years for other applications). Projections of 150 to 200 years using current techniques appear to be overly optimistic. Similarly, projections of 3 to 15 years seem overly conservative. The estimate of 40 to 45 years provides a resonably conservative estimate based on the reliability of currently available projection techniques. Further research is warranted to identify more reliable testing methods and to develop a longer term field information base. Available testing methods should be evaluated and standard techniques developed. However, based on the results available at this time, an anticipated service life of a well designed liner, which is chemically resistant to leachate attack, appears to be in the range of 40 to 45 years.

which is chemically resistant to leachate attack, appears to be in the range of 40 to 45 years.

### 1.2.4 Failure Modes

The vapor transport mechanism is often included as a synthetic liner failure mode. This does not appear to be justified, since vapor transport is an intrinsic property of synthetic liner materials and does not represent a material failure. Therefore, vapor transport has not been addressed as a failure mode in this report.

The evaluation of installed synthetic liners revealed the presence of various types of holes in the liner material. Liner holes refer to pinholes which are caused by some manufacturing processes, penetration holes due to installation damage, and tears in the liner due to wind or equipment damage. The significance of the presence of holes in the liner to overall liner performance depends on the tyupe and amount of holes present. Manufacturers indicate that proper quality assurance procedures can effectively minimize and even eliminate liner pinholes. The use of properly selected liner bedding materials and soil sterilization techniques can be used to reduce the number of installation induced holes. Any major tears should be repaired during the liner installation phase. A comprehensive quality control and inspection procedure is required during liner manufacture, placement and operation to minimize the number of holes in the liner system. However, some holes can be expected in the final liner, even if proper quality assurance is implemented.

An analysis of the net effect of the presence of holes in the liner was conducted. Assuming a 1 meter square hole or 25 million pinholes per acre of liner material, the effective leakage rate for the synthetic liner would be significantly less than the leakage rate through a well designed clay liner system. Proper quality assurance could reduce the number of holes to significantly less than the assumed case. Therefore, a properly installed synthetic liner system can be expected to have some holes. However, the net leakage through the system would be minimal if proper quality assurance procedures were applied.

The second principal failure mode identified for synthetic liners is referred to as the "bathtub effect". The "bathtub effect" refers to the gradual filling of the disposal facility with leachate due to increased permeability of the facility cap and failure of the leachate collection system. Essentially, the problem is a reflection of cap subsidence problems or faulty facility design. As the leachate level rises, it will emerge from the facility either through the cap or by over-topping the side walls. The result is eventual leachate contamination of local surface water bodies and streams in the facility area.

Several techniques are available to detect and avoid the problem. The proper design of the cap system to prevent infiltration of precipitation is the most important preventative measure. However, due to waste subsidence discussed previously, failure of even well designed caps can occur. The leachate collection system provides the necessary backup system to remove leachate in a controlled manner to avoid buildup. A properly designed and installed leachate collection system will allow the identification of a cap failure due to increased leachate infiltration. A final backup system is

- The cap and leachate control system provides a critical role in minimizing facility leakage.

- Holding climate constant, more conservative facility designs (double liners, leachate control, etc.) act to reduce the total leakage of the facility.

The results of the HELP simulation indicate that climate is the most important variable in facility design. Facilities located in moist climates produced more total leakage than facilities located in dry arid climates, regardless of facility design. The results indicate the overall importance of rainfall to the determination of facility leakage. Essentially, all water which percolates into the facility is available for ultimate leakage.

The results of the HELP model simulation emphasize the importance of cap design to the overall facility performance. This suggests that additional emphasis be placed on the design and installation of cap systems. It is also recommended that leachate level monitoring be required within the facility to provide an early warning system for the detection of cap failure. In the event that failure occurs, the leachate level rise would be detected before contaminant release occurred from the facility.

The HELP model provides a valuable tool for the evaluation of design alternatives. Further research is required to verify the HELP model before the results can be considered more than comparative.

## 1.3 CONCLUSIONS AND RECOMMENDATIONS

### 1.3.1 Overall Conclusions Regarding Synthetic Liners

Synthetic liner systems can be used effectively to control leachate migration from hazardous waste facilities. However, synthetic liners cannot achieve the current facility containment goals expressed in the Interim Final Land Disposal regulations. Well designed synthetic liners will be penetrated by a number of pinholes and installation holes, and will leak as a result of vapor transport through the liner systems. Properly installed and tested synthetic liners will reduce the effective leachate leakage rate below that obtainable through the use of well designed soil liners. Several significant problems remain regarding the use of synthetic liner materials in a hazardous waste environment. The most significant problem remaining is the projection of the anticipated service life of synthetic materials. Current experience provides a 10 year data base for waste disposal applications and a 25 year data base for other uses. Therefore, synthetic liner service life is currently based on laboratory testing of the rate of change of liner properties as a result of leachate exposure. The results of laboratory projections indicate that synthetic liners can be expected to perform in accordance with design specifications for a period of 40 to 45 years.

### 1.3.2 Requirements Needed to Minimize Synthetic Liner Leakage

The singularly most important result of the present project is the need for mandatory quality assurance of synthetic liner installation operation and maintenance activities. The investigation of existing facilities has indicated a general lack of comprehensive quality control of synthetic liner installation at existing facilities. This problem pervades facility design, liner installation and maintenance programs. The technology required to design and construct an acceptable hazardous waste facility is available. However, the review of existing facilities indicates a general disregard for the critical factors of synthetic liner installation. The review of existing facilities indicates significant problems in the following areas:

- o Geotechnical investigation of facility areas;
- o Subgrade and bedding material selection and preparation;
- o Synthetic liner seaming operations;
- o Waste placement and compaction;
- o Adequate facility cap design; and,
- o Appropriate quality assurance control.

Further standardization of chemical resistance testing procedures is also required. The present techniques rely on a subjective evaluation of results. There are no established testing protocols and criteria to define acceptable chemical resistance of selected liner materials to leachate streams. Finally, the specification of procedures to identify representative test leachates have not been defined.

### 1.3.3 Recommendations

#### 1.3.3.1 Regulatory Changes

Recommendations for further action are provided in the areas of regulation review, guidance material preparation and further research. The recommendations provided are based on the analysis of the data obtained during the course of this investigation by the consultants involved.

Regulation Review

- o The objective of containing all leachate emanating from hazardous waste facilities during the active life of the facility should be reviewed to determine if a "de minimus" leakage level would be acceptable.

- o Leachate levels should be monitored within the waste facility during operation and after closure.

- o The closure period should be extended to allow the installation of temporary caps in order to allow the rate of waste subsidence to stabilize prior to installation of the permanent cap. Leachate collection must continue during this interim period.

- o A formal quality assurance program covering all aspects of facility design, installation, operation and maintenance should be established as part of the permit process.

- o Standard chemical resistance testing procedures and criteria must be specified in the regulations.

- o The definitions of "long term" and "service life" of synthetic materials should be clarified.

- o The requirement to limit leachate rise above the liner to 30 cm should be modified to 60 cm for synthetic systems in order to allow adequate protection of the synthetic liner system.

1.3.3.2 Guidance Material

- o Guidance material should be developed regarding standard methods for resistance testing of liner materials. Standardization of testing protocols, sample preparation and representative leachate should be accomplished.

- Guidance material should be developed regarding the use of current liner property testing methods to project ultimate liner performance.

- A comprehensive quality assurance program should be developed to support the permitting of hazardous waste facilities. The program may be designed using other formal EPA quality assurance programs as guidelines.

#### 1.3.3.3 Future Research

- Further research is needed to develop appropriate testing methods to verify the attainment of design specificastions of manufactured liner materials.

- A central data base of chemical resistance testing results should be established.

- Solubility parameter theory should be developed to provide an acceptable screening technique to narrow the selection of acceptable synthetic materials for specific leachate types.

- Further research is required to progress further in the standardization of chemical resistance testing procedures to allow direct comparison of results.

- An investigation of synthetic liner properties is warranted to determine specific criteria for synthetic liner chemical resistance determinations.

- Further investigation of the vapor transport mechanism should be conducted to determine specific leachate tyupes and the response of specific synthetic liner materials.

- Testing methods should be developed to support liner resistance monitoring at hazardous waste facilities during and after the operational phase of the facility.

- The HELP model should be tested to determine the sensitivity of predicted results to model assumptions and, if warranted, field verification should follow.

- A research effort should be conducted to examine the stability of a conservatively designed waste facility in the presence of upward hydrostatic forces. Such conditions could result in uplifting and associated liner failure.

# 2.0 INTRODUCTION

An evaluation of synthetic material performance in cap and liner systems at hazardous waste storage and disposal facilities was conducted. This evaluation, part of a more comprehensive assessment of the ability of clay and synthetic materials to meet performance requirements established at 40 CFR Part 264, was intended to provide the U.S. Environmental Protection Agency (EPA) with information which it may use in performing its responsibilities under the Resource Conservation and Recovery Act (RCRA).

## 2.1 BACKGROUND

The EPA, Office of Solid Waste (OSW), initiated a broad technical evaluation project in response to comments received following publication of the interim final land disposal regulations. The project was organized to provide a summary of current information in the following technical areas:

- Clay Cap/Liner Systems
- Synthetic Cap/Liner Systems
- Leachate Quality
- Fate and Transport Analysis
- Evaluation of Failures at Existing Facilities

The EPA project was designed to provide a review of the Part 264 Land Disposal Regulations to assess the need for further research, additional technical guidance and possible regulatory reform. The following report provides a summary of the advantages and disadvantages of the use of synthetic materials for containment of hazardous wastes.

### 2.1.1 Current Material Use And Research

Synthetic materials are currently used for barriers to waste and liquid flow in liner and cap systems at hazardous waste storage and disposal facilities as well as solid waste landfills, canals, and reservoirs.

These barriers, commonly referred to as synthetic liners, polymeric membranes and liners or flexible membrane liners (FML), characteristically have low permeability. Polymeric membrane technology for waste containment application relies on a wide variety of types of materials which vary in physical and chemical properties, installation methods and performance. Variations also occur within a polymer type due to differences in compounding, manufacturing, and fabrication. Polymers used in making synthetic membranes, have been available for less than 50 years, and consist of plastics and rubbers. Other raw materials used in manufacturing synthetic membranes include fabrics (scrim) and other constituents (fillers/pigments, plasticizers, crosslinkers, antidegradants, and processing aids) to improve manufacturing or material characteristics. Polymer membrane manufacture and use were described by Haxo (Haxo, 1983). They are summarized here to provide a brief understanding of the synthetic membrane industry and the application of membranes in hazardous waste facility cap and liner systems.

The polymeric membrane industry, represented in Figure 2-1, consists of four components:

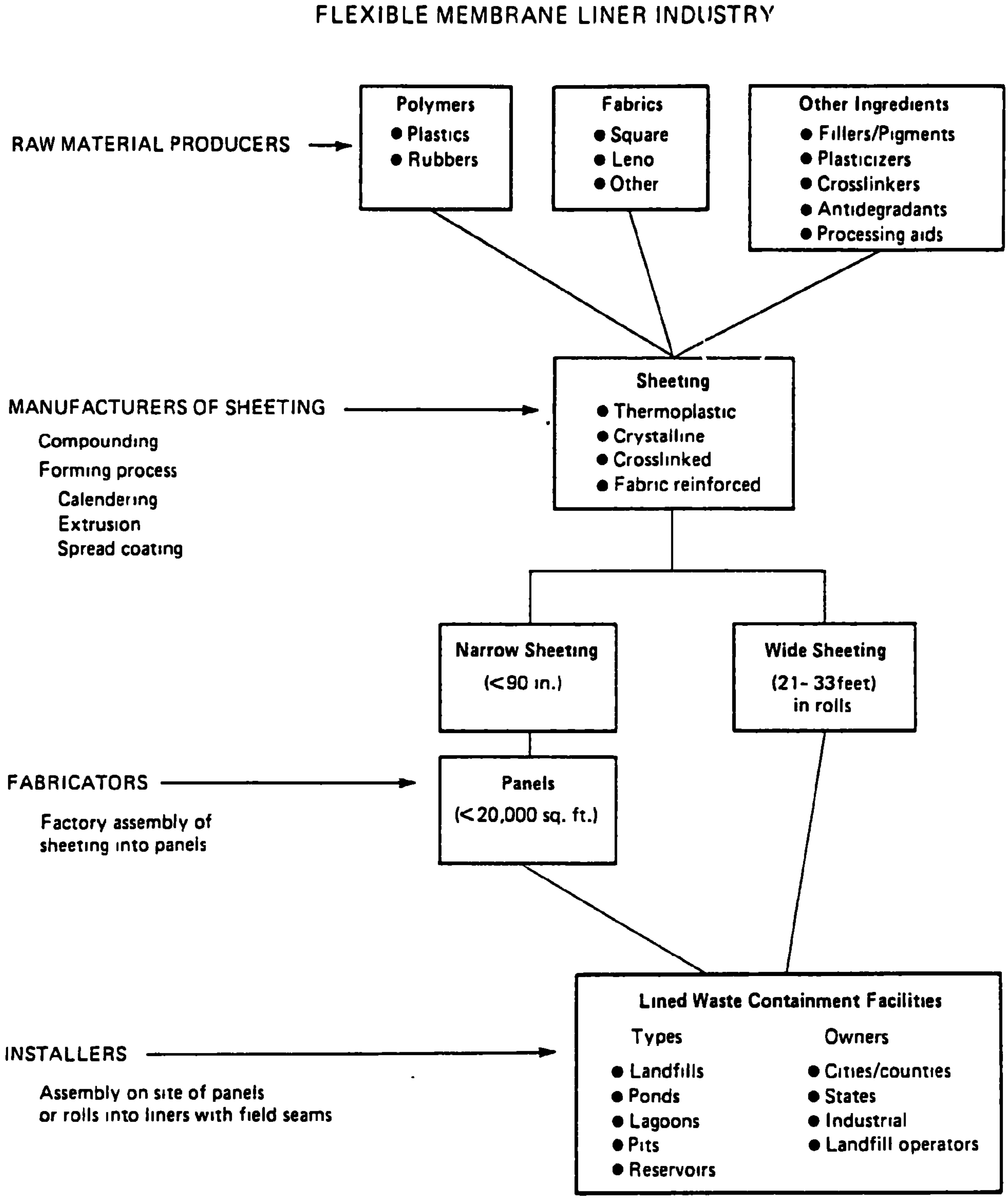


Figure 2-1 Basic structure of the polymeric membrane liner industry.

Source: E.C. Jordan, Inc.

- raw material producers;
- manufacturers of sheeting or roll goods;
- fabricators of panels or segments of barriers; and
- installers.

More than one company is typically involved in the production and installation of synthetic liners. Design of the containment facility and selection of the synthetic material is typically performed by engineering firms. The polymer producers normally supply technical service to sheeting manufacturers, including recommended formulations and manufacturing procedures. Random monitoring of the sheet manufacturers by the polymer producer is occasionally conducted.

The expertise of the sheeting manufacturer in formulating (compounding), mixing and forming sheets will control the properties of the finished liner. Fabrication of panels by seaming of sheets is limited in size (up to 30m by 60m) by weight and the ability of a crew to place it in the field. Factory seams are usually more reliable than field seams since they are made under carefully controlled conditions. Recent introduction of wide (6.7 to 10m) sheeting has reduced the need for prefabricated panels. Installation of the synthetic material should be performed by personnel experienced in liner installation and associated earthwork and piping installation. All field seams require 100% inspection to assure seam integrity.

Polymers used in the manufacture of lining materials may be classified into four types:

- o Rubbers (elastomers) which are generally cross-linked (vulcanized)
- o Plastics which are generally unvulcanized, such as PVC
- o Plastics which have a relatively high crystalline content, such as the polyolefins
- o Thermoplastic elastomers, which do not need to be vulcanized.

Table 2-1 lists the various types of polymers that are used and indicates whether they are used in vulcanized or nonvulcanized form and whether they are reinforced with fabric. The polymeric materials most frequently used in liners are polyvinyl chloride (PVC), chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), butyl rubber, ethylene propylene rubber (EPDM), neoprene, and high-density polyethylene (HDPE). The thickness of polymeric membrane for liners range from 20 to 120 mils, with most in the 20-60 mil range. Most polymeric lining materials are based on single polymers. However, blends of two or more polymers, e.g. plastic-rubber alloys, are being developed and used in liners.

Most of the membrane liners currently manufactured are based on thermoplastic (soft and moldable when subject to heat) polymers because it is easier to obtain reliable seams and to make repairs in the field. Vulcanized (heat treated) or crosslinked polymers increase the strength and elasticity of the liner. Fabric reinforcement also increases the strength of the liner. Synthetic materials are used at hazardous waste facilities as a component of cap or liner systems. Proper material selection, evaluation, installation and maintenance of each component is necessary to assure the proper functioning of the system. Cap and liner systems are constructed on compacted subbase materials and the synthetic barrier is placed between two layers of

Table 2-1. POLYMERIC MATERIALS USED IN LINERS

| Polymer | Use in Liners | | Fabric reinforcement | |
|---|---|---|---|---|
| | Thermo-plastic | Vulcanized | With | W/O |
| Butyl rubber | No | Yes | Yes | Yes |
| Chlorinated polyethylene | Yes | Yes | Yes | Yes |
| Chlorosulfonated polyethylene | Yes | Yes | Yes | Yes |
| Elasticized polyolefin (partially crystalline) | Yes | No | No | Yes |
| Elasticized polyvinyl chloride | Yes | --* | Yes | No |
| Epichlorohydrin rubber | Yes | Yes | Yes | Yes |
| Ethylene propylene rubber | Yes | Yes | Yes | Yes |
| Neoprene (chloroprene rubber) | No | Yes | Yes | Yes |
| Nitrile rubber | Yes | --* | Yes | --* |
| Polyethylene (partially crystalline) | Yes | No | No | Yes |
| Polyvinyl chloride | Yes | No | Yes | Yes |

*Not Available

Source: E.C. Jordan, Inc.

bedding material. Overlying the upper bedding material is a drainage layer for removal of leachate or infiltrating precipitation. Cap systems also consist of an upper vegetated soil layer to control erosion.

Current research includes development of industry-wide standards, improved formulations and compounding, evaluation of installation procedures and bedding materials, chemical resistance and testing methods, improved seaming techniques, prediction of service life, and development of quality assurance and quality control procedures to enhance and assure synthetic barrier performance.

### 2.1.2 Regulated Performance Requirements

The EPA has promulgated interim final regulations which establish performance requirements for barriers used in liner and cap systems at hazardous waste treatment, storage and disposal facilities. The goal of these performance requirements is to prevent migration of wastes to the subsurface soil or to ground water and surface waters during the active life of the facility and to minimize the leachate remaining after closure. These performance requirements are found in: 40 CFR Part 264.

In general, the regulations require liners for all new facilities to prevent waste migration to subsoils during the active life of the facility. The regulations further require that the liner be constructed of materials that prevent wastes from migrating into the liner during the active life of the facility for landfills, and for waste piles and surface impoundments that are designed to close with wastes left in place. The liner must be constructed of materials that prevent failure due to the following conditions:

- o hydraulic pressure gradients (static head and external hydrogeologic forces);
- o physical contact when exposed to wastes or leachate;
- o climate;
- o installation stresses; and
- o operational stresses.

The liner must be designed to prevent failure due to settlement, compression, or uplift by providing a foundation capable of supporting the liner.

Final cover or cap systems placed during closure of surface impoundment, waste pile or landfill facilities which contain wastes or contaminated soil must be designed and constructed to meet the following performance requirements:

- o keep migration of liquids through the facility to a minimum over a long term;
- o function with minimum maintenance;
- o promote drainage and keep erosion or abrasion of the cover to a minimum;
- o accommodate settling and subsidence so that the cover's integrity is maintained; and
- o have a permeability less than or equal to the permeability of the liner system or natural subsoils present.

These requirements are intended to prevent the accumulation of liquids inside the facility to a level which causes failure of the containment system or an increased rate of transport of wastes or hazardous constituents through the liner system to ground water or surface water.

The EPA stated the goals of the performance requirements and provided guidance in the Preamble to the published regulations (EPA, 1982). Additional guidance has been provided in several draft RCRA Guidance Documents. Included in the Guidance Documents are discussions of the preference for synthetic materials to meet the performance requirements for liner and cover systems. The EPA has suggested that synthetic liners may be expected to provide a service life of 30 years. Additionally, the Guidance Documents encourage the use of a soil liner under a synthetic liner which serves as the lower barrier for a double-lined facility with an operating life greater than 30 years.

The performance of the leachate collection and removal system was also established by the Part 264 regulations. The Regional Administraator is required to specify design and operating conditions which ensure that leachate depth over the liner does not exceed 30 cm (one foot). The system must be constructed of materials that:

- are chemically resistant to wastes and leachate; and
- prevent collapse due to pressures of overlying wastes, cover materials, and operating equipment.

The system must also be designed and operated to function without clogging through the scheduled closure of the facility.

These regulations do not prescribe liner performance. The ability of synthetic materials to meet the liner performance requirement is influenced by the conflicting requirements for adequate protective liner bedding layers and the potentially conflicting performance requirement for a maximum depth of liquid of 30 cm (one foot).

An implicit goal in the regulations is the desire to contain hazardous wastes to the maximum extent possible. This goal is not established in a performance regulation for individual hazardous waste facilities, but the regulations do attempt to attain the goal through performance regulations of individual components (e.g. liner, leachate collection and removal system, final cover) of the surface impoundment, waste pile or landfill facility.

### 2.1.3 Need for Detailed Assessment

The Office of Solid Waste (OSW) undertook a detailed assessment of these regulations and others pertaining to the 40 CFR Part 264 Hazardous Waste Treatment Storage and Disposal (TSD) Facilities. The need for the assessment was caused by several factors:

- o promulgation of regulations based on an assessment that was less thorough than desired by OSW, to allow compliance with a court ordered mandate;
- o issues raised during the comment period for the interim final standards; and
- o evolving hazardous waste management technology and practices stimulated by the Interim Standards (40 CFR Part 265), Temporary Standards (40 CFR Part 267) and previously enacted by incomplete standards for treatment storage and disposal facilities (40 CFR Part 264).

The project was conducted to assess the technical adequacy of the Interim Final Regulations and to identify any deficiencies which require further regulatory action or research. A rapid evaluation was needed to respond to comments received from the regulated community and other interested groups following publication of the Interim Final Regulatory Program. Early resolution of the technical problems identified was required to insure the orderly expansion of properly managed and permitted hazardous waste facilities.

Issues raised during the comment period that were related to synthetic materials were grouped into the following categories:

- Liner/waste interactions;
- Installation problems;
- Serviceable life;
- Failure modes; and
- Subsidence problems;
- Short- and long-term performance

Resolution of these issues required a detailed review of the technology, practices and experiences in the synthetic liner field.

As a result of ongoing research results and stimulation provided by the 264, 265 and 267 standards, the technology and practices of the hazardous waste management field are changing. This afforded an opportunity for a larger data base and improved understanding of the management of wastes. In the synthetic liner area, research and experiences in chemical resistance testing, installation practices, evaluation of leachate collection and removal systems, projection of performance, and quality assurance suggested a more detailed assessment was warranted.

## 2.2 OBJECTIVES

The primary objective of this study of synthetic materials was to assess their performance as barriers in liner and cap systems at hazardous waste facilites and identify appropriate regulatory reforms and/or research needs. In order to accomplish this objective, questions raised during the comment period for the 40 CFR Part 264 interim final standards were addressed.

- Identify and evaluate the physical and chemical properties of synthetic materials that are important in assessing chemical resistance to wastes, and evaluate testing methodology.
- Identify installation problems, preventive measures and corrective actions which affect the performance of synthetic masterials.
- Determine the service life of synthetic materials based on existing information and projections of changes in physical and chemical characteristics.
- Identify subsidence problems, preventive measures and corrective actions which affect synthetic material performance.
- Identify failure modes which determine the performance of synthetic materials as barriers in waste facilities, and put these failure modes into a perspective which allows a full assessment of synthetic materials.
- Projected performance of synthetic materials used in liner and cover systems were addressed based on the results of the above findings, assumed modes of failure, design and hydrogeologic location.
- Assess the ability of synthetic liners to comply with existing performance standards.

These objectives were accomplished through a cooperative investigative program involving EPA technical staff and supporting consultants. This report presents detailed discussion of the results of this investigative program, and provides perspective on the advantages and disadvantages of the use of synthetic materials in liner and cap systems of hazardous waste management facilities.

## 2.3 APPROACH

The general approach used in assessing performance of synthetic materials was to: 1) collect and review existing information; 2)determine current practices and review their adequacy; 3) assess anticipated performance; 4) identify deficiencies in the data base; and 5) compare projected performance to the performance standard.

Many sources of information were used to develop an understanding of the current technology, practices, and information available on the use of synthetic materials at hazardous waste facilities. These included computerized literature searches (including computerized data bases and referrals), personal interviews, reports of site visits conducted by OSW technical staff, reports of ongoing research, and information provided during the comment period. Interviews were conducted with individuals of the following groups:

- Suppliers, manufacturers, fabricators, designers, and installers of synthetic material, clay and other liners;

- Owners/operators of hazardous waste management facilities;
- State regulatory agencies;
- Researchers in academic and research organizations; and
- Trade/professional associations and standards setting organizations.

This report is a summary of reports and information prepared by several contractors and EPA technical staff from OSW and the Municipal Environmental Research Laboratory (MERL) in Cincinnati. Major contributions to this report included the following:

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| TRW, Inc. | "Assessment of Technology for Construction and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities." |
| A.D. Little, Inc. | "Analysis of Flexible Membrane Liner Chemical Compatibility Tests." |
| OSW, MERL and ERTEC | "Projected Performance of Hazardous Waste Facilities for Selected Design, Failure Modes and Hydrogeologic Settings." |
| E.C. Jordan, Inc. | "Preliminary Draft Interim Report II Synthetic Cap and Liner Systems." |

Observations and conclusions made by TRW in assessing construction and installation technology and A.D. Little in analyzing chemical compatability and expected life were used to define the design and failure modes for the projection of performance.

The purpose of this report is to summarize the significant findings of the contributors. Specific details may be found in the respective reports. Compilation and assessment of these major contributions was conducted by ERTEC Atlantic and E.C. Jordan. Extensive review was provided by the team assembled by OSW to perform the broader assessment of clay vs. synthetic liner performance which will be described in a final project report. This report is intended to contribute to that assessment.

# REFERENCES

Haxo, H.E., Jr. 1983. Lining of Waste Impoundment and Disposal Facilities. U.S. Environmental Protection Agency, Cincinnati, OH. 448 p.

EPA, 1982. Federal Register Vol. 47, No. 143, July 26, pp.32274.

## 3.0 PROPERTIES OF SYNTHETIC CAP AND LINER MATERIALS

The performance of synthetic cap and liner materials in a hazardous waste facility is essentially determined by the permeability of the installed liner system and its change with time. Assuming proper installation, liner permeability may increase with time as a result of weathering, exposure to waste leachate or physical deformation of the liner material. Weathering and deformation are primarily site specific problems, which require the matching of physical liner properties to the environment and geology of the facility location. Liner exposure to waste leachate is a more complex problem resulting from the wide variation observed in the chemical properties of both the waste leachate and the polymeric liner itself. The ability to predict the performance of synthetic liners in a hazardous waste facility requires a complete knowledge of the chemical and physical properties of the polymeric liner material and its exposure environment. Various testing methods and procedures are available to determine most of the required liner properties, however, not all procedures are fully standardized. Further, there are no commonly accepted techniques for testing long-term liner performance.

The following sections provide a brief discussion of the chemical and physical properties of liner materials and their relationship to liner performance criteria established in the regulations. Available testing procedures are introduced as the principal method available for determining the chemical resistance of liner materials to hazardous waste leachates.

The classification of liner properties adopted is somewhat arbitrary, but reflects the classification scheme used in the supporting consultant reports and the general literature. Under this classification scheme, physical properties are defined as liner qualities which can be measured externally. Properties which are intrinsically associated with material chemistry are classified as chemical properties. The ambiguity inherent in this classification approach does not significantly affect the study results since the classification of properties is primarily a construction for convenience.

## 3.1 PERFORMANCE CRITERIA

Liner and cap systems at hazardous waste facilities are intended to contain hazardous constituents and prevent liquid movement. The major function of the facility cap is to prevent the infiltration of precipitation to the underlying waste and the subsequent formation of leachate. The function of liner systems is the prevention of outward migration of leachate and hazardous constituents and to prevent the inward movement of groundwater. When properly functioning, the liner and cap systems approach the overall facility performance objective to prevent waste migration from the facility during the operational life of the facility and minimize migration thereafter. The cap system essentially controls the principal leachate source, while the liner provides the final containment barrier to prevent waste migration from the facility.

Cap and liner barriers are subject to a variety of conditions which result in material stress. The barrier material must be capable of resisting or relieving this stress in order to function properly. In cover systems using synthetic barriers, consolidation of waste can subject the barrier material to tensile stress, which may result in barrier failure. In liner systems, excessive hydraulic pressures, collapse of leachate removal pipes, and subsidence of underlying materials may also cause failure. In addition, barrier exposure to sunlight, ozone, chemicals contained in the waste, and other environmental hazards may affect cap and liner resistance to stress and general performance. A properly designed synthetic barrier must be sufficiently durable to withstand the effects of physical stress and weathering during the life of the waste facility and beyond.

Synthetic barrier materials meeting the performance goal would be expected to possess the following characteristics:

- Flexibility to conform to new surface contours which may result from subsidence in a well designed facility;
- Tensile strength to resist stresses imposed;
- Low permeability to liquids and chemicals;
- Chemical resistance to waste constituents; and
- Resistance to weathering.

Flexibility, tensile strength and resistance to weathering (including wind) are also important considerations during construction of the facility. The duration over which barrier materials should possess these properties is dependent on the waste characteristics. The importance of these properties is influenced by site specific factors such as waste to be contained, soil stability, climate and facility construction and operation practices. Essentially, cap and liner performance depends on the ability of the material to resist stress, weathering and chemical attack by waste leachate. Thus, evaluation of anticipated liner and cap performance requires a detailed knowledge of the physical and chemical properties of the synthetic material used and the leachate generated within the facility.

## 3.2 PHYSICAL PROPERTIES

Physical properties of synthetic liner materials refer to those liner attributes which can be measured externally using various laboratory or field techniques. The importance of these physical properties is twofold. First, physical properties provide a suitable method of verifying liner design specifications. Secondly, any change in physical properties resulting from exposure of the liner material to waste leachate provides a measure of the chemical resistance of the liner to the leachate encountered. Unfortunately, complete standardization of liner physical properties and testing protocols has not been achieved due to the extremely wide range of synthetic liner materials available.

Physical properties vary between different types of materials and among different formulations of the same type of material. The large number of polymer formulations available for synthetic barriers do not allow a succinct summary of material properties. Haxo (1983) has provided a summary of suggested standard properties for the following materials:

- o crosslinked and thermoplastic membranes without scrim;
- o partially crystalline membranes without scrim; and
- o thermoplastic coated membranes with scrim.

These suggested standard properties are based on test results of material specimens and are intended for use as a means of establishing the quality of synthetic materials and not as a means of assessing chemical resistance and durability. Such an assessment may result in barrier material specifications which differ from those suggested by Haxo. In the absence of chemical exposure, materials meeting the suggested properties would be expected to perform satisfactorily if properly installed, maintained and operated.

The most significant physical properties of synthetic liner materials are flexibility, strength, permeability and abrasion resistance. Each of these properties is dependent on the particular polymer formulation and the presence of reinforcing materials within the synthetic liner material. Intrinsic liner permeability refers to the internal capacity of the liner to transmit a specific chemical and should not be confused with the effective permeability of an installed liner. The effective permeability of an installed liner refers to the overall liner permeability due to the presence of pinholes, tears and does not provide a measure of intrinsic permeability.

### 3.2.1 Flexibility

The flexibility of synthetic liners is controlled by the polymer and additives used in the formulation and the fabricated material thickness. All of the synthetic materials exhibit, to varying degrees, an ability to stretch, deform or bend repeatedly without detrimental cracking. The thickness of some materials, such as 100 mil HDPE, reduces flexibility compared to regular 30 to 50 mil barriers, but provides greater tensile strength and resistance to puncture and tearing.

Flexibility is also reduced by exposure to cold temperatures. A variety of test procedures are available for low temperature exposure testing. Test conditions vary, so results may not be directly comparable. High temperatures generally increase flexibility, but may also reduce tensile strength and affect dimensional stability of some synthetic materials.

Exposure to chemicals or other environmental conditions, such as exposure to ozone or ultraviolet light may also reduce flexibility. These exposures may alter the flexibility of the polymer by breaking long polymer chains or increasing crosslinking of the polymer chains. The loss of plasticizers from some types of materials (e.g. PVC) by volatilization or extraction would also reduce flexibility. Synthetic materials can be formulated to provide the flexibility required to meet specific service conditions. A measure of flexibility is also provided by the material's elongation property. Elongation is discussed in the following section.

### 3.2.2 Strength

The strength of synthetic materials is usually characterized by measuring the following properties:

- o Puncture resistance;
- o Tear resistance;
- o Tensile properties; and
- o Seam strength.
- o Hydrostatic resistance.

These properties have been used in evaluating the ability of synthetic materials to meet specific service conditions and thus are used in selecting liner materials.

### 3.2.2.1 Puncture Resistance

Since sythetic materals are thin, they are susceptible to puncture from bedding materials which may contain sharp objects, or from operations conducted above the material during installation or facility operations. Several test methods have been used to measure puncture resistance caused by the gradual exertion of force (Haxo, 1973). No method exists for measuring the resistance to puncture of a liner by sharp objects dropped during installation.

### 3.2.2.2 Tear Resistance

Tear resistance measures a material's capability to resist stresses encountered during installation or subsequent to puncture. Low resistance to tear would be undesirable because a hole in the liner would expand. The use of reinforcing fabrics in laminated materials can greatly increase the liner's tear resistance. Tear resistance was not included in the standards for synthetic materials suggested by Haxo (1983). Fabric reinforced test specimens show an unusually high tear resistance if standard samples are used. However this may represent a testing problem since the use of larger sized samples show a moderate increase in tear resistance.

#### 3.2.2.3 Tensile Properties

Measurement of tensile properties usually includes the following determinations:

- o Tensile strengths (the stresses at the yield point, fabric break or unreinforced material break);
- o Modulus of elasticity (measure of the rigidity of stiff materials at a specified percent of initial specimen length); and
- o Ultimate elongation (percent of initial specimen length at breaking).

Tensile strength required for a particular application may be determined by an analysis of forces to which the synthetic material may be exposed. Comparison of specimen test results with the required stress can then be used to select a synthetic material where tensile strength is an important consideration. Temperature conditions of the tensile test affect measurements significantly. Tensile stress values for a given polymeric material vary with speed of test, specimen size, grain orientation, temperature and humidity. Consequently, reported test results, measured under different conditions, are not directly comparable.

The modulus of elasticity is usually determined only for the more rigid, crystalline polymers. Elongation at yield and material and fabric break have been used as indicators of flexibility and may be used to monitor material quality during production, installation and chemical resistance testing.

#### 3.2.2.4 Seam Strength

Factory and field seams are equally important in determining the capability of materials to meet liner performance requirements. Because of greater control of seaming conditions, factory seams are generally stronger. Specimens have been tested in shear and peel and loaded statically and dynamically. Seam strength may be used to evaluate alternative seaming methods for specific applications. The peel test is significantly more sensitive to chemical and weather exposure than the shear test and should be used to insure proper field seaming.

#### 3.2.2.5 Hydrostatic Resistance

Synthetic materials may be subject to hydrostatic pressures where there are voids underlying the barrier. The bursting pressure is commonly determined for all barriers using a method developed for fabric reinforced materials more sensitive to chemical and weather exposure than the shear test.

### 3.2.3 Permeability

Most synthetic liner materials have very low permeability to liquids. However, synthetic liners do have a finite permeability to aqueous liquids as a result of vapor transport (diffusion) through the liner. The driving force for the vapor transport mechanism is the concentration gradient or difference of partial pressures across the synthetic liner material. Test procedures have been developed to determine the vapor loss across a polymeric boundary for specific chemicals. The results show that most synthetic liner materials possess very low, yet finite, permeability to water. Essentially the determination of the significance of vapor loss through a liner is complicated by the presence of multiple chemical species in leachate as well as the liner itself. Theoretically, vapor transport can be determined from a knowledge of the driving gradient, the diffusion coefficient of the chemical through the liner and the thickness of the material. Unfortunately, the diffusion coefficient of a multi-component leachate through a complex polymeric liner can not be determined. However, general conclusions can be developed based on an understanding of the vapor transport process and available test results. A brief description of the vapor transport process is provided for completeness. A more detailed discussion is provided in the supporting technical consultants report (ADL - 1983).

"The transmission of a chemical through a polymer film free from cracks, pinholes, or other flaws normally occurs by a diffusion process (i.e., vapor transport). The chemical dissolves in the surface layers, diffuses through the bulk material under the influence of a concentration gradient, and evaporates or desorbs the other, low concentration surface. Diffusion in a polymeric material is a function of the energy and molecular size of the chemical and the freedom of movement of the molecular changes of the polymer. In general, higher degrees of freedom are associated with rubbery materials and less freedom is found in crystalline polymers." (Swope, et. al 1983) Limited data in the literature with undiluted chemicals under conditions of maximum concentration gradients are shown in Table 3-1 and indicate that the transport rates range from less than 1 x $10^{-4}$ kg/day/$m^2$ to greater than 10 kg/day/$m^2$ for certain chemical and 30 mil material exposures. Lower values, below 1 x $10^{-4}$ kg/day/$m^2$, are associated with water and inorganic and ionic constituents of aqueous systems.

Water is a volatile material and therefore is subject to vapor transport through synthetic materials. However, the vapor transport of water through the liner should not be confused with the permeation of water through a soil material or a liner with holes. Permeation refers to a physical process whereby liquid material passes through a material under hydraulic pressure. Vapor transport is a process whereby gaseous material passes through a barrier due to the diffusion process under the presence of a concentration gradient. The net effect of either process is leakage, however the permeation rate is proportional to hydrostatic head and the vapor transport rate is dependent on the concentration gradient. Water as a volatile material can be transported or permeated through synthetic materials if holes as present.

Transport through synthetic material requires a finite time to reach a steady state. This time (induction time) is dependent on the conditions which control the predominant driving forces of vapor transport, including type of hazardous constituent, material composition and environmental conditions. The induction time was calculated for 30 mil synthetic materials to range from less than one hour for materials with high diffusion coefficients to more than 80 years for materials with small diffusion coefficients. August and Tatzky reported induction times of 4 days to 8 weeks. These times agree with those calculated by Swope et. al. for diffusion coefficients of $10^{-8}$ cm/sec.

The application of vapor permeation theory to hazardous waste facility evaluation is new and not verified. It does, however, provide a conceptual basis for evaluating the regulatory performance standard for hazardous waste barriers. The theory can be applied using weight change data which is frequently determined during chemical resistance testing. A detailed description of steady state permeation rates and time to reach steady state is provided in a contributing report (Swope, _et_. _al_. 1983).

TABLE 3-1 TRANSMISSION OF UNDILUTED CHEMICALS THROUGH SELECTED POLYMER MATERIALS

| MATERIAL | CHEMICAL[a,b,c,d] Carbon Tetrachloride | Methanol | Heptane | Toluene | Benzene | Water |
|---|---|---|---|---|---|---|
| Polyethylene, low density (LDPE) | 0.32 | 0.001 | -- | -- | -- | -- |
| Polyethylene, high density (HDPE) | 0.05 | 0.0001 | 0.03 | 0.06 | -- | $1.0 \times 10^{-4}$ |
| Styrene-Butadiene rubber (SBR) | 19.3 | 0.04 | -- | -- | -- | -- |
| Acrylonitrile-butadiene rubber (NBR) | 4.2 | 0.5 | -- | -- | -- | -- |
| Chloroprene (Neoprene) | 11.2 | 0.09 | -- | -- | -- | $1.0 \times 10^{-2}$ |
| Polyvinyl Fluoride (PVF) | 0.0004 | 0.0003[e] | -- | -- | -- | -- |
| Polyethylene Terephthalate (PET) | 0.00005 | -- | -- | -- | -- | -- |
| Polyamide (Nylon 66) | 0.0003 | 0.02 | -- | -- | -- | -- |
| TFE (Teflon) | 0.00001 | 0.00003 | -- | -- | -- | -- |

[a] $kg/day/m^2$

[b] Maximum concentration gradients with undiluted chemicals.

[c] Temperature 20-40°C; Thickness: 0.76 mm (30 mil)

[d] No detectable leakage --

[e] ethanol

The importance of this transport mode has been reported for aqueous mixtures of hazardous constituents, August and Tatzky (1982) reported the transmission rates for aqueous saturated solutions of toluene and xylene ranged from 0.002 to 0.012 kg/day/$m^2$ in tests of Polyethylene, Polyvinyl Chloride and Ethylene propylene rubber materials. These rates were 10 to 50 times lower than rates measured with pure solvent. Their data further indicated that the transmission rate was dependent but not directly proportional to material thickness. Transmission rates for thicker materials were less than for thinner materials. Concentrated transmission rates for toluene were comparable to that reported by Swope, <u>et</u>. <u>al</u>. (1983).

The reported study results were conducted for purely hypothetical situations using pure chemicals in direct contact with liners. Within a hazardous waste facility the leachate in contact with the liner is generally regarded as a dilute aqueous leachate. Further, the liner is covered by a porous leachate collection layer which would act to avoid direct liner-waste contact. Nevertheless, the values reported are significant for some liner/waste combinations and should not be ignored. However further testing is required to determine the significance of the vapor transport process in a hazardous waste environment.

### 3.2.4 Abrasion Resistance

An important property of synthetic materials subjected to abrasion is its hardness or resistance to abrasion. The property is easily measured and can be used to monitor material quality during production and installation. It is also a useful indicator of material quality change during chemical resistance testing.

### 3.2.5 Summary

The primary importance of the physical properties of synthetic liners is their utility in verifying liner manufacturer specifications and in the evaluation of chemical resistivity. Facility design should include technical specification of acceptable ranges of these parameters using specified testing procedures and conditions. Of the physical properties specified, testing procedures exist for all but liner resistance to the impact of sharp projectiles and the evaluation of intrinsic liner permeability. However, the procedures used are not fully standardized. The impact of sharp projectiles on overall liner performance can be minimized by eliminating unnecessary objects during liner installation and through proper training of installation personnel. Permeability represents a more complex problem due to the lack of sufficiently realistic test data for hazardous waste facility leachate.

Where organics are present in two phases (water saturated and organic layers), the vapor transport may be quite significant, as much as 20 kg/day/$m^2$ for carbon tetrachloride (see Table 3-1). Appropriate selection of synthetic materials may reduce transmission rates by a factor of more than 200 to a seepage rate of less than kg/day/$m^2$. Among the currently available barrier materials summarized by Swope et. al., HDPE consistently exhibited the lowest transmission rate for a limited number of pure organic chemicals. The rates ranged from 1 to 600 times the vapor transport rate for water.

The reduction of transmission rates of 10 to 50 times reported by August and Tatzky (1982) for aqueous solutions of organic chemicals, compared to pure chemicals, tentatively indicates the actual transport rate for specific chemical constituents of an aqueous hazardous waste leachate (absence of an organic layer) would reduce the concentration of carbon tetrachloride to 0.005 to 0.001 kg/day/$m^2$. This rate of transport is 10 to 50 times greater than the transmission rate of water through HDPE.

Current experimental data are based on test conditions which imposed the maximum driving force of concentration differences by removing transported chemicals from the barrier material. Reductions of the driving force may be achieved by retaining transported materials at the barrier material surface. The "de minimus" performance standard may be approached using a water-saturated clay under the synthetic barrier material or possibly a composite barrier system consisting of two types of polymer materials, each with vapor transport characteristics that supplement the other.

The phenomenon of vapor transport through polymeric materials is well established. There is uncertainty associated with the magnitude of the rate which may be experienced in a hazardous waste liner service environment. It is possible that if organic chemicals are present at concentrations less than their water solubility, then the rate of specific chemical release may be comparable to the transmission of water through synthetic barrier materials ($10^{-4}$ kg/day/$m^2$ for HDPE and $10^{-2}$ kg/day/$m^2$ for Neoprene). Based on this information leachate leakage due to vapor transport would be negligible compared to leakage due to the presence of a moderate number of liner pinholes (See Chapter 4.0).

## 3.3 CHEMICAL PROPERTIES

The chemical properties of synthetic liner materials are determined by the particular polymer and polymer formulation technique used in their manufacture. Chemical properties are important in evaluating the suitability of a liner material for hazardous waste containment. Chemical liner properties are used to verify attainment of liner design specifications and are used as the principal indicators of liner resistance to hazardous waste leachates. The broad range of synthetic liner materials available and the complexity of the chemical composition of hazardous waste leachate complicate the problem of determining chemical resistance of cap and liner materials.

The following section provides a description of the most significant types of liner materials currently proposed for hazardous waste containment. A brief description of the principal types of leachate encountered in typical waste facilities is also provided. Finally, the concept of solute transport theory is defined. The material presented in section 3.3 provides the information required to evaluate the testing procedures and concepts introduced in section 3.4.

### 3.3.1 Polymeric Material Composition

The physical and chemical properties of synthetic materials are controlled largely by the polymer. Certain properties are improved by the addition of selected chemicals during formulation. A brief summary of the polymers listed in Table 2-1, the more commonly used synthetic barrier materials, was excerpted from Haxo (1983):

- Butyl rubber is a copolymer of isobutylene (97%) with small amounts of isoprene introduced to furnish sites for crosslinking.
  It is generally compounded with fillers and some oil, and vulcanized with sulfur.

- Chlorinated polyethylene (CPE) is produced by a chemical reaction between chlorine and a high-density polyethylene. Presently available polymers contain 25-45% chlorine and 0-25% crystallinity. CPE is compounded and used in both thermoplastic and crosslinked compositions. CPE can be crosslinked with peroxides but, in liner compositions, it is generally used as a thermoplastic. CPE can be compounded with other polymers, making it a feasible base material for a broad spectrum of liners. CPE can be alloyed with PVC, PE and numerous synthetic rubbers. Nevertheless, at least half the polymer content of CPE liners is CPE resin.

- Chlorosulfonated polyethylenes (CSPE) are a family of polymers prepared by reacting polyethylene in solution with chlorine and sulfur dioxide. Presently available CSPE polymers contain from 25 to 43% chlorine and from 1.0 to 1.4% sulfur. They are used in both thermoplastic (uncrosslinked) and crosslinked (with metal oxides) compositions. Usually, they are reinforced with a polyester or nylon scrim and generally contain at least 45% of CSPE polymer.

- Epichlorohydrin rubbers (CO and ECO) are epichlorohydrin-based elastomers which are saturated, high molecular weight, aliphatic polyethers with chloromethyl side chains. The two types include a homopolymer and a copolymer of epichlorohydrin and ethylene oxide. These materials are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group. Such reagents include diamines, urea, thioureas, 2-mercaptimidazoline, and ammonium salts.

- Ethylene propylene (EPDM) rubbers are a family of terpolymers of ethylene, propylene, and a minor amount of nonconjugated diene hydrocarbon. The diene supplies double bonds to the saturated polymer chain to supply chemically active sites for vulcanization, usually with sulfur. These rubbers vary in ethylene:propylene ratio, in the type and amount of the third monomer, and in molecular weight. Although EPDM liners are generally based on vulcanized compounds, thermoplastic EPDM liners are also available. Because of its excellent ozone resistance, minor amounts of EPDM are sometimes added to butyl to improve the weather resistance of the latter.

- Neoprene is the generic name of synthetic rubbers based upon chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur.

- Nitrile rubber is a family of copolymers of butadiene and different amounts of acrylonitrile ranging from 18 to 50%. The principal feature of these copolymers is their oil resistance, which increases with increasing acrylonitrile content. Nitrile rubber is prepared by emulsion at different temperatures. In most applications, nitrile rubber is compounded with plasticizers and is vulcanized. However, it is also blended with other polymers such as polystyrene, phenolics, and PVC to produce thermoplastic compositions that range in flexibility from rubbery compositions to hard impact-resistant plastics. Nitrile rubber is used by the lining industry generally in blends of polymers to produce thermoplastic sheetings which feature oil resistance. The nitrile rubber is mixed with PVC in amounts less than 50% to yield compounds in which the PVC acts as a nonmigrating and nonextractable plasticizer.

- Polyethylene is a thermoplastic crystalline polymer based upon ethylene. It is made in three major types: (1) low-density polyethylene (LDPE), (2) linear low-density polyethylene (LLDPE), and (3) high-density polyethylene (HDPE). The properties of a polyethylene are largely dependent upon crystallinity and density. The addition of 2 to 3% carbon black can produce improved ultraviolet light protection. Polyethylenes, as generally used, are free of additives such as plasticizers and fillers.

- The polymer polyvinyl chloride is produced by any of several polymerization processes from vinyl chloride monomer (VCM). It is a versatile thermoplastic, which is compounded with plasticizers and other modifiers to produce a wide range of physical properties. PVC compounds contain 25% to 35% of one or more plasticizers to make the sheeting flexible and rubber-like. They also contain 1% to 5% of a chemical stabilizer and various amounts of other additives. The use of the proper plasticizers and an effective biocide can virtually control plasticizer loss.

- Thermoplastic elastomers (elasticized polyolefin and PVC in Table 2-1) are a relatively new class of rubbery materials. They include a wide variety of polymeric compositions from highly polar materials, such as the polyester elastomers, to the nonpolar materials, such as ethylene-propylene block polymers. These polymers are thermoplastic and nonvulcanized. They are processed and shaped at relatively high temperatures at which they are plastic; then they are cooled to normal ambient temperatures. They behave like vulcanized rubbers.

The composition of a formulation is considered proprietary and generally not made public.

### 3.3.2 Analytical Properties

In addition to direct chemical analysis, several analytical properties of synthetic materials have been found useful in identifying materials and monitoring their quality during selection and production and while in service. The following summary of tests used to measure these properties was adapted from Haxo (1983).

Volatiles. "Volatiles" is the percent weight lost by a specimen of liner on drying in a desiccator at 50°C and then heating in an oven at 105°C. If the synthetic barrier has been exposed and has absorbed volatile liquids, the portion of weight lost in the desiccator represents the water fraction, and the portion lost at 105°C represents the low-boiling organic fraction that the material absorbed. Changes in the volatile fraction can be used as a means of monitoring a material during exposure to waste liquids. The percent of swell can be estimated from the ratio of volatiles to the nonvolatile fraction. The amount of plasticizer lost to the waste liquid can be calculated from an analysis of the "extractables" (see below) if the original plasticizer content is known.

Ash. The ash content of a barrier material is the fraction that remains after a sample is thoroughly burned at an elevated temperature, e.g. 550°C. The ash content is usually made up of inorganic materials that have been used as fillers or as curatives in the polymeric coating compound. As different manufactures formulate their compounds differently, determining the ash content can be a way to "fingerprint" a polymeric barrier. The residue obtained by ashing can be retained for further analyses, such as metals content etc. Trace element analysis of the ash provides information regarding the amount of contaminants absorbed by the barrier. The test method described in ASTM D297, Paragraph 34, is generally followed in performing this analysis.

Extractables. The extractable content of a polymeric sheeting is the fraction that can be extracted from a sample of the barrier material with a solvent that neither decomposes nor dissolves the barrier. "Extractables" consist of plasticizers, oils, or other solvent-soluble constituents that impart or help maintain specific properties, such as brittleness or processability. A measurement of extractable content and analytical study of the extract can be used as part of the "fingerprint" of a sheeting. An important use of this test is monitoring of the effects of exposure to waste liquids. During exposure to a waste liquid, constituents in the original barrier compound may be extracted, which can result in a change in the properties of the barrier. The measurement of extractable is particularly useful for the detection of liner softening due to the absorption of non-volatile oils from the waste leachate.

Crystalline Structure Heat of Fusion. Differential scanning calorimetry (DSC) is a thermal technique for measuring the melting point and the level of crystallinity in partially crystalline polymers, such as the polyolefins, e.g. polyethylene and polybutylene. This technique measures the heat of fusion of a crystalline structure. It can also indicate modification of crystalline sheeting with other polymers by alloying. Thus, this type of analysis can be used as a means of fingerprinting crystalline polymeric barrier materials, particularly high-density polyethylene, and assessing the effects of aging and exposure to wastes. The DSC process can also be used to measure the temperature at which a polymer converts from a brittle, glassy state to an amorphorus, rubbery state and is thus related to its low temperature properties.

Specific gravity. Specific gravity and density are important, easy to determine, characteristics of a material which can give an indication of the composition and identification of a compound. On exposed liners, specific gravity can be measured only after the barrier material has been devolatilized. Care must be taken to thoroughly dry the specimen before placing it in the oven at 105°C to avoid bubbles forming in the sample. ASTM Method D792, Method A, and D297, Paragraph 15, are generally used in performing this test.

### 3.3.3 Hazardous Waste Leachates

The performance of synthetic barriers is strongly affected by the nature of hazardous wastes to which the barriers are exposed. Exposure of greatest concern is leachate originating from the waste and from water that enters the facility and leaches soluble waste constituents. The following description of waste liquids to which barrier materials are exposed and Figure 3-1 which describes components of liquids in hazardous waste facilities are adapted from Haxo (1983).

Organic and inorganic chemicals are dissolved in the leachate of a waste, regardless of the composition of the principal liquid of the waste.

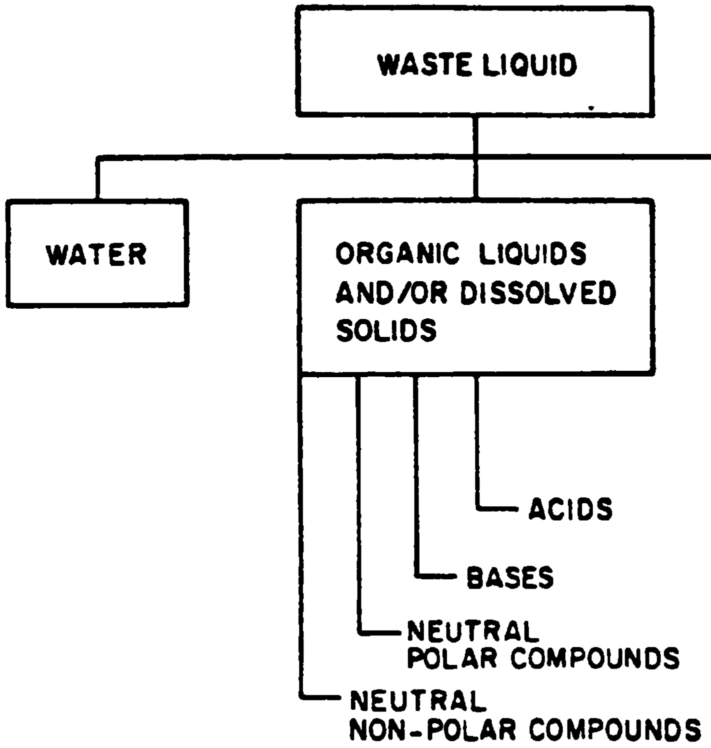


Figure 3-1 Conceptual composition of waste liquids. (Haxo, 1983)

However, the relative abundance of a given dissolved component will depend on the composition of the principal liquid. For instance, if the liquid is neutral nonpolar organic, it will have a large carrying capacity for other neutral nonpolar organic chemicals. If the liquid phase is predominantly aqueous, its carrying capacity for nonpolar organics in its dissolved phase will be relatively small.

Water has a relatively large carrying capacity for polar organic chemicals (they may be miscible in each other in all proportions) and for inorganic acids, bases, and salts. Strong inorganic acids and bases, which are invariably water-based, may be especially aggressive to synthetic barrier materials.

In the case of polymeric barriers, the relative solubility parameters of the polymer and the organic solvents that are present, either alone or in solution or dispersed in the water, can have major effects on the barrier. When the solubility parameters of the solvent and the polymer are close, severe swelling of the liner and even dissolution can occur.

For the purpose of assessing the effects organic liquids may have on the integrity of a barrier material, the liquids may be classified into four groups. These groups (which are specified in Table 3.3.3-1), are based on the physical and chemical properties that govern their interactions with barrier materials. These properties include acidity, basicity, polarity, and solubility parameters of the organic components.

TABLE 3.3.3-1 PHYSICAL CLASSES OF WASTE LIQUIDS

| Class of waste liquid | Solvent | Solute |
|---|---|---|
| Aqueous-inorganic | Water | Inorganic |
| Aqueous-organic | Water | Organic |
| Organic | Organic liquid | Organic |
| Sludges | Organic liquid or water | Organic and inorganic |

Aqueous-inorganic liquid wastes are those in which water is the liquid phase and the dissolved components are predominantly inorganic. Examples of these dissolved components are inorganic salts, acids, bases, and dissolved metals. Examples of waste liquids in this category are brines, electroplating wastes, metals etching wastes, and caustic rinse solutions.

Aqueous-organic liquid wastes are water based solutions of predominantly organic solute. Organic solute material can be either acidic functional groups or polar organic molecules. Acidic groups are formed principally through the anaerobic decay of organic waste materials. Polar, organic molecules are miscible in water and are primarily a result of percolation leaching within a waste facility. Examples of aqueous-organic leachate producing waste streams are wood preserving wastes, water-based dye wastes, pesticide container rinse water and ethylene glycol production wastes.

Organic liquid wastes are those that have an organic liquid phase and the dissolved components are other organic materials. Essentially these solutions are composed of neutral organic compounds with no net charge and negligible polarity. These compounds do not mix with water, although water would be present to some extent in any leachate. Examples of this class of wastes include oil-based paint wastes, pesticide manufacturing wastes, spent motor oil, spent cleaning solvents, solvent refining and solvent processing wastes.

Sludges represent the fourth class of wastes. They are generated when a waste stream is dewatered, filtered, or treated for solvent recovery. Sludges are characterized by high solids content such as those found in settled matter of filter cakes and consist largely of clay minerals, silt precipitates, fine solids, and high molecular weight hydrocarbons. Examples of this class of waste are American Petroleum Institute (API) separator sludge, storage tank bottoms, treatment plant sludge, and filterable solids from any pollution control process.

### 3.3.4 Solubility Parameter Theory

Assessment of polymer chemical resistance based on polymer and waste constituent properties would enable rapid screening for chemical resistance of the large number of possible liner and cap material combinations. The solubility parameter theory provides a quantitative basis for making such an assessment. The theory is based on comparison of the strength, or cohesive energy density (CED), of intermolecular forces. Similar strength between polymer and waste indicates low chemical resistance between materials and thus low probability of acceptable performance as a barrier material. A solubility parameter is calculated from the CED.

Solubility parameter theory was initially developed for comparing liquid solutions. The CED was readily calculated from the heat of volatilization of the liquids. Polymeric barriers have no vapor pressure, so the CED and the solubility parameter cannot be calculated or measured directly. Instead, the solubility parameter may be estimated by immersing the polymer in a variety of liquids and assigning to the polymer the solubility parameter of the liquid which produced the greatest weight and dimension change. This method is useful for liner and cap materials which contain one polymer and a small percentage of additives. Alternatively, the solubility parameter can be estimated by an empirical method referenced by Swope et. al. (1983).

Deficiencies of the solubility theory limit its application to preliminary screening of barrier materials for identification of those which are least resistant.

The deficiencies include:

- Reliance on weight gain and dimensional stability as the only indicators of chemical resistance;

- Interactions among components of liquids or polymers may affect the solubility parameter; and

- Currently the approach has been used for short term testing only. Extension of the theory to the long-term determination of solubility will be required before the procedure can be used for hazardous waste applications.

Further research is required to determine the applicability of solute transport theory to the problem of hazardous waste liner stability. Additional investigation appears to be warranted since the technique may provide the capacity to rapidly screen liner materials based on anticipated leachate characteristics. Final testing for chemical resistance of specific liner and leachate combinations would still be required, but the range of potential liners could be narrowed significantly.

### 3.3.5 Summary

The evaluation of the long-term chemical resistance of liner materials to leachate attack represents the most critical aspect of hazardous waste facility design. The problem is complicated by the broad range of polymeric formulations available for liner materials and the equally broad range of chemical contaminants found in hazardous waste facility leachate. Researchers have attempted to resolve the problem in alternate ways. The first approach attempts to define the characteristics of general classes of liner materials and waste stream leachate, to allow, prediction of effective chemical resistance. The second approach attempts to measure the chemical resistance of specific liner materials with a representative leachate material or a pure chemical. Limitations exist with both approaches. The first technique assumes that the chemical properties of specific liner or leachate materials within a general class do not vary significantly. This has not been' demonstrated. The second technique is impractical due to the broad range of materials and leachate available for testing. The most acceptable approach appears to be a combination of these alternatives. The first technique would be used to narrow the selection process by providing a initial screening of liner materials and leachates. The second approach could then be used to determine the most suitable liner material for a specific leachate through direct testing. However, this approach does not completely resolve the problem, since chemical resistance measuring techniques are presently not standardized (testing is discussed in detail in section 3.4).

Disregarding the lack of standard chemical resistance testing procedures, the approach is workable if suitable screening methods can be developed to narrow the list of available synthetic materials for testing. Solute transport theory represents the most promising approach toward defining screening techniques. However, the applicability of solute transport theory to the assessment of long term chemical resistance has not been verified. Further research is required to assess the overall applicability of this approach to the hazardous waste containment problem.

In conclusion, the chemical resistance of liner materials to hazardous waste leachate can be conceptually determined, assuming standard testing methods can be established. However, the broad range of synthetic materials and leachate components render direct testing impractical. Further research must be conducted to investigate the significance of leachate variations to liner resistance and to assess the utility of solute transport theory as an initial compatibility screening approach. The problems associated with available testing methods are discussed in section 3.4 of this report.

## 3.4 CHEMICAL RESISTANCE TESTING

The selection of a synthetic liner material which is resistant to leachate attack is critically important to the design of hazardous waste facilities. The selection requires direct testing of the potential liner materials with representative leachate samples to evaluate anticipated long and short term liner performance. The following provides a discussion of two general types of resistance testing. The first type, exposure testing, provides a simulation of in-service liner conditions. The second testing approach, material property testing, provides a comparative basis to establish liner property changes after leachate exposure. The interpretation and reliability of the various methods are discussed in the conclusion of this section.

### 3.4.1 Exposure Test Methods

Exposure testing methods are designed to provide a direct measure of liner performance during direct exposure to either pure chemicals or sample leachates. Testing conditions may be varied to investigate particular chemical interactions or to test broad classes of chemical types. Similarly, the period and temperature of exposure can be varied to provide information on the short and long term resistance of the liner material. Several specific exposure test methods have been developed. The following methods have been defined for hazardous waste facility liner testing:

- o Immersion;
- o Pouch (limited to thermoplastics and crystalline materials);
- o Tub; and
- o In-service

These methods are considered the most significant for hazardous waste applications, however other methods have been proposed. The selection of the most appropriate technique depends on the particular properties to be tested and the anticipated facility design. Detailed discussions of these and other testing methods are provided by Haxo (1983).

### 3.4.1.1 Immersion Exposure Methods

Several methods exist for conducting immersion testing. The following techniques have been used for hazardous facility testing:

- o EPA Method 9090 Compatibility Testing of Membrane Liners (draft)
- o National Sanitation Foundation Recommended Test Method for Determining Long-Term Performance of Membrane Liners in a Chemical Environment. (Proposed)
- o ASTM D471-79 Rubber Property-Effect of Liquids
- o ASTM D543 Resistance of Plastic to Chemical Reagents
- o Matrecon Test Method 3 Immersion of Membrane Liner Materials for Compatibility with Wastes

The Matrecon and EPA methods were specifically developed to evaluate synthetic barrier materials exposed to hazardous waste. All of the above methods use similar procedures. Samples of the specific barrier materials are immersed in the waste and the effects of the immersion are determined. Tested parameters include changes in sample weight, dimensions and a selected number of physical properties as a function of immersion time. By immersing the samples totally in the waste fluid, a somewhat accelerated test is generated. Further acceleration can be effected by increasing the temperature. However, the closer the temperature and exposure conditions are to actual service, the more reliable the results will be. Also, the greater the test duration, the more reliable it will be. These types of tests should be initiated early in the design phase of the waste facility. An exposure period of twelve months is desirable. Samples can be withdrawn at one, two, four, etc., months to assess the effect as a function of time. (Haxo, 1983). Immersion tests are not suitable for direct measurement of permeabilty.

While these published methods establish protocols for conducting immersion tests, there is sufficient variability between the methods to prevent direct comparison of subsequent material property measurements. Method 9090 establishes a temperature at which the exposure should be conducted as well as time periods for sample removal and testing. The Matrecon method does not specify temperature conditions. None of the methods specify appropriate procedures for obtaining waste liquids for use in the test. Similarly, there is no detailed procedure for assuring maintenance of the waste liquid or prevention of volatile losses from the immersion tank. Temperatures at which material properties are to be measured are not specified. Test methods for specific material properties are specified but no guidance is given on how to use the measurements obtained, particularly with respect to estimating long-term material properties and/or performance with respect to waste containment. In general, there is a need to vigorously review the existing methods and to develop more analytically consistent procedures to allow interlaboratory material property measurements to be directly compared.

Immersion exposure testing is most frequently conducted by the polymer barrier industry. A review of their test conditions indicated a large variance in temperature and duration of exposure. In addition, material properties measured subsequent to exposure are different. Tensile strength was the only property measured by all laboratories. Weight change and elongation were measured by most laboratories. (Swope, et. al., 1983).

3.4.1.2 Pouch Test

The pouch test was designed to measure the permeability of polymeric barrier materials to water and to dissolved constituents of the wastes. A sample of the waste is sealed in a small pouch fabricated of the liner material which is then placed in distilled or deionized water. Measurements are taken periodically to determine the extent of movement of water into the membrane and/or leakage of waste into the water. A concentration gradient is created by the deionized water on one side of the membrane and the waste on the other side. This test environment results in the movement by osmosis of water and ions and other dissolved constituents through the membrane due to the differences in concentrations on either side of the membrane. Changes in liner materials are observed and subsequently physical properties are tested. At present, this test is limited to thermoplastic and crystalline membranes. However, it can be used to assess the compatibility of wastes with these materials. (Haxo, 1983).

The pouch test is the only exposure method which allows direct measurement and calculation of permeability. A rigorous protocol should be developed for this test and the scope of the test expanded to evaluate crosslinked polymer formulations as well. Accelerated testing at higher temperatures (comparable to EPA Method 9090) should be evaluated, to assure reliability.

3.4.1.3 Tub Test

The tub test consists of constructing a tub of synthetic liner material, filling the tub partially with waste and exposing the test cell to the environment. The level of waste is allowed to fluctuate to simulate the rise and fall of surface impoundment waste levels. This results in an alternating exposure of a portion of the liner to air and waste. The effects of exposure to the sun, temperature changes, ozone, and other weather factors can be evaluated, as well as the effect of a given waste on a specific barrier. The fluctuation of the level of the waste is significant in that a horizontal section of the barrier is subjected to the effects of both the waste and weather. This alternating of conditions is especially harsh on barrier materials and is usually encountered at surface impoundments. (Haxo, 1983)

Measurements of material properties of specimens exposed by the tub test are particularly dependent on climatic conditions. Reporting of values measured should include the following information:

- waste liquid level variation;
- quantities of waste liquid added;
- sunlight exposure;
- temperature variations;
- formation of ice; and
- wind conditions.

The frequency of waste liquid renewal should be more vigorously established and included in method documentation. The tub test does not provide a direct measure of liner permeability, and is primarily useful for surface impoundment applications.

#### 3.4.1.4 In-service Exposure

Coupons or test samples are occasionally used to monitor material properties of installed barriers. Test samples at surface impoundments have included tubs fabricated with the liner material and weighted with sand at the closed end to provide vertical test strips for exposure to waste on one side only, throughout the facility depth. At landfills and waste piles, coupons are placed in leachate sumps. No standard method or guidance exists which specifies test sample size or configuration, number of test samples, exposure conditions or frequency of withdrawal and testing. However, with proper standardization, in-service testing can provide valuable information regarding the long term resistance of synthetic materials to hazardous waste leachate.

### 3.4.2 Material Property Tests

Material property testing provides a technique to determine the significance of exposure testing on the liner material under investigation. Following liner material exposure to waste material or leachate, the liner material properties are reanalyzed to determine if significant changes have occurred. Currently there are no standards established regarding the specific properties tested or the level of change which should be regarded as significant. The following properties are most frequently tested:

- Weight change;
- Dimensional stability; and
- Strength parameters

Other properties which are infrequently reported include analytical properties (volatile fraction, ash content etc.), hardness, and occasionally CED (cohesive energy density). Permeability of the liner to water may also be reported. In addition, most laboratories report visual observations including the presence of cracks, evidence of delamination and discoloration.

### 3.4.2.1 Weight Gain

The evaluation of reactivity often includes weight change. Experience in the plastic and rubber industry supports the presumption that materials exhibiting high weight gains or losses are less likely to serve as functional liquid barriers. Materials exhibiting low weight gains or losses, however, do not mean the material will definitely serve as an effective barrier. Upper limit values of reported weight changes were reported to be 2 to 40-50 percent. A generally accepted value, but not a standard for acceptable weight change, in the industry is 10 percent. Weight change, if it occurs, appears to provide a good measure of poor liner resistance, however the converse is not valid. It is an important parameter of vapor transport theory and solubility parameter theory. Some synthetic materials are formulated with compounds that may be readily extracted by certain solvents, resulting in loss of a physical property which was provided by their presence. Weight loss (in the absence of an off-setting weight gain) may indicate shortened service life if the extracted material affects a property necessary during operation, closure and post closure. A synthetic material may be formulated with a non-migrating compound if the loss is considered significant.

Weight gains are usually accompanied by losses in strength and other barrier properties. Large weight gains may result in softening of the material which in turn may reduce resistance to abrasion, weathering, wave action, and fluid flow.

3.4.2.2 Dimensional Stability

Changes in specimen size indicate swelling or shrinkage. There is no general agreement regarding acceptable levels of dimensional changes. The levels may be expected to be dependent on specific site applications and may decrease as the rigidity of the material increases.

Swelling may produce buckling with resulting increased stress on seams. Shrinkage may tighten the material resulting in increased stress, reduced ability to conform to irregularities of the bedding media, and possible tearing or puncture. Where dimensional stability is of concern, the material may be reinforced with a scrim.

3.4.2.3 Strength

The tensile strength of synthetic materials, (the stress at the yield point, beyond which the material will not return to its original length) is an important design parameter that may also indicate changes in material properties not detected by dimensional or weight changes. Increased tensile strength may indicate a loss or mitigation of plasticizers. Lower tensile strengths indicate a softening of the liner. Similarly, 100 percent modulus (stress required to double the specimen length) and ultimate elongation (percent of initial length at breaking) also provide insight to reactivity between the waste and synthetic material. For design purposes, tensile strength should be conducted with a scrim if it is planned to be included in the final synthetic material.

Tear testing simulates the behavior of the material following the formation of a hole due to puncture or excessive creep. Reduction in tear strength may be indicative of material or scrim degradation and/or delamination. Propagation of a tear in a field application would require stresses not relieved by the formation of the hole.

#### 3.4.2.4 Visual Inspection

Inspection of the material may reveal changes not necessarily detected in the above quantitative tests. Reactivity may be manifested by pitting, discoloration of waste or material, delamination and bubbling.

### 3.4.3 Applicability of Test Results

The testing methods discussed were essentially developed by the liner industry to provide direct short-term liner performance data. In general, the procedures are well suited to this purpose and have proven effective in determining liner resistance to weathering and chemical attack. The lack of standardization presents a significant problem since it prevents the development of a comparable data base for a wide range of liner materials and waste streams. The development of standard testing methods and procedures would significantly improve the utility of these methods.

Long term projection of liner performance is currently extrapolated from the short term test results using the degree of change of liner parameters as an indicator of long term performance. Since material property testing provides a measure of the change in liner properties with time, the results can be easily extrapolated to any length of service. However, due to lack of long term field experience with synthetic liners, the applicability of this procedure can not be verified.

It is assumed that the rate of change of liner properties can be used as an indicator of long term performance. Liner property changes may occur at different rates over the lifetime of the liner or may cease altogether after some initial period of change. Barriers which exhibit a continuing change in material properties are considered unacceptable. Conversely materials which exhibit no change are considered acceptable.

While this may be true, the following should be considered when selecting such a material:

- o exposure period may have been too short
- o accuracy and precision of the test method may be insufficient to detect small changes.

Barrier materials with one or more properties which initially change and then remain constant are suspect. But if the properties retained after a change has ceased are sufficient to meet design strength and permeability requirements, then the material may be considered acceptable. However, a thorough evaluation of the potential causes and long-term effects of the material property changes is required.

Projection of long term retention of material property values based on short-term exposure is common in materials testing. Selection of a barrier material that exhibits no change in monitored property values provides better confidence in long-term performance than one which exhibits a change. Projection of rates of change are possible, but the relatively short history of chemical resistance testing does not provide insight as to the long-term performance of the material under field conditions.

### 3.4.4 Summary

The polymers used to fabricate synthetic liners possess unique chemical resistance characteristics which must be evaluated by chemical resistance testing with the hazardous wastes to be contained. A single polymer formulation which can be used for all wastes was not identified. Analytical properties of barrier materials can be used to identify specific formulations and are useful in assuring quality of the selected material during fabrication, installation and facility operation. Test methods for these properties are currently available and considered applicable to evaluating barrier materials.

The most widely used methods for determining chemical resistance of liner materials with wastes are a series of immersion exposure tests followed by measurement of selected material physical properties. Commonly measured properties include:

- o appearance;
- o weight change;
- o dimensional stability; and
- o tensile properties (including strength, elongation, tear, and modulus of elasticity)

A modest chemical resistance testing data base has been developed, principally by manufacturers and fabricators of synthetic barrier materials. This data base provides insight on short-term reactivity. The measured results are not correlated with long-term performance or long-term chemical resistance, since virtually nothing is known about either. Additionally, the properties measured are not directly related to long-term performance. This series of tests can be effectively used to identify unsuitable synthetic materials. The tests can also be useful in selecting materials, although the usefulness is quite limited.

Several methods are currently available for conducting immersion tests. A common deficiency of these methods is the absence of appropriate specific procedures for obtaining waste liquids for use in the tests. Such procedures should provide waste liquids which may represent worst-case as well as typical conditions. Development of the procedures should consider the mobility and leaching characteristics of hazardous waste constituents. A protocol, (such as EPA Method 9090) which combines the immersion test, material property tests, and procedures for obtaining waste liquids should be developed. Detailed specification of test conditions such as time, rate of stress application (tensile properties) and temperature should be included. When developed, a test method for permeability should be included in the protocol. Although constrained by a lack of field data, the protocol should also include guidance on how to use the reported measurements to estimate long-term performance.

The pouch test is potentially capable of providing results which can be directly related to long-term chemical resistance of synthetic materials. This test places wastes inside a pouch and measures the quantity of chemicals that have migrated from the pouch to the surrounding water. At present, the amount of data and type of parameters measured (pH and conductivity) is quite limited. However, this method has the potential of providing direct measurement of vapor transport under conditions which most closely resemble landfill exposures. This test warrants further development and standardization.

Liner testing methods provide a subjective basis for assessing liner resistance to waste leachate. Standardization of the testing methods and procedures must be accomplished in order to improve the utility of the available liner testing data base. EPA has established a testing procedure (Method 9090) which represents an important first step in standardization. This approach should be expanded to include the pouch test and in service testing procedures. Finally, criteria should be established to determine the degree of liner property change, if any, which can be regarded as insignificant in determining liner resistance to waste leachate.

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## 4.0 SYNTHETIC LINER/CAP INSTALLATION

Liner installation represents a critical phase of the construction of any hazardous waste facility. Problems which go undetected and unresolved during liner or cap installation invariably result in cap or liner performance problems. The following discussion of the principal aspects of synthetic liner installation was obtained from a supporting report by TRW (1983).

Following the site selection and design phase of a waste facility the liner installation phase proceeds. Prior to actual liner placement the site is excavated, the foundation is prepared and excess material is stockpiled for subsequent use. Berm construction and surface water drainage systems are also installed prior to liner placement. Upon completion of the preliminary field preparation, the liner, leachate collection and leak detection systems are constructed. Following completion of the operating phase of the facility, the cap and final cover systems are installed as required. Faulty construction practices or the use of sub-design materials during these critical installation phases will result in subsequent liner or cap performance problems.

Due to the critical nature of the installation phase, a systematic quality control and inspection program is needed to insure adequate liner performance. The investigation of documented facility failures generally shows that faulty liner or cap installation procedures lead to most of the seepage and percolation problems reported. Regardless of the quality of the facility design, final facility performance depends on properly installed synthetic barriers.

The following section provides a brief discussion of the most significant problems associated with faulty liner and cap installation procedures. Further details regarding the scope of adequate installation procedures are provided in the supporting consultants report (TRW 1983) and the companion report on clay liner systems (ERTEC 1983). Specific problems peculiar to the installation of synthetic liner and cap systems are discussed in further detail. The concluding section provides an assessment of the significance of liner installation problems and the need for adequate quality assurance monitoring of the installation process.

## 4.1 FOUNDATIONS

The structural stability of the subgrade or foundation must be capable of supporting the waste facility components, including the weight of the wastes, without damaging the liner. Problems noted which are attributable to the structural stability of foundation include:

- Subsidence after placement of the liner;
- Excess moisture prior to placement of the liner;
- Failure to sterilize for plant control;
- Inadequate definition of subsoil conditions prior to construction, and failure to consider these conditions in design and installation.

Each of these problems can result in synthetic liner failure and leakage. However, proper construction and design techniques are available to avoid these problems. A thorough geotechnical evaluation of the site area geology and hydrogeology is required to avoid subsidence problems. Adequate field dewatering procedures and established methods of soil sterilization are also available. A proper facility design should specify the necessary field procedures to avoid these problems. And, a formal quality assurance program should be used to verify attainment of design specifications during installation.

Associated with preparation of foundations is the construction of dikes and berms. At least two failure modes for side slopes that have been constructed too steeply were reported:

- o Failure due to equipment mobility causing liner damage; and
- o Sloughing of the earthen side walls.

The use of heavy equipment on dikes should be limited, since damage to the liner may occur as a result of maneuvering on steep slopes. A maximum slope of 3:1 (horizontal to vertical) appears to be the common recommendation to protect liners. Sloughing of soil from side walls can stretch and possibly tear a liner. Appropriate design would avoid using a soil susceptible to sloughing due to high moisture content. Where high moisture conditions cannot be avoided, the use of a drainage layer or other means of controlling soil stability is encouraged.

Concrete or asphaltic concrete surfaces can also be used to support liners. Preparation of these surfaces is briefly discussed in a draft manual for AWWA on flexible tanks, covers and linings for potable water reservoirs (AWWA, 1982). Care must be taken to assure all surface areas are smooth and that no sharp edges contact the liner. The foundation or subbase for the concrete pad should be carefully evaluated, designed and constructed to minimize settlement and the risk of liner failure. Cracks larger than 1/16 inch should be filled and leveled (TRW, 1983). At least two sites constructed on concrete bases used a more conservative approach by providing a bedding material of one foot of sand above the concrete.

Inadequate foundation preparation has resulted in several synthetic liner problems at existing facilities. These problems can be avoided through proper design and the implementation of an adequate quality assurance program. Facility cap installation and subsidence problems are discussed in section 5.6.

## 4.2 BEDDING MATERIALS

Synthetic liner materials are relatively thin and can be punctured by contact with sharp or irregularly shaped objects. The risk of puncture is increased during installation of the leachate collection system over a liner material placed on a bed of irregular material. Further, the induced stress on liner materials placed over course aggregates such as gravel can lead to a weakening of the liner material with time. This process was evidenced by a decrease in hydrostatic resistance and some delamination of a liner placed over 1 to 1 1/2 inch loose aggregate. Previous studies indicated that liners are often placed without complete smoothing of the bedding material.

Bedding materials above and below the polymeric barrier are critical in determining performance of a polymeric barrier. The bedding material surface should be smooth to avoid indentation or distortion of the barrier material. Depending on the smoothness of the subbase surface, only a few centimeters of bedding material may be needed to provide an appropriate surface for barrier placement. To overcome deformations in the subbase surface during construction, bedding material depths of 15 cm or greater is recommended.

The depth of granular material required to protect a synthetic liner is not adequately defined. Current estimates range from 2 inches to one foot, most researchers agree that 5 to 7 inches of protective material is sufficient. Similarly, the grain size of the protective material is presently unspecified. However, most experts agree that almost any clean soil or sand which passes a No. 4 seive is suitable as a protective bedding material. More definitive guidance would be useful in reducing the wide range of materials and bedding depths currently employed to protect synthetic liners.

Each of the sub-liner material layers should be sterilized prior to liner placement. Design specifications should include criteria specifying the maximum organic content for all soils which remain on site. Soil sterilant should be applied and moistened over the entire site area and then allowed to dry prior to liner placement. Application rates and procedures should follow those specified by the sterilant manufacturer. The application and verification of herbicide placement should be subject to quality assurance review and inspection.

## 4.3 MATERIAL STORAGE AND HANDLING

Proper storage and handling of liner and cap materials is necessary to prevent degradation due to exposure to the elements and to ensure that the properties of the materials that are installed are the same properties specified in the design. Specific regulatory requirements do not exist nor are they needed for storage and handling at this time. Appropriate construction specifications and a quality control program can assure proper handling and storage of polymeric barriers.

Weather can affect the integrity of a stored or unfolded liner in the following ways:

- Winds >10 mph can lift and tear the material;
- Ultraviolet light exposure accelerates aging to a limited extent;
- Hail punctures liner; and
- Blocking, resulting from sunlight and overburden pressures, causes the rolled up material to stick together.

These can be readily controlled by providing storage space, preferably in a secure place to prevent vandalism. Folding and unfolding a liner, especially at low temperatures, should be avoided since cracking or weakening of the liner material may result.

## 4.4 SEAMING

Researchers generally agree that improper seaming is responsible for most synthetic liner failures. Seaming represents the most critical aspect of liner installation, since the presence of improper seams may result in significant leakage and expose the synthetic material to a higher risk of chemical decay. Some seaming generally occurs at the factory as well as in the field. Factory seams are considered more reliable, since better environmental controls are available. Depending on the synthetic liner material selected for the facility, one of the following three seaming techniques are used.

- o Bodied solvent;
- o Heat; and
- o Contact adhesive.

Regardless of the process used, the technique for accomplishing the seam is as follows:

- o Clean the seaming surface;
- o Apply solvent, heat or adhesive;
- o Apply pressure; and
- o Provide time for airing.

Facility liner seams should be oriented upward from the facility floor to the top of the side walls in a ribbing pattern to avoid excessive stress due to liner slippage or sloughing.

Several problems can occur during field seaming operations, due to the lack of environmental control. The most significant problems identified are discussed briefly in the following sections. Proper scheduling and quality assurance review can be used effectively to minimize the effects of these problems on synthetic liner performance.

Prior to field seaming, the material should be properly oriented to avoid stretching the material around protrusions or folded seams. Bridging of voids in the subbase by the liner material should be avoided. This often happens around protrusions, and where the bedding or subbase was not properly constructed. Wind damage has occurred frequently during installation and is aggravated when the anchoring trenches are installed and backfilled before seaming is completed.

Scheduling is an important part of successful liner installation. Expendiency is important to keep field-time, and hence risk of rain-days, to a minimum. However, careful attention to quality workmanship is more important. Installation is sometimes scheduled during evening hours to avoid sunlight and associated high temperatures and ultraviolet exposure. Such preconditions of the facility. Documentation of a quality control program should include the following elements:

- o Polymer material;
- o Seaming material;
- o Compatibility of material and seaming method;
- o Condition of bedding material (see Section 5.4 for specific elements);
- o Placement of panels;
- o Orientation of seams;
- o Seaming procedures;
- o Solvent type and quantity used;
- o Weather conditions;

- Seam samples for testing and reference;
- Seam inspection (100 percent);
- Names of personnel; and
- Herbicide application, type and quantity

Implementation of a quality control program containing these elements should identify problems which have been reported. A corrective action program needs to be developed and implemented when problems are encountered. When properly conducted, field seams are not considered to be a significant factor controlling polymer barrier material performance.

## 4.5 DRAINAGE SYSTEMS

The installation of drainage systems over the synthetic liner, or under it for multiple liner facilities; requires careful design and installation. Design considerations must include an assessment of the load bearing capacity of the porous drainage layer material and the drainage pipes installed. Lack of adequate bearing load capacity or premature operation of heavy construction equipment can result in damage to the underdrain system. Drainage pipes could be crushed or broken and may puncture the synthetic liner, as well as reducing the effectiveness of the leachate collection system. The problem of liner and leachate collection system vulnerability to damage by equipment results from the requirement that a maximum of 30 cm of leachate above the liner in an operating landfill.

The expansion of the leachate collection drainage layer and the liner protection layer would significantly decrease the risk of liner or pipe damage due to construction and operational activities. However, this would require an increase in the maximum allowable leachate head. Since synthetic liners are less susceptible to increased leakage due to hydrostatic pressure, an increase in the allowable leachate head from 30 to 60 centimeters would be appropriate. With this recommended leachate head increase and proper construction and maintenance practices, the potential for liner or leachate collection system damage would be significantly reduced.

## 4.6 QUALITY ASSURANCE

The installation problems identified during the course of this project demonstrate the need for comprehensive quality assurance review of all aspects of synthetic liner installation. A suitable quality assurance program is required since the use of improper construction techniques or field procedures may jeopardize the performance of the synthetic barrier system. The following elements must be subject to quality assurance verification if design specifications are to be attained:

- Liner bed material selection, placement, and grading;
- Foundation compaction and preparation;
- Liner material storage facilities and handling techniques;
- Seaming techniques and materials;
- Seam testing; and
- Personnel experience and qualifications.

Quality assurance procedures should insure that proper documentation, in the form of material specification sheets, daily field logs and testing certifications, is maintained throughout the liner installation phase. Owing to the importance of proper liner seaming, a particularly strong material certification and field inspection program is required for the seaming operation.

Materials and equipment used for the liner or cover installation should be inspected to ensure they are in good condition and within specifications. Improper materials and equipment should be removed from the site to avoid subsequent confusion. The inventory of liner panels should be checked against design plans and specifications before they are seamed.

Testing of field seams is well established in the industry. The sensitivity of liner performance to leaking seams should dictate the extent of seam testing performed. The recommended practice is to field test 100 percent of the seams. The associated cost, while appreciable, represents only a fraction of the cost of the facility and potential liabilities in the event of failure.

Available test methods include non-destructive testing such as air lance, vacuum, ultrasonic and visual. Destructive testing requires the removal of samples from the liner and subsequent patching. A less acceptable alternative would be to have extra material seamed by the work crew as they progress throughout the day. Tests which are usually performed on such samples include peel adhesion and shear strength. Additionally, the quality assurance program should provide for collection and appropriate storage of record samples of all materials in the liner system, including:

- pipe material;
- pipe cement;
- drainage soils;
- liner material; and
- solvents/adhesives.

Additional samples of liner material should be collected and used for periodic assessment of reactivity with wastes, sludge, and air exposure of surface impoundments or in leachate sumps at landfills.

## 4.7 SUMMARY

The proper installation of synthetic liner and cap systems is critically important to the overall performance of the facility. Several problems documented at existing facilities have been linked to liner installation problems. However, all of the problems identified could be avoided using available installation techniques and construction practices. Failure to achieve proper liner installation is attributed to the lack of adequate quality assurance and the apparent lack of understanding on the part of installers regarding the critical importance of properly installed liner systems.

Liner subsidence problems are primarily associated with poor foundation preparation techniques. Suitable techniques are available to avoid these problems. Cap subsidence represents a more difficult, yet manageable problem area. Studies have shown that over 90 percent of the total waste consolidation occurs within 5 years of facility closure. Further, proper waste stacking and filling can minimize this consolidation. It is recommended that a cap inspection program be required for a minimum of 5 years after facility closure.

Liner stress due to the use of sharp or irregular bedding materials represents a material selection problem. Similarly, improper grading of the liner bed is easily avoided through quality assurance inspection prior to liner placement.

The installation of field seams represents the most critical aspect of the liner installation phase. However, the most significant problems encountered at existing facilities were the result of the use of the wrong bonding materials and techniques. A comprehensive quality assurance program is required to verify the use of proper bonding techniques and materials. Further, 100 percent testing of all field seams is recommended. Testing should be performed using non-destructive field techniques. However, peel and shear testing should be performed on sample seam patches.

In conclusion, synthetic liner installation represents a particularly critical phase of hazardous waste facility development. Several problems encountered at actual facilities are attributed to installation problems. However, current techniques are available to insure proper synthetic liner installation. It is strongly recommended that a stringent quality assurance program be developed to cover this critical phase of facility development.

## REFERENCES


TRW, 1983. Assessment of Technology for Constructing and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities. U.S. Environmental Protection Agency, Washington. D.C.

AWWA, 1982. Manual, Flexible Tanks, Covers and Linings for Potable Water Reservoirs. Draft. American Water Works Association, Denver, CO. 57 pp.

# 5.0 SYNTHETIC CAP AND LINER PERFORMANCE

Assessment of synthetic material performance in cap and liner systems included evaluation of the service life for installed barrier materials, the failure from subsidence of barrier supporting materials and the combined performance of the two systems.

## 5.1 SERVICE LIFE

The issue of service life of synthetic materials in waste management facilities was addressed by reviewing data on actual field service experience and by evaluating current methods for projecting longevity and acceptable performance from experimental and field data. Service life of barriers depends on chemical and physical properties of the barrier material and how it is protected in the cap or liner system.

The regulations do not identify a period over which the performance must be acceptable. It is expected, however, that if leachate is no longer present, nor likely to be generated in the future, the performance life of the liner system can terminate. A performance standard, established for cover systems at disposal facilities, requires long-term minimization of the migration of liquids through the closed facility. No guidance is provided in the regulations regarding the period referred to as the long term.

Conceptually, service life, as well as long-term, may be stated in terms of waste degradation and release characteristics from the containment. An analysis of risks to health and the environment might also be included to determine an acceptable level of release from the facility, and thereby identify maximum required service life in terms of performance. While risk analysis may be used as a management tool for evaluating alternatives (such as selecting remedial alternatives for clean-up of uncontrolled hazardous waste sites) it was found unacceptable for establishing regulations for hazardous waste facilities under RCRA.

Alternatively, service life may be stated in terms of material characteristics, such as permeability or tensile properties. Unfortunately, there is no data available which allows correlation of specific liner properties with overall performance or finite service life. Therefore, it is doubtful that a scientifically supportable definition of service life or long-term can be developed, based on current knowledge of barrier material properties and field performance.

## 5.2 PHYSICAL AGING OF SYNTHETIC LINERS

The ultimate service life of a synthetic material which is properly installed and protected from chemical attack is determined by the chemical stability of the liner structure. Polymeric liners rely primarily on long-chain organic molecules for stability. Long chain molecules degrade over time through three primary mechanisms: the action of sunlight; chemical attack by small molecules; and, biodegradation. A brief description of each mechanism is provided in order of their potential significance to liner decay.

The sunlight mechanism, which includes photochemical and oxidation processes, represents the most rapid deterioration mechanism. Significant degradation, as evidenced by discoloration and cracking has occurred for particularly sensitive liner materials after 200 hours of exposure. Several defense mechanisms are available, ranging from simple burial of the synthetic material to the addition of polymer stabilizers and pigmentation. If properly accounted for, liner exposure to the atmosphere does not present significant degradation problems.

Attack of the liner by small molecules, termed hydrolytic and solvolytic degradation, occurs on a slower scale, particularly if the liner has been shown to be chemically resistant to the waste leachate. A polyethylene terephthalate liner with reinforcing fabric would be expected to hydrolyze in a few hundred years at 30 to 40$^{\circ}$C and 100 percent relative humidity, when exposed to aqueous leachate. The use of available chemical resistance testing methods appears to provide sufficient information for the evaluation of this aging mechanism.

Biodegradation is the least significant decay mechanism, since polymer chain attack proceeds from the ends of the long chain molecules. Except for particularly sensitive liners biodegradation would be expected to occur over several hundred years for most polymer liners. Longer decay times, would be expected for saturated polymeric materials. Avoidance of particularly sensitive materials would effectively eliminate biodegradation from concern for liner systems.

In actual field installations all three mechanisms would be expected to contribute to liner decay simultaneously. No suitable laboratory techniques have been developed to measure the rate of this liner weathering.

Therefore, it is necessary to evaluate actual field performance data to assess the anticipated life of synthetic liners in the field.

## 5.3 FIELD SERVICE EXPERIENCE

Most of the polymers used for waste containment have been commercially available for less than 10 years. This places an upper limit on actual field service experience. Based on published material and manufactures' literature, a listing of field service experience was prepared (Table 5-1). Information on service life is available for some materials and is reviewed in Section 5.4. The information, however, was collected for applications which are not specifically related to waste containment. If the barrier material selected is chemically resistant, current data indicates that the actual service life of polymeric barriers used in cap and liner systems ranges from 5 to 45 years, depending on type of polymer used. These projections of service life are based on the ability of the barrier material to retain its original chemical and physical properties.

## 5.4 PROJECTED SERVICE LIFE

Service life of a barrier material may be projected from measured changes in material properties. Sufficient information on field performance and measured material properties do not exist for any type of polymer to determine how much change would result in failure or termination of service life. However, it is useful to review existing information on long-term changes of material properties.

TABLE 5-1 POLYMER FIELD SERVICE EXPERIENCE PERIOD[a] (LYMAN, 1983)

| SOURCE[b] | MATERIAL[c] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PVC | LDPE | HDPE | CPE | CSPE | ECH | N | B | EPDM | A/B |
| Kays (1977) | | | | 12 | 8 | | | 17 | | 25 |
| NCASI (1980) | 14 | | | | 6 | | | | | |
| Lauritzen (1967) | | | | | | | | 19 | | |
| Hercules (1981) | | | | | | 5 | | | | |
| Dupont (1983) | | | | | 11-17 | | | | | |
| Dupont (1983) | | | | | 15 | | 45* | | | |
| Gundle (1983) | | -20 | -20 | | | | | | | |
| Schlegal (1982) | | | 9 | | | | | | | |
| B.F. Goodrich (1982) | | | | 3 | 17 | | | | | |
| Dow (1982) | | | | 12-20 | | | | | | |
| Anonymous (1976) | | | | | | | | | | 13 |
| Polysar (1982) | | | | | | | | 25 | | |
| The Asphalt Inst. (1976) | | | | | | | | | | 4-23 |
| Strong (1980) | 13-22 | | | | | | | 11 | 8 | |

[a] Years
[b] See Lyman, et al., (1983)
[c] PVC - polyvinyl chloride
HDPE - high density polyethylene
CSPE - chlorosulfonated polyethylene
N - non-linear neoprene rubber
A/B - asphalt/bitumen
LDPE - low density polyethylene
CPE - chlorinated polyethylene
EPDM - ethylene propylene rubber
B - butyl rubber
ECH - epichlorohydrin rubber

Experience with several polymer materials exposed to a minimum of 25 years to sunlight, oxygen, and rain in tropical climates indicates that the materials were still functional. In many cases, elongation and tensile properties retained at least 70 percent of the original values (Figure 5-1). Changes in tensile strength of low density polyethylene (LDPE) were negligible after 20 years of outdoor exposure in Canada. After 14 years of exposure, increased tensile strength and diminished elongation were reported for a PVC canal liner (test section) in New Mexico.

A summary of lifetime data for a number of materials is presented in Figure 5-2, where length of time the materials have been exposed to weathering, to soil burial, and to sea immersion is shown. The arrows indicate that the materials were still functional at the last sampling, and therefore material service life is at least as long as the period shown.

Also shown in Figure 5-2 are predicted service lives based on laboratory heat aging tests, which, while generally unreliable, have some utility for butyle rubber and chlorosulfonated polyethylene. Based on these laboratory measurements, it was reported that butyl rubber would retain 60 percent of its elongation characteristic in 50 years and 40 percent in 150 years. This projection was the longest time period reported for any property. However, since butyl rubber was commercialized only 41 years ago, it has yet to be validated. Due to the uncertainty concerning the applicability of these test results, a more conservative estimate of anticipated field service life must be used. Based on the evaluation of the available test data, an average service of approximately 25 years appears appropriate at this time. Further refinement of liner life prediction techniques should be developed as the

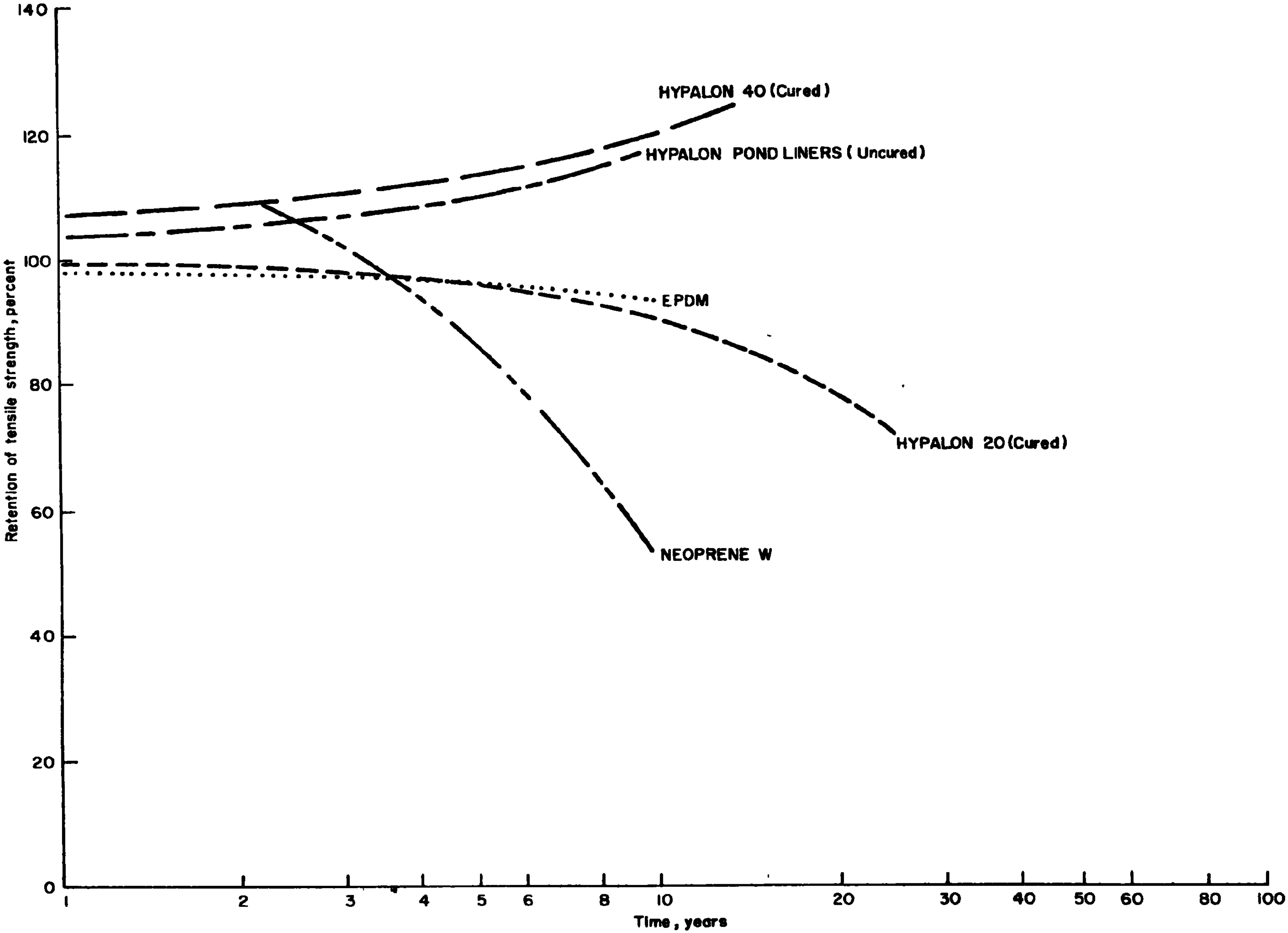



Figure 5-1 Retention of tensile strength for selected barrier material exposed in tropical climates.

(Lyman et al., 1983)

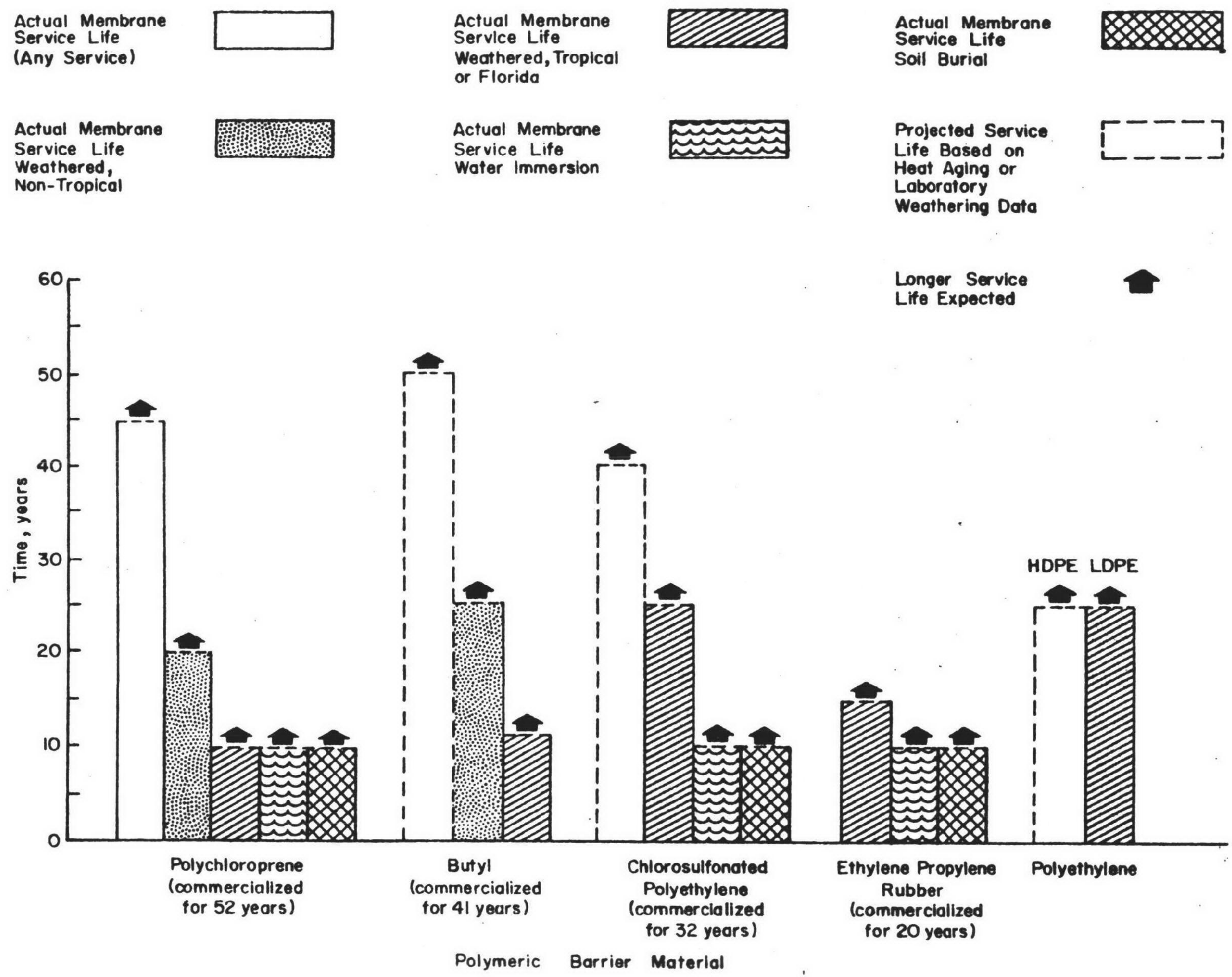



Figure 5-2 Representative service life data. (Lyman, et al., 1983)

liner experience base improves.

There is no question that a polymeric material can function as a containment barrier to liquids for at least 25 years. Extrapolation of material property data such as that shown in Figure 5-1 suggest retention of tensile strength greater than 80 percent can be expected over a 100-year period. Whether this is sufficient will depend on the anticipated stresses to which the material is subjected.

## 5.5 SUBSIDENCE OF LEACHATE BARRIERS

A properly designed leachate barrier system, based on a geotechnical analysis of soil and subsurface water conditions and loads imposed by the facility, should not suffer from serious subsidence problems. The geotechnical analysis should include an assessment of expansion of soils due to relaxation of stresses from removal of overlying soils, total subsidence, and differential subsidence. The analysis should be conducted for conditions anticipated during development and construction of the facility and in response to variable loading conditions during the operating and post-closure periods of the facility. The analysis should also include conditions to determine the effect of potential failures, such as collapse or hydraulic overload of a leak detection system. An analysis of impact on liner performance would evaluate the amount of subsidence, the area over which subsidence occurs, and the rate of subsidence.

Assurance that design specifications are met during construction can be accomplished by implementing a quality control program developed for the facility. Elements of such a quality control program may include the following documentation requirements:

- o Textural analysis, quantity, and source of fill material;
- o Conformance with specified depth, area and volume of earth removal;
- o Groundwater conditions;
- o Underlying soil conditions;
- o Density, location, placement, thickness, grade and moisture content of compacted material;
- o Location, material type and quantity of emplaced equipment, structures or piping;
- o Compaction equipment and use;
- o Herbicide type, quantity, and method of application;
- o Presence of materials not confirming to specifications (e.g. sticks, vegetation, rocks, etc.);
- o Names of construction personnel; and
- o Date, time, and weather conditions.

Current quality control practices are not well-defined. Quality control is generally provided at all facilities, but the scope and documentation of quality control programs vary. Available documentation indicates that compaction density of subgrade materials of at least 90 percent of Proctor Density (ASTM D698) was achieved at all sites surveyed. Excavation and recompaction of "soft" sections of subgrades and a placement of earth fill in accordance with standard engineered earthwork construction techniques was recommended as a result of a quality control program.

No field data were reported regarding total or differential subsidence or the rates of subsidence for liner systems at hazardous waste facilities. Where subsidence does occur, the liner would be expected to conform with the surface of the underlying soil. Based upon current understanding of the properties of synthetic materials, the ability of these materials to elongate and relax in response to differential subsidence may be limited by the pressures exerted from the weight of the overlying containment systems and the waste. This is not considered to be a serious problem provided appropriate design and quality assurance procedures are followed.

## 5.6 SUBSIDENCE OF COVER SYSTEMS

Cover system sensitivity to subsidence is similar to that of the liner system, except there is greater potential for total and differential subsidence as waste consolidation occurs. The rate of subsidence, in response to waste volume reduction, may exceed material elongation capacity resulting in cover failure. The use of fabric-reinforced materials or geotextiles underneath the barrier can reduce the significance of subsidence.

The nature of wastes, operations and closure at the facility will greatly influence the subsidence to which the cover system is subjected. Procedures to place wastes and cover to keep subsidence to a minimum can be incorporated into the facility's operational plan. Such procedures should reduce the volume of bulk waste through compaction and reduce voids between wastes by filling with compacted soil. No quantitative information was found regarding subsidence of cover systems at facilities where wastes were managed in such a controlled manner. Several feet of differential subsidence was reported at sites which did not practice waste volume reduction.

Municipal refuse landfill subsidence cannot be compared directly to hazardous waste facility subsidence due to differences in waste composition and degradation. However, relative comparisons of subsidence data are of some use. Up to 20 percent subsidence may be expected at municipal landfills with a significant portion of it occurring in the first year. Similar observations of subsidence during the first year after operations stopped were made during personal interviews with hazardous waste facility owners and operators. These observations indicate that delayed placement of cover systems may reduce the total subsidence to which a barrier may be exposed. Placement and monitoring of settlement markers provides a quantitative basis for judging the rate of subsidence. Placement of the cover system may then be an economic choice between the cost of leachate management and cost-savings incurred by delayed cover placement. Alternatively, a temporary cap of natural materials may be replaced after the subsidence rate has decreased.

Subsidence characteristics of uniform waste deposits can be determined experimentally. Methods have been developed to estimate subsidence from such wastes. Surcharging the waste with soil or installation of drainage layers in the waste can be used to accelerate subsidence of some uniform wastes.

Differential subsidence in cover systems occurs as a result of nonuniform settlement, particularly in the underlying waste. Waste placement procedures can greatly reduce potential differential subsidence. Where differential subsidence is anticipated, the barrier material may be designed to resist the stresses of material overlying the displacement, such as with the use of fabric reinforcement. Alternatively, the barrier material specifications may require elongation and tensile strength characteristics which will allow the barrier to conform to the displacement. Stresses imposed in carrying the weight of unsupported soils overlying the displacement are not expected to be great due to the limited depth of such soils and the support which will be provided by adjacent soils.

Experience with cover system subsidence is not quantitative. Failures have occurred, particularly where waste placement practices result in large void volumes which eventually collapse as the wastes degrade or consolidate. Predictable rates and total amount of subsidence may be used to design an appropriate cover system. Large initial rates of subsidence may warrant delaying complete cover system placement until the rate of subsidence slows.

## 5.7 SUMMARY

The existing data of a actual service experience for hazardous waste facilities is limited to less than 10 years, and for other applications it is limited to 25 years. This provides a minimum service period. Exposure and testing of samples indicate much longer service can be expected. The EPA guidance of 30 years is therefore considered conservative. Projections to 45 years have been made and seem reasonable. On the other hand, projections of 150 to 200 years on the basis of actual service appear optimistic.

The ability to project long-term integrity of physical properties for synthetic materials is tentative due to the relatively short period of data collection, and the lack of direct correlation between these somewhat arbitrary physical properties and the long-term projection of failure. Explicit determination of service life is not possible based on those available procedures.

There is very little information relating failure of a synthetic liner to subsidence problems. The technology does exist for studying, analyzing, designing, and constructing foundations suitable for supporting a synthetic liner at a hazardous waste facility without subsidence problems. Many of the problems envisioned with cover systems can also be resolved through geotechnical analysis. There is a greater uncertainty, however, concerning the subsidence of cover systems because of the nature of the hazardous waste operations, and the potential for significant waste consolidation after facility closure. Differential subsidence is not expected to be significant where waste placement practices which reduce void volumes in the contained waste are included in the operations design plan. Where differential settlement is anticipated, the barrier can be designed to conform to the displacement or to support the overlying soil by the use of fabric reinforcement. Either of these procedures would introduce stress on the cap liner, which could affect the long-term performance of the system adversely.

Total and differential subsidence is not expected to affect liner system performance when the design incorporates recommendations of a thorough and complete geotechnical assessment and when a well-developed quality control program, which includes regular inspection, maintenance, and repair provisions is implemented. Construction of a temporary cap of natural materials for the duration of the primary subsidence period is an alternative approach which would adequately address the subsidence problem.

# REFERENCES

Lyman, et. al. 1983. Expected Life of Synthetic Liners, Draft Final Report. U.S. Environmental Protection Agency, Washington, D.C.

TRW, 1983. Assessment for Constructing and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities, U.S. Environmental Protection Agency, Washington, D.C.

# 6.0 FAILURE MODES

## 6.1 DEFINITION

The assessment of synthetic material performance requires a clear definition of failure which specifies modes and the mechanisms and conditions or sources that contribute to failure. A simple definition of failure is: "the inability of a cover or liner system to meet performance standards".

The 40 CFR Part 264 regulations establish such performance standards. The standards require that migration of wastes to the subsurface soil or to ground water and surface water during the active life of the facility be prevented, and that migration of liquids through the facility be kept to a minimum over a long term after closure. More detailed requirements of cap and liner systems specified by these regulations are presented in Section 2.

Contrary to the common perception of synthetic liners, some leakage will occur through the liner by vapor transport for most leachates. Therefore, synthetic liners in general cannot meet the criteria established in the interim final regulations. The vapor transport mechanism was discussed in Chapter 3 of this report. Since vapor transport is an intrinsic property of the liner and does not represent a material "failure" per se, vapor transport has not been included in this section. It is recommended that the regulation be modified to allow "de minimus" leakage through the liner to avoid this obvious contradiction.

The following sections provide a discussion of the significant failure modes investigated for synthetic liner systems. The information presented in this section was obtained from the supporting consultant reports.

## 6.2 LINER HOLES

Holes appear in synthetic liners in the form of pinholes, tears, faulty seams, cracks and windows (large openings). Pinholes may occur during liner manufacture as a result of inferior product quality control procedures. Holes may occur after liner installation due to mechanical stress and chemical decay of the liner materials. During liner installation, holes can occur due to faulty field procedures. These problems were discussed previously and can be repaired prior to operation of the facility.

The synthetic liner is only one component of the entire leachate barrier system. The performance of the liner as the principal containment barrier is dependent on the proper functioning of the entire barrier system. Failure of other units, such as the leachate collection system, will result in excessive hydraulic pressure on the synthetic liner. An analysis of the consequences of potential component failures can identify problems which may lead to failure of the synthetic membrane. Such a fault-effect analysis is considered a key factor in the ability of synthetic materials to perform in liner and cover systems at TSD facilities. With the single exception of climate, all sources of liner failure can be controlled by thorough analysis of the facility design based on an awareness of the total system and development and implementation of thorough operation and maintenance, and quality assurance programs. Seaming and other critical liner installation processes should not be attempted during adverse weather conditions. An effective quality assurance program would include monitoring of synthetic material coupons to obtain an early warning of the symptoms of material failure.

### 6.2.1 Sources of Potential Failure

The occurrence of holes in barriers may be a result of stresses exerted by various chemical or physical problems. A brief description of these sources and pinholes resulting from manufacturing problems is provided. More detailed descriptions were presented by Lyman et al. (1983) and Haxo (1983).

#### 6.2.1.1 Design

A thorough and complete design includes definition of the performance goal and provides a sound conceptual structure for the facility through detailed analysis, and preparation of specifications, construction drawings, procedures and schedules, provisions for material transportation and storage, operation and maintenance plans and a quality assurance program. Each component of the facility must be designed to function as an integral part of the total facility. Almost all of the sources of failure identified can be controlled, if not eliminated, by a thorough and complete design. Inadequate attention to design details can enhance the occurrence of failures.

Establishment of a design performance goal should consider the characteristics of the wastes in the facility including persistence and mobility, the duration of desired facility operation, and the hydrogeological and environmental setting. Haxo (1983) and Lutton (1982) have described the important design considerations for barriers.

The design process should include analysis of the effect of specific subsystem failures and their effect on synthetic barriers. Such 'fault-effect' analysis identifies elements of the facility design which are critical to the successful performance of polymeric materials (e.g. removal or detection systems, etc.). The design should not rely on the polymer barrier for long-term structural performance. Corrective actions during design can then be identified, evaluated and included in the final plans.

A thorough geotechnical analysis of all dikes, berms and supporting soils can virtually eliminate these sources of subsidence stress on synthetic materials. Bedding materials can be designed to provide the required protection of barriers and incorporate a leachate detection and removal system that will not fail due to overburden pressures or facility construction and operation stresses. Close coordination between the designer and the geotechnical engineer in preparing the operations and maintenance plan can drastically reduce cover barrier failures due to subsidence.

6.2.1.2 Manufacture and Fabrication

There appear to be significant differences of opinion among the experts interviewed on the pinhole problem and its significance in liner performance. Some indicate that it is not possible to produce pinhole-free liners. Others believe that pinholes in liner sheets are a problem of the past and that the present manufacturing methods, and the quality control which is exercised in the manufacturing step, can guarantee liners without pinholes. There appears to be a lack of technical data to support either assertion. Some manufacturers interviewed indicated that their material would be "nominally" pinhole-free and that they "would be hard put" to guarantee that their product is completely free of pinholes. Pinholes which penetrate the liners are considered less of a problem for multi-ply than for single-ply liners because the chances of a pinhole in one ply matching up with pinholes in a second ply are very small. There might be some potential problems, however, if a pinhole exposes the scrim, such that contact with waste fluids could cause wicking along the scrim, build-up of fluid between plies, and eventual delamination. The probability of this happening is greatest for tightly-woven scrims and thick yarns, but in any case is small.

Pinholes can originate during the calendaring process where air bubbles, contaminant particles, or poorly dispersed granules (e.g. unmelted modules of carbon black or scrim scrap) in the mixed stock can mar the otherwise smooth surface between rolls and result in indentations which pass through the liner. The pinholes can vary in size, from a few microns in diameter to a size which can be spotted by the naked eye when the sheet is held against light (e.g. passed over a light bar). Quality control for pinhole prevention during manufacturing can include fine screening of the mixed stock before calendaring or extrusion, limiting the amount of scrap recycling, and visual inspection of the sheets on both sides to identify and repair pinholes.

Liner designers and installers generally down-play the significance of pinholes in liner performance and find little evidence indicating pinholes as a cause of liner failure. One designer reports that, based on one study with a water containment system, 2000 pinholes may be considered equivalent to one hole of 10mm diameter or ten holes of 2mm diameter. The amount of seepage through pinholes would probably be orders of magnitude less than through a bad seam or a substantial tear. Pinhole enlargement during actual use would be unlikely, since liner selection would provide a material with puncture and tear resistance.

#### 6.2.1.3 Storage and Installation

Damage to materials during storage may occur as a result of tears from vandalism, holes from hail, and exposure to sunlight. Storing of materials securely to protect them from the elements was found to be successful in reducing these problems.

Installation procedures are a common cause of liner failure. A more detailed description of problems encountered and remedies available was presented in Section 4. In general, problems are attributed to the lack of proper site preparation and adequate quality control, material handling and seaming operations.

#### 6.2.1.4 Biological Intrusion

Preparation of the foundation and bedding for cover and liner systems should include the removal of vegetation and sterilization of soil to avoid damage to the synthetic material. Use of sterilants and grubbing is an effective means of controlling vegetation damage to liner systems.

Cover system installations must be performed with the same precautions as with liner systems. In addition, the cover must be designed to prevent any damage from burrowing animals. Coarse grained soils which have a low angle of repose (side slope) are more effective than clay soils in controlling burrowing animals. Results from experiments conducted at Los Alamos indicate a layer of cobbles may be an effective barrier to burrowing animals.

Selection of shallow-rooted vegetation will reduce the possibility of root penetration through the synthetic material. Grasses are the most common species selected for final cover. Root structure of grasses is typically confined to the upper six inches of soil, although deep-rooted species do exist. Available species and factors to consider when selecting grasses for hazardous waste cover applications were provided by Lutton (1982). It is desirable to avoid deep-root vegetation to protect the polymeric barrier. Vegetation has been observed to puncture a liner when the bedding material or subbase was not properly prepared. It is doubtful that roots will penetrate downward through a barrier to an anaerobic, toxic environment, but control of this potential source of failure is prudent.

6.2.1.5 Physical Polymer Aging

Polymers are materials which exhibit properties similar to elastic solids and viscous liquids. In the short term, polymers respond much like an elastic solid (Elasticity = stress/ strain). When the material is stressed over a period of years, there is a steady increase in strain or creep and a decrease in rupture stress. Data obtained over one year of high (100 kilogram force (weight) per centimeter squared ($Kgf/cm^2$)) stress with polypropylene indicate a loss of tensile strength of up to 50 percent. However, long-term tensile stresses in a hazardous waste facility application are not expected to be as great. Eight years of service in a pneumatic structure indicated reinforced PVC retained more than 90 percent of its tensile strength. The rate of long-term creep varies for synthetic materials depending on polymer composition, type of load, temperature, chemical reactivity, and the material present as fillers and reinforcing scrim. Absorption of chemicals into a synthetic material can increase the rate of creep. Repetitious and dynamic (moving) loads appear to accelerate the decrease in long-term strength.

The information collected in this assessment indicates that polymeric materials lose their ability to resist mechanical stress when under constant loads. Liner design should not rely on polymeric barriers for long-term structural strength.

### 6.2.2 Significance of Holes

The presence of holes in a liner does not constitute failure, unless a performance requirement is not achieved. During landfill, waste pile or disposal surface impoundment operation, the presence of a hole constitutes failure to achieve the 40 CFR Part 264 requirement to prevent migration of wastes into the barrier unless the de minimus provisions allow a variance. After closure, holes in a liner may not violate the per-formance requirement, particularly when the cap barrier meets the requirement for smaller permeability than the liner barrier. Holes in cap barriers may result in failure of the cover system. In each of these situations, an analysis of the effect on barrier system capability to control liquid and/or waste constituents is warranted.

Field experience has provided several examples of the significance of holes in synthetic barriers (Lyman, et al., 1983). The seepage rate for a 45 mil synthetic liner was reported to be $2.9 \times 10^{-8}$ cm/s., lower than most clays. The rate was calculated to be about five times greater than could be accounted for by moisture vapor transport. It was concluded that the liner had holes. Similarly, a 6 mil polyethylene liner was found to have a seepage rate of $10^{-6}$ cm/s. Inspection revealed the presence of pinholes.

The rate of water leakage through a hole depends on hole dimensions, surface tension and pressure gradients. Very small holes in non-wetting materials such as HDPE supported by well-drained soil will not release water because of surface tension forces. When the hydraulic head exceeds these forces, then flow will occur. Surface tension becomes less important as hole dimensions increase.

Seepage through a larger hole is often controlled by other factors. When seepage from a synthetic material does begin, the rate cannot exceed the maximum that the underlying material will allow. The soil underlying a barrier will be the rate limiting factor, and the magnitude of the leakage rate will depend on the wetted area of soil, the soil hydraulic conductivity, and the hydraulic gradient. Since the wetted area is likely to be a very small fraction of the site covered by the material, the "average" seepage through the material may be quite low. For example, in a one acre site ($4047 m^2$), if an FML with a hole as large as $1 m^2$ overlies soil with a permeability $10^{-4}$ cm/s, the total apparent permeability of the FML plus soil could be as low as $1/4047 \times 10^{-3}$ cm/s or about $2.5 \times 10^{-8}$ cm/s. Where large holes do occur, an analysis of the specific conditions is necessary to assess the seepage rate.

The significance of holes in terms of liquid release rates in a liner may be indicated by determining an equivalent hydraulic conductivity for the facility. This was performed for landfill facilities constructed and operated in accordance with the Guidance Document (EPA, 1982) and summarized in Table 6-1.

The results presented in Table 6-1 indicate synthetic liners with hole areas less than 1 square meter per acre would be expected to leak at similar rates to a well constructed clay liner. This represents a liner with approximately 25 million pinholes per acre, which is unrealistic if proper manufacturing and installation procedures are used. In general, the results indicate that properly installed synthetic liners would be expected to leak at a slower rate than well constructed clay liners for surface impoundments, waste piles and landfill facilities. However, such performance would not comply with the criteria established in the Interim Final Land Disposal Regulations during the facility operating period.

Holes in cover system barriers may be more significant than holes in liners. Although the equivalent hydraulic conductivity for materials containing holes is low, the presence of holes in a cover barrier system represents a potential failure if the liner barrier retains its designed performance. Water, which may infiltrate through holes in the cover barrier, may accumulate above the liner. Such accumulation may lead to unanticipated effects on the liner barrier, resulting in failure. This failure mechanism is discussed in Section 6.3. The probability that this type of failure will occur is low, provided the cover system design accounted for subsidence of the contained waste. Infiltrating water would not be expected to pond on the cover barrier and thus would not be avilable to drain through holes. The

Table 6-1. EQUIVALENT HYDRAULIC CONDUCTIVITY FROM HOLES IN A HAZARDOUS WASTE LANDFILL[a]

| Equivalent Pinholes millions | AREA OF HOLES Hole Area $m^2$ | Facility Area percent | EQUIVALENT FACILITY Hydraulic Conductivity cm/s |
|---|---|---|---|
| 0.25 | .01 | .0002 | $10^{-9}$ |
| 2.5 | .1 | .002 | $10^{-8}$ |
| 25 | 1 | .02 | $10^{-7}$ |
| 250 | 10 | .2 | $10^{-6}$ |
| 2500 | 100 | 2 | $10^{-5}$ |

[a] One acre site (4047 $m^2$) in compliance with Draft RCRA Guidance Document Landfill Design, Liner Systems and Final Cover. U.S Environmental Protection Agency, Washington, D.C.

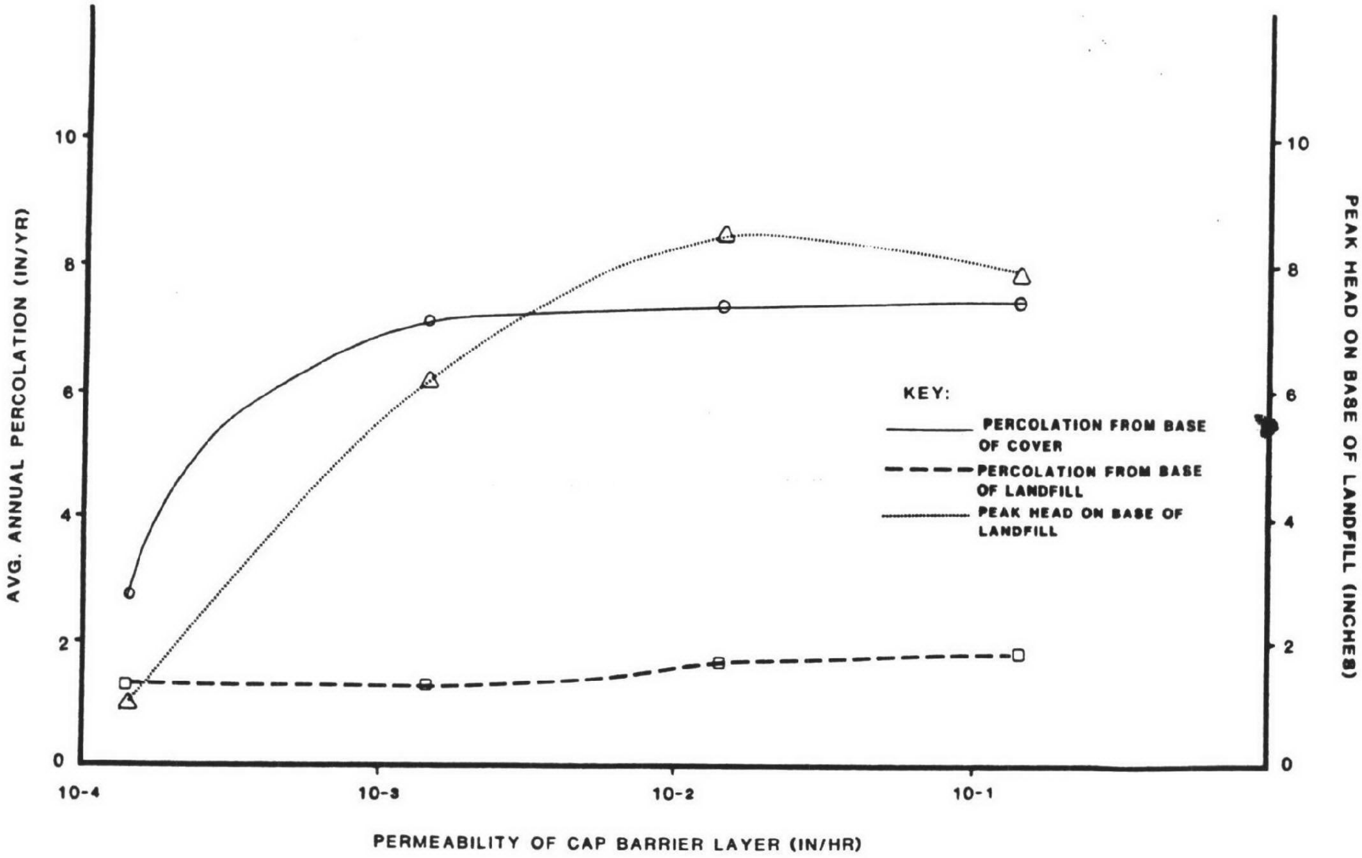
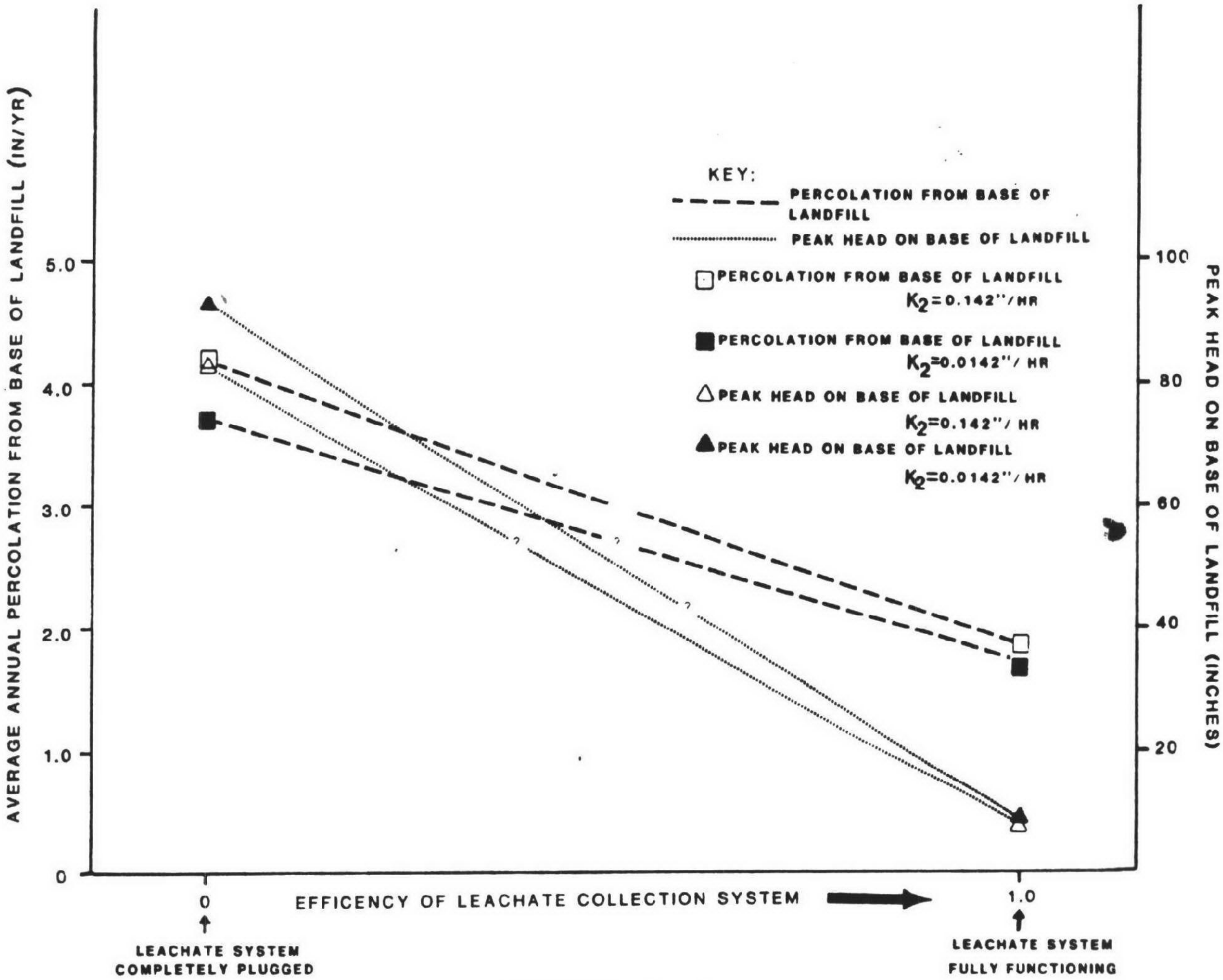



**FIGURE 6-1**

**PERMEABILITY OF CAP BARRIER LAYER VS. PERCOLATION AND HEAD**

NOTE: RESULTS SHOWN ARE BASED ON OUTPUT FROM THE HELP PROGRAM IN WHICH FIVE YEARS OF OPERATION WERE SIMULATED USING CLIMATIC DATA FROM EAST ST. LOUIS, ILLINOIS. THE ASSUMED PERMEABILITY OF THE BARRIER LAYER AT THE BOTTOM OF THE LANDFILL WAS 7.1X10-5 INCHES/HOUR.




## FIGURE 6-2

## LEACHATE SYSTEM EFFICIENCY VS. PERCOLATION AND HEAD

NOTE: RESULTS SHOWN ARE BASED ON OUTPUT FROM THE HELP PROGRAM, IN WHICH FIVE YEARS OF OPERATION WERE SIMULATED USING CLIMATIC DATA FROM EAST ST. LOUIS, ILLINOIS. THE ASSUMED PERMEABILITY OF THE BARRIER LAYER AT THE BOTTOM OF THE LANDFILL WAS 7.1X10-5 INCHES/HOUR . "$K_2$" REFERS TO THE VERTICAL PERMEABILITY OF THE SECOND LAYER (THE CAP BARRIER LAYER).

estimates for liner performance in Table 6-1, therefore, represent an overestimate of the quantity of water which may pass through the cover barrier. It is expected that sound design, and proper barrier construction and installation would avoid failure of a cover system.

### 6.2.3 Summary

Liner holes have been detected in most in-place hazardous waste liners. The holes result from installation problems, mechanical stress, chemical aging and in part from inferior manufacturing processes. Several techniques are available to decrease the number of holes in a liner material, but elimination of all holes is not feasible. A comprehensive quality assurance program should be implemented which covers all aspects of synthetic liner selection, installation and monitoring, including:

- o The liner manufacturing process;
- o Liner foundation preparation;
- o Liner placement and installation;
- o Chemical resistivity testing;
- o Liner seam testing; and,
- o Liner maintenance and inspection.

The quality assurance program will minimize the number of holes in the facility liner, but some holes will remain. The evaluation of hole leakage indicates that the presence of holes does not significantly alter the performance of synthetic liner materials. However, small amounts of leakage will occur. While this does not present a significant problem from a practical perspective, synthetic liners cannot meet the performance objective stated in the Interim Final Land Disposal Regulation. It is recommended that the regulation be modified to allow "de minimus" leakage from a disposal facility during the period of operation of the facility.

## 6.3 BATHTUB EFFECTS

The phenomenon of "bathtub effect" occurs at a landfill when the permeabililty of the cover or cap, or of the upper portion of the waste if exposed, is significantly greater than the permeability of the underlying barrier layer (liner). In a landfill, trenches to accomodate the waste have usually been below land surface. Because of the relatively high permeability of the cap, a significant fraction of rain water infiltrates into the landfill and into the contained waste. The water level in the landfill trench then tends to build up unless an efficient leachate collection system is in operation just above the bottom barrier liner. Thus, a local perched water table can develop at the landfill. In the extreme case, where the underlying materials are of very low permeability and infiltration through the cap (cover) has been relatively rapid, the perched water table can rise to the top of the excavated trenches and even to the surface of the landfill cover over a period of several months or years.

An effect similar to the bathtub effect is seen at landfill or waste-pile facilities in which rainfall infiltration into the waste is significantly greater than the downward movement through the underlying barrier layer, but where no excavation or only minimal excavation below grade has been performed prior to the filling or piling of the waste. We have termed these effects as "tarmac effects", because of the effects of storing or stockpiling material on tarmac aprons. In this case, although there is no "bathtub" to visualize as filling up with rainwater/leachate, the environmental effects are very similar to those resulting from the "bathtub effect". Consequently, we have chosen to discuss in this report these so-called "tarmac effects" along with those that may be considered to be strictly "bathtub effects".

The environmental effects of the "bathtub effect" range from nuisance-level to serious effects, depending on the nature of the waste and the quality of the resulting leachate, and on the proximity of population centers to the landfill. When the perched water level attains a height greater than the top of the filled landfill trench, the leachate will begin to move laterally and is likely to appear as seeps along the lower slopes at the periphery of the landfill. These seeps generally result in overland flow to the nearest stream tributary and consequently result in contamination of stream water. In certain cases, the perched water may rise to such an extent that it begins to pond in depressions in the landfill cover. This produces not only an unsightly appearance but may result in the transfer of hazardous volatiles into the atmosphere by vaporization.

Another possible serious consequence of "bathtub effects" is the lateral sub-surface movement of the leachate into adjacent surficial aquifers of the area. The movement is brought about by the higher head within the landfill. Depending on local sub-surface flow conditions, deeper aquifers may also be contaminated by the leachate that has migrated laterally away from the landfill.

### 6.3.1 Causes of the Bathtub Effect

Bathtub effects or tarmac effects may be considered to be caused by deficiencies in landfill design or by the use of immproper construction or operation procedures. These deficiencies result in the failure of the landfill cap/cover or a failure of the leachate collection system. One would hope that if the cap and the leachate collection system are properly designed and constructed, the likelihood of failure of those two important components during the active life of the facililty and during the post-closure care period would be minimal. Nevertheless, cap or leachate collection system failure can occur during this period even under the best design and construction/operation regimens.

The mechanics of cap/cover failure which serve as indicators of the presence of, and the potential for, bathtub effects are: 1) the presence or development of holes in the cover; 2) subsidence or settlement of the cover; and, 3) weathering and aging of cap liners.

Holes can develop in cap/cover systems in various ways. Pinholes in synthetic liners can originate during material fabrication. However, data appear to indicate that the presence of only a few pinholes would not be a likely cause of cap failure and the onset of bathtub effects. Holes can also result from various storage and installation factors, including: vandalism; exposure to sunlight; failure to sterilize bedding materials; improper use of construction vehicles; improper seaming techniques; and, penetration of the synthetic barrier by coarse-grained materials in the overlying drainage layer. Biological intrusion mechanisms which may cause cap/cover failure include root penetration and small animal burrowing. An indirect method of failure of the synthetic barrier can result from the formation of desiccation cracks in overlying soils. These cracks propagate from the surface down to the synthetic barrier, thus increasing the effects of weathering agents on the synthetic liner.

As discussed herein, cap subsidence refers to localized differential subsidence due to collapse or rapid consolidation of the waste material. This has been referred to as the most prevalent failure mode for caps with synthetic barriers (A.D. Little, 1983); and can result in the formation of depressions and ruptures of the cap/cover system which promote rainwater infiltration into the landfill trench. Cap settlement refers to a more uniform settlement of waste materials but which can also enhance rainwater infiltration.

Weather can have several adverse effects on synthetic liners. Prolonged exposure to sunlight and to ozone can effect the integrity of the membranes. Wide fluctuations in temperature can lead to stress cracking of the membrane resulting from repeated expansion and contraction of the material. Synthetic liner aging considers both the physical aging process as well as polymer degradation. The physical stress required to induce membrane rupture decreases with time. Polymer degradation can result from thermal, mechanically-initiated, chemical, photochemical and biologically-initiated processes which often act together. These processes can effect the tensile strength, tear strength, impact strength and resistance to stress-cracking of the membrane.

The reader is referred to Section 4 for additional discussion of the sources of potential synthetic liner failure and preventative measures that can be imposed. Additional reference should be made to Sections 4 and 5 regarding installation-related issues and subsidence problems, respectively.

Failure of the leachate collection system can result from pipe cracking during installation or during the early stages of landfilling, or by clogging of the system by physical, chemical, biochemical or biological mechanisms. Physical clogging mechanisms are generally failures in design, such as insufficient drain pipe capacity. Chemical and biochemical mechanisms involve pipe incrustation by precipitation of insoluble compounds. Biological clogging occurs by organism reproduction to the point of filling the interstices of the drainage materials.

The lack of a thorough design which provides a sound conceptual structure and detailed provisions for materials trans-port, storage, installation, and operation and maintenance programs probably has the greatest potential for causing bathtub effects. Some common design errors include:

- Failure to establish a performance goal;
- Failure to specify a minimum of three layers in the cap;
- Failure to specify adequate waste compaction procedures;
- Failure to specify, or improperly specified, surface preparation, liner installation and cover maintenance and operation procedures;
- Inadequate design of leachate collection system components in an integrated manner to accomodate the maximum expected leachate volumes;

- o Inadequate, or lack of, monitoring and maintenance plans for leachate collection systems to provide early warning of system failure; and,

- o Failure to specify QA/QC plans.

Improper or careless construction and operating practices can create conditions which result in bathtub effects. Some of these poor practices that can result in damage to the leachate collection system or the liner include:

- o Inadequate compaction of waste material to reduce potential for subsidence or settlement;

- o Failure to provide a suitable-constructed bedding layer (should be smooth, free from sharp objects, and properly sterilized) for the liner;

- o Improper liner storage and handling procedures;

- o Improper seaming practices;

- o Failure to provide interim cover to divert, collect and remove rainwater;

- o Use of heavy equipment during the leachate collection system installation and early stages of landfilling; and,

- o Failure to implement effective construction/operation QA/QC plans.

A more complete assessment of design installation considerations are provided in Sections 4 and 5 of this report, and <u>Report on Bathtub Effects in Hazardous Waste Facility Operation</u> (Ertec, 1983).

### 6.3.2 Remedial Measures for Bathtub Effects

A number of corrective measures have either been instituted in the field or recommended to bring under control rising perched water levels in landfills. In many instances, a combination of two or three of the following remedial measures has proven to be most effective.

#### 6.3.2.1 Pumping and Treatment of Leachate

Where a leachate-collection system exists, it may be possible to accelerate flow and lower water levels in the trench by simply pumping from sumps in the system on a nearly continuous basis. The leachate is then treated at a treatment unit on site, or pumped into tank trucks for transportation to suitably licensed treatment facilities.

#### 6.3.2.2 Cap Reconstruction

Once a bathtub or tarmac effect is identified, there is probably no more important remedial measure than that involving sealing the cover so that subsequent infiltration of rainwater into the waste will be negligible, or at least extremely small. Generally, this remedial measure is combined with some sort of drainage system designed to remove the existing accumulated leachate.

#### 6.3.2.3 Surface-Water/Ground-Water Diversion

The diversion of surface-water runoff from a landfill cover is perhaps one of the first, and least expensive, remedial actions to be performed at a site experiencing bathtub/tarmac effects. In most cases, infiltrating rainfall or runoff waters generate much more leachate than do surficial ground waters. In the process of regrading the site and cap reconstruction, surface-water runoff diversion is also usually provided for.

In some situations, ground-water flow toward a landfill may constitute a significant component of leachate generation. In such cases, the construction of a ground-water interceptor trench, or cutoff wall, on the upgradient side of the landfill may be the most efficient way to prevent ground water from reaching the waste.

6.3.2.4 Treatment of the Leachate Collection System

Treatment of leachate collection systems can often increase the effectiveness and longevity of these systems, provided that the problem is identified early. Thus, monitoring is an essential component in the maintenance of leachate-collection systems.

Methods of treatment of leachate-collection systems include (Bass, et al, 1982):

- o Excavation and replacement: generally expensive, difficult and dangerous to implement
- o Physical methods: use of mechanical devices and hydraulic cleaning
- o Chemical methods: generally involves the use of acids

6.3.3 Sensitivity Analysis for Bathtub Effect

A set of sensitivity runs were performed by Ertec Atlantic, Inc., in Report on Bathtub Effects in Hazardous Waste Facility Operation (1983) using program HELP and climatological data for East St. Louis, Illinois, to illustrate the relative importance of different factors in inducing bathtub effects. A summary of the results of the runs is provided in Table 6.2. The factors that were varied included: (1) vertical permeability of the cap barrier layer; (2) evaporative zone depth; (3) the porosity and field capacity of the waste layer; and, (4) the presence or absence of a leachate collection system. Of these, the two most critical factors contributing to a rise in the head on the base of the landfill were the vertical permeability of the cap barrier layer (refer to the curves of Figure 6-1) and the presence or absence of a leachate collection system (see Figure 6-2). The most dramatic change in the head (or water level) measured from the base of the landfill was effected by the presence or absence of a functioning leachate collection system. As the permeability of the cap barrier layer increases from $10^{-4}$ to $10^{-2}$ inches/hour, the peak head on the base of the landfill, for this case, gradually rises from less than 1 inch to more than 8 inches. In this case, increasing the permeability of the layer beyond $10^{-2}$ inches/hour had no effect in increasing the head on the base of the landfill.

Table 6-2 shows that decreasing the evaporative zone depth from 8 inches to 6 and thence to 4 inches results in no significant change in the peak head on the base of the landfill, as long as the leachate collection system is operating efficiently. The resulting increase in the average annual percolation from the base of the cover is completely accommodated, in this case, by lateral drainage from the base of the landfill (via the leachate collection system). Increasing the porosity of the waste material from 0.52 to 0.60 and then to 0.70, with corres-ponding proportional increases in field capacity, resulted in slight decreases in the peak head on the base of the landfill, as is shown in Table 6-2. In general, however, a relatively

TABLE 6-2

SUMMARY OF SENSITIVITY RUNS ON PROGRAM HELP
FOR ANALYSIS OF BATHTUB EFFECTS

RESULTS OF 5-YEAR SIMULATION, 1974-1978
USING E. ST. LOUIS CLIMATOLOGICAL DATA

| Run | $K_2$ (in/hr) | E.Z.D. (inches) | L.C.S.? | $POR_3/FC_3$ | Avg. Annual Percolation from Base of Cover (in/yr) | Avg. Annual Drainage from Base of Landfill (in/yr) | Avg. Annual Percolation from Base of Landfill (in/yr) | Peak Head from Base of Landfill (inches) |
|---|---|---|---|---|---|---|---|---|
| 1a | 0.000142 | 10 | yes | 0.52/0.32 | 2.51 | 1.21 | 1.27 | 1.1 |
| 1 | 0.000142 | 8 | yes | 0.52/0.32 | 2.71 | 1.35 | 1.33 | 1.0 |
| 2 | 0.00142 | 8 | yes | 0.52/0.32 | 7.10 | 5.53 | 1.36 | 6.2 |
| 3 | 0.0142 | 8 | yes | 0.52/0.32 | 7.36 | 5.54 | 1.70 | 8.5 |
| 4 | 0.142 | 8 | yes | 0.52/0.32 | 7.42 | 5.45 | 1.86 | 7.9 |
| 5 | 0.0142 | 8 | yes | 0.60/0.38 | 7.36 | 5.51 | 1.73 | 8.3 |
| 6 | 0.0142 | 8 | yes | 0.70/0.46 | 7.36 | 5.48 | 1.75 | 8.2 |
| 7 | 0.0142 | 6 | yes | 0.52/0.32 | 8.99 | 6.91 | 1.94 | 8.4 |
| 8 | 0.0142 | 4 | yes | 0.52/0.32 | 11.41 | 9.26 | 1.98 | 8.4 |
| 9 | 0.0142 | 8 | no | 0.52/0.32 | 7.36 | 0 | 3.73 | 93.4 |
| 10 | 0.142 | 8 | no | 0.52/0.32 | 7.42 | 0 | 4.20 | 83.4 |

$K_2$ = vertical permeability of the cap barrier soil layer

E.Z.D. = evaporative zone depth

L.C.S.? = leachate collection system operative?

$POR_3$ = porosity of the 3rd (waste) layer

$FC_3$ = field capacity of the 3rd (waste) layer low porosity for the waste material is desired, and is produced in the field by regular and frequent passes of heavy equipment to effect compaction of the waste. This helps to minimize the occurrence of localized subsidence later in the life of the landfill.

Comparison of the peak heads in Table 6-2 for Runs 3 and 4 as well as for Runs 9 and 10, shows that in both pairs of cases increasing the permeability of the cap barrier layer from 0.0142 to 0.142 inches/hour actually results in a lower (7 to 12 percent) peak head on the base of the landfill. The reason for this is unclear, but it is believed to be a function of the HELP program's convergence routine, and does not reflect the real world conditions.

Climatic factors also play a role in the development of bathtub or tarmac effects. Other things being equal, areas with high rainfall and low potential evapotranspiration will develop bathtub effects more quickly than areas with lower rainfall and higher potential evapotranspiration. Once an "overflowing" condition is established, the rate of flow from seeps and outward sub-surface flow will tend to be higher in more humid areas. Moreover, the "activity" of seeps will tend to follow the incidence of rainy days and rainy seasons. In areas having very low annual rainfall and high evaporative potential, bathtub or tarmac effects may not develop during the operational and post-closure care periods, even in cases where the permeability of the cover material is several orders of magnitude greater than that of the bottom barrier layer.

### 6.3.4 Summary and Conclusions

Bathtub or tarmac effects generally develop when rain and runoff water percolate into a waste facility at a rate greater than the leachate moves below the bottom of the facility. The cause of these effects has usually lain in the absence of sound design installation and/or maintenance procedures. The single most important design deficiency has been the lack of an effective cap that incorporates a low-permeability barrier layer, a drainage layer and a vegetative cover. A proper cover design should also include appropriate surface runoff diversions as well as erosion-control measures. The absence of a functioning leach-ate-collection system has also contributed to the development of bathtub/tarmac effects in many cases. Maintenance of such collec-tion systems requires the operation of a regular trench-water monitoring system. When monitoring indicates small but significant rises in the trench water levels, implying potential clogging of the system, appropriate drain-cleaning remedies can be undertaken. The basic remedy for the bathtub/tarmac effect generally involves: (1) collection and treatment of the existing leachate from the waste facility; and, (2) the simultaneous regrading and reconstruction of the cap so that infiltration of rain and runoff water can be kept to a bare minimum.

# REFERENCES


Haxo, H.E., Jr. 1983. (See References, Section 3)

Lutton, R.J. 1982. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867 (Revised Edition). U.S. Environmental Protection Agency, Washington, D.C.

Lyman, W.J. 1983. Expected Life of Synthetic Liners and Caps (Draft Final Report). U.S. Environmental Protection Agency, Washington, D.C.

EPA, 1982. Draft RCRA Guidance Document: Landfill Design, Liner Systems and Final Cover. U.S. Environmental Protection Agency, Washington, D.C.

## 7.0 PERFORMANCE MODELING OF SYNTHETIC LINER SYSTEMS

The development of the HELP model and the basic research and analyses involved in model verification, sensitivity analyses and production runs for selected waste-facility design scenarios were conducted directly by the EPA Office of Research and Development in Cincinnati, Ohio, with the participation of the U.S. Army Engineer Waterways Experiment Station at Vicksburg, Mississippi. A detailed summary of the supporting technical documentation was provided to the EPA by Ertec in memorandum form in May, 1983 (Ertec Atlantic, Inc., 1983b). This section provides a summary of the results of this research and modeling task.

### 7.1 METHODS OF INVESTIGATION

The purpose of modeling the performance of caps and liners was to compare the release rates for a range of waste-facility designs under different climatic conditions. By comparing the computed order-of-magnitude seepage rates through the bottom liner of waste facilities with differing design characteristics, it was hoped that it would be possible to compare the effectiveness of each type of design in containing the waste. For example, one of the primary purposes of the simulations with the HELP model was to compare the theoretical short- and long-term impacts of waste facilities with clay liners and with synthetic flexible membrane liners (FMLs) on the uppermost ground water. The HELP model in its present form was not designed to produce highly accurate predictions of seepage for individual cases. It is felt, however, that it provides a reliable basis for assessing order-of-magnitude seepage rates, so that valid comparisons of the effectiveness of different design cases can be made. The conclusions from such comparisons would, it was hoped, be useful with respect to reform of the Interim Final Part 264 RCRA regulations.

Another purpose of the HELP simulations herein summarized, was to provide release rates, as "source terms," for generic fate and transport modeling of leachate migration in ground water. This fate and transport modeling was part of the locational study, which constituted another major task under EPA's current land-disposal study to assess the role of caps/liners and locational factors in mitigating or promoting ground-water contamination under different hydrologic and climatological conditions.

Design/operation scenarios were developed for four facility types: landfills; disposal surface impoundments; storage surface impoundments; and waste piles. These were evaluated for three varying climatic conditions represented by data compiled for a 20-year period for: New Orleans, Louisiana; Hartford, Connecticut; and Denver, Colorado. The design of the systems and values for materials were selected to be representative of current technology. Operating conditions were determined based on review of data from the U.S. EPA Office of Solid Waste (OSW) site visits, review of new facility permit applications and professional experience.

In most cases, seepage rates through the bottom liner were calculated with the use of the Hydrologic Evaluation of Landfill Performance (HELP) model. The exception is for surface impoundment facilities during the operating period, which were analyzed using Darcy's Equation, constant head assumptions, and steady-state drainage calculations. The HELP model is an improved extended version of the Hydrologic Simulation model developed for the EPA by the U.S. Army Engineers Waterways Experiment Station for estimating percolation into the waste layer of Solid Waste Disposal Sites (HSSWDS). HELP is a quasi-two-dimensional, deterministic model that computes the daily water budget for a landfill design considering vertical percolation through successive horizontal layers and lateral drainage in the coarse granular layers overlying the barrier layers. The model was applied to each design facility component (e.g., cell) to develop the mean monthly seepage and lateral drainage values for that component. A 20-year daily precipitation record was used to develop the mean monthly release rate for each climate. Thus, the comparison of the facility-design scenarios is based on expected monthly values rather than on time-series release rates with hydrologically-related fluctuations. Once the HELP model was applied to determine the mean monthly release rates for each operating condition (i.e., operation, post-closure care, post-care), a computer program called POSTHELP was used to combine the release rates of all the cells into the overall facility release rate.

A detailed discussion of the development history of the HELP model is beyond the scope of this report. Interested readers are directed to the HELP model user guide and the documentation which are included in the appendix to the Ertec memorandum previously referenced. Similarly, the results of verification of the HELP model using another more sophisticated model will not be presented. For further details, the reader is referred to a report on the University of North Carolina's DRAINFIL model (Skaggs, 1982) and to a report on the HELP sensitivity study included with the appendix to the referenced Ertec memorandum.

inches/year for the 20-year period used. Denver represents a dry climate where designed drainage features may not result in a dramatically reduced leachate generation.

Data representing the distribution of twenty monthly release rates for a given month (one for each of the 20 years simulated) from the HELP model runs could usually be fit (within 95% Kolmogorov-Smimov confidence intervals) with a normal distribution with coefficients of variation (i.e., standard deviation divided by the mean) of less than 0.5. Thus, individual monthly values will be variable but not highly variable. For example, at least 95% of the release rates for a given month would be less than twice the mean release rate for the month, if the coefficient of variation is 0.5. Comparison of different climatic conditions, designs and waste-level controls was performed in this analysis by comparing the mean monthly rates of seepage below the bottom of the facility, as computed by HELP. Hence, it is important to note that extreme hydrologic conditions, both wet and dry, were not addressed by this analysis of facility designs. The effects of extreme droughts that could severely damage the vegetative cover and cause desiccation and cracking of soil layers were not considered, nor were the effects of heavy storms or floods that could severely erode the cover, damage berms and increase seepage rates.

### 7.2.3 Design Scenarios

The design of the systems and specification of values for material properties were selected to be representative of current technology. Specifically, the design of the systems was based on the following: 1) current

Part 264 regulatory requirements along with suggested guidance; 2) new facilities applications under part 264; 3) public comments on Part 264 (July 1982); and 4) existing Interim Status Standard (ISS) facilities. The values for material properties were selected from studies and published data. Specifically, the values for the expected life of synthetic liners was derived from review of Analysis of Flexible Membrane Liner Chemical Compatibility Tests (A.D. Little, 1983) and Expected Life of Synthetic Liners and Caps (A.D. Little, 1983). In-place permeability of the clay materials was derived from review of Performance of Clay Caps and Liners for Disposal Facilities (Research Triangle Institute, March 1983) and Assessment of Technology for Constructing and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities (TRW, February 1983).

A summary of the design scenarios developed for the landfill, disposal surface-impoundment, storage surface impoundment and waste pile facilities are shown in Tables 7.2-1 through 7.2-4, respectively. The designs are expressed in terms of level of waste control, as characterized by the following parameters:

- Final cover design
- Permeability of the clay barrier layers in the cap and bottom liner
- Presence and design of a leachate collection system
- Presence and design of a leak detection system
- Liner design

TABLE 7.2-1

LANDFILL DESIGN SCENARIOS

| PARAMETER | LEVEL OF WASTE CONTROL | | |
|---|---|---|---|
| | I | II | VI |
| Final Cover Design [1] | 24" vegetated layer<br>12" drain layer<br>20 mil FML [2]<br>2 ft. of clay | 24" vegetated layer<br>12" drain layer<br>20 mil FML<br>2 ft. of clay | 24" soil layer |
| Permeability of Clay [3] (cm/sec) | $1 \times 10^{-7}$ | $1 \times 10^{-7}$ | $1 \times 10^{-4}$ |
| Leachate Collection System | present [4] | present [4] | not present |
| Leak Detection System | present [5] | present [5] | not present |
| Liner Design | double liner<br>30 mil FML | A) double liner<br>30 mil FML<br>2 ft. of clay | none |

TABLE 7.2-1, continued

NOTES: (1) Final cover design includes a final grade of 3-5%; the hydraulic conductivity of the drain layer equals that of the drain layer in the leachate collection system.

(2) FML = Flexible Membrane Liner.

(3) Refers to the permeability of the clay used in both the final cover and liner designs.

(4) Minimum design criteria are at least 12-inch thick drainage layer with hydraulic conductivity $10^{-2}$ cm/sec. Minimum slope of drainage layer 2 percent. A drainage tile system designed to collect and remove the expected quantity of leachate that will be produced with 50-foot spacing.

(5) Minimum design criteria are at least 12-inch thick drainage layer with hydraulic conductivity $10^{-3}$ cm/sec. Minimum slope of drainage layer 2 percent. A drainage tile system designed to collect and remove the expected quantity of leachate that will be produced with 50-foot spacing.

TABLE 7.2-2

DISPOSAL SURFACE IMPOUNDMENT DESIGN SCENARIOS

| PARAMETER | LEVEL OF WASTE CONTROL I | LEVEL OF WASTE CONTROL II |
|---|---|---|
| Final Cover Design (1) | 24" vegetated layer<br>12" drain layer<br>20 mil FML (2)<br>2 ft. of clay | 24" vegetated layer<br>12" drain layer<br>20 mil FML<br>2 ft. of clay |
| Permeability of Clay (3) (cm/sec) | $1 \times 10^{-7}$ | $1 \times 10^{-7}$ |
| Leachate Collection System | not present | not present |
| Leak Detection System | present (4) | present (4) |
| Liner Design | double liner<br>30 mil FML | A) double liner<br>30 mil FML<br>2 ft. of clay |

TABLE 7.2-2, continued

NOTES: (1) Final cover design includes a final grade of 3-5%; hydraulic conductivity of drain layer is $10^{-2}$ cm/sec.

(2) FML = Flexible Membrane Liner.

(3) Refers to the permeability of the clay used in both the final cover and liner designs.

(4) Minimum design criteria are at least 12-inch thick drainage layer with hydraulic conductivity $10^{-3}$ cm/sec. Minimum slope of drainage layer 2 percent. A drainage tile system designed to collect and remove the expected quantity of leachate that will be produced with 50-foot spacing.

## TABLE 7.2-3

## STORAGE SURFACE IMPOUNDMENT DESIGN SCENARIOS

| PARAMETER | LEVEL OF WASTE CONTROL I |
|---|---|
| Final Cover Design | 24" vegetated layer |
| Permeability of Clay (cm/sec) | not applicable |
| Leachate Collection System | not present |
| Leak Detection System | not present |
| Liner Design | single liner 30 mil FML[1] |

NOTES: [1] FML = Flexible Membrane Liner.

TABLE 7.2-4

WASTE PILE DESIGN SCENARIOS

| PARAMETER | LEVEL OF WASTE CONTROL<br>I |
|---|---|
| Final Cover Design[1] | 24" vegetated layer<br>12" drain layer<br>20 mil FML[2]<br>2 ft. of clay |
| Permeability of Clay[3] (cm/sec) | $1 \times 10^{-7}$ |
| Leachate Collection System | present[4] |
| Leak Detection System | not present |
| Liner Design | single liner<br>30 mil FML |

NOTES: (1) Final cover design includes a final grade of 3-5%; the hydraulic conductivity of the drain layer equals that of the drain layer in the leachate collection system.

(2) FML = Flexible Membrane Liner.

(3) Refers to the permeability of the clay used in both the final cover and liner designs.

(4) Minimum design criteria are at least 12-inch thick drainage layer with hydraulic conductivity $10^{-2}$ cm/sec. Minimum slope of drainage layer 2 percent. A drainage tile system designed to collect and remove the expected quantity of leachate that will be produced with 50-foot spacing.

The applicability of these parameters varies by facility type and level of waste control. Refer to the above referenced tables for specifications.

The selected designs range in level of waste control from double- and single-lined systems which meet current regulatory requirements and conform with suggested guidance documents, to systems which are either partially or totally in non-compliance with said requirements and good practice. This range in design was set by EPA to establish a suitably extensive data base for comparative purposes.

Schematic cross sections indicating design features have been prepared for each of the four facility types based upon the most conservative design scenario for a given facility (that is, the design effecting the highest level of waste control). Figures 7.2-1 through 7.2-4 show these cross sections for landfills, disposal surface impoundment, storage surface impoundment and waste piles, respectively. These figures are intended to facilitate interpretation of the design parameters in a generic sense. Extrapolation is required to interpret design specifications for the less conservative levels of waste control scenarios. Also, a typical landfill facility profile illustrating the modeled liquid routing system is shown in Figure 7.2-5.

### 7.2.4 Operating Conditions

Operating data for the modeling were selected by the EPA based on site visits, review of new facility permit applications and professional

# TYPICAL CROSS-SECTION FOR LANDFILL DESIGN LF I

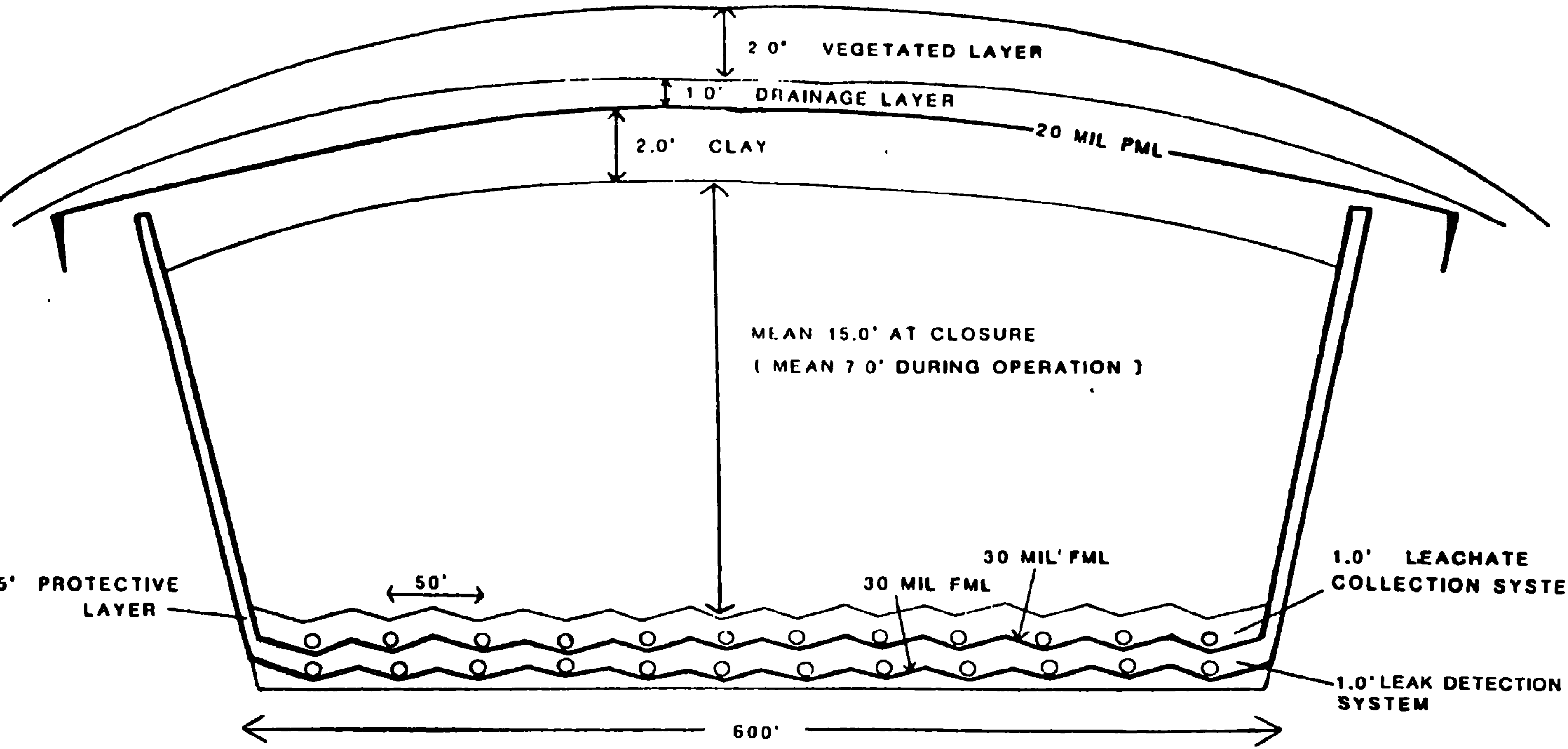





FIGURE 7.2-1

# TYPICAL CROSS-SECTION FOR SURFACE IMPOUNDMENT - DISPOSAL DESIGN SD I

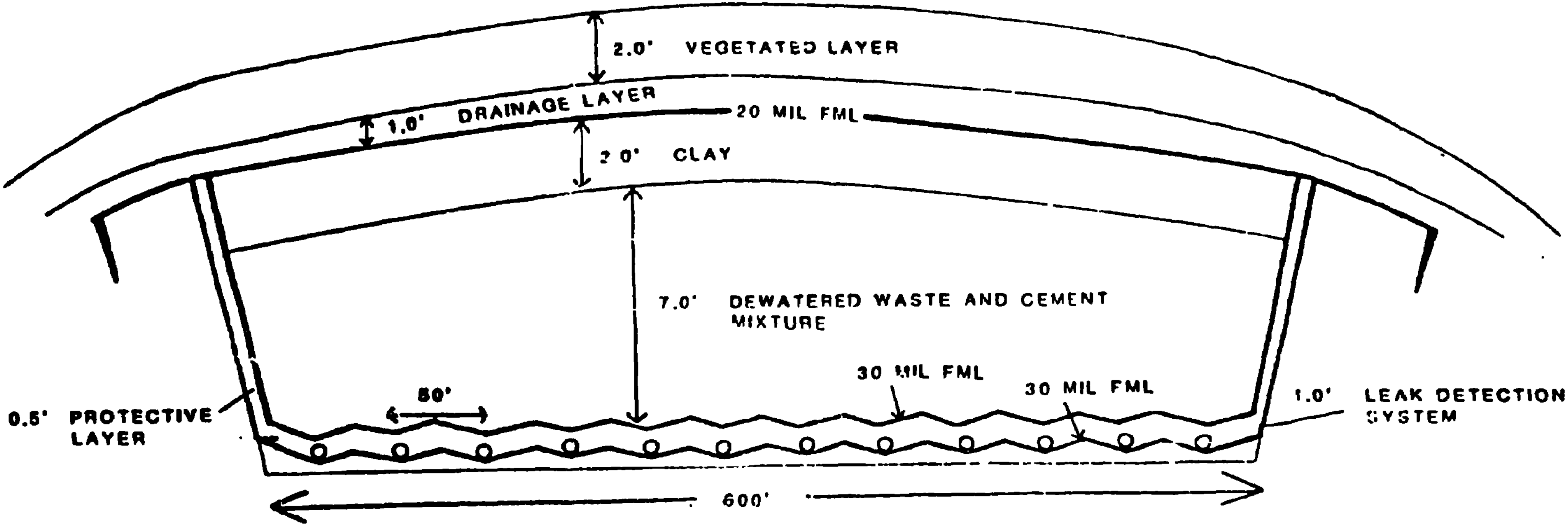
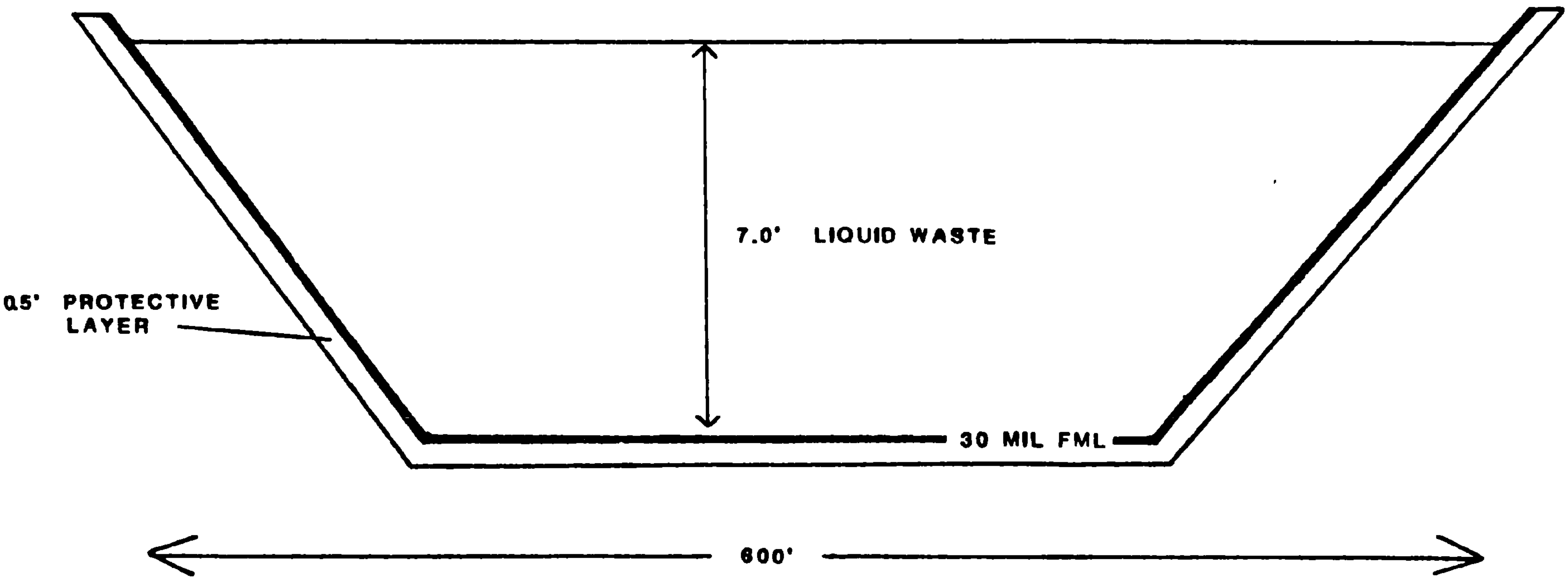



FIGURE 7.2-2

# TYPICAL CROSS-SECTION FOR SURFACE IMPOUNDMENT - STORAGE DESIGN SS I




NOTE: AT CLOSURE THE WASTE AND BOTTOM LINER AND ANY CONTAMINATED SUBSOIL ARE REMOVED FROM THE SITE AND DISPOSED OF AT APPROPRIATE FACILITY. THE SITE IS RECLAIMED TO CONFORM TO ORIGINAL CONTOUR PER ACCEPTED PRACTICES.

FIGURE 7.2-3

## TYPICAL CROSS SECTION FOR WASTE PILE DESIGN WP II

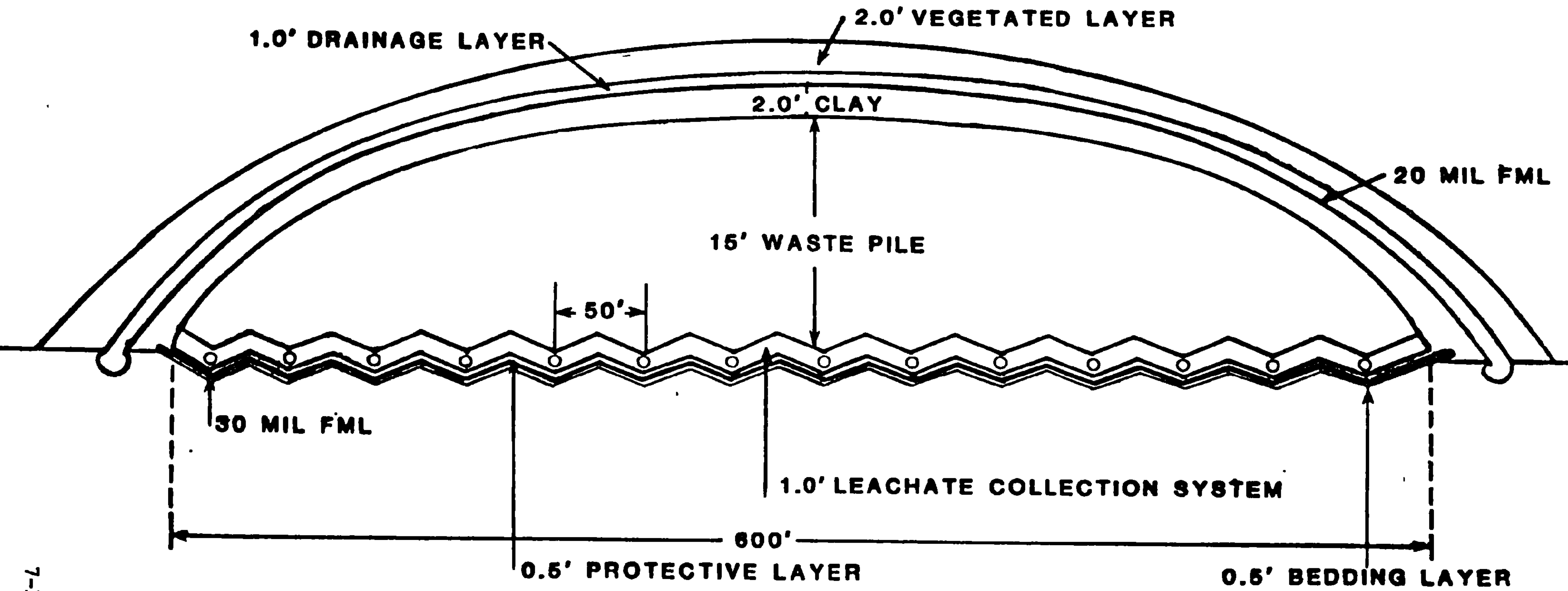
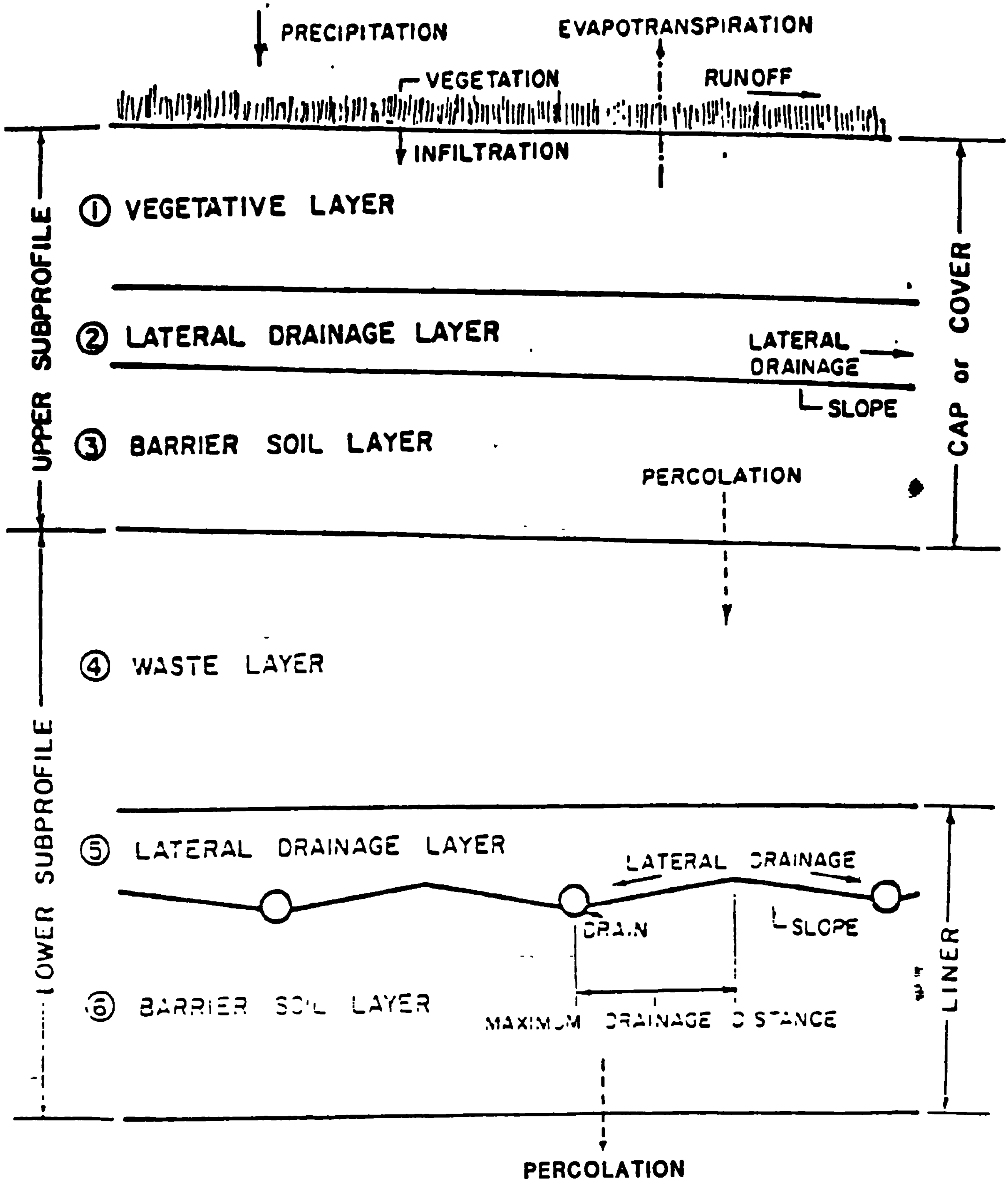



FIGURE 7.2-4




SOURCE : EPA

**FIGURE 7.2-5**

TITLE : TYPICAL LANDFILL LIQUID ROUTING PROFILE experience. To an extent, operating conditions were standardized among facility types. Each facility or unit is comprised of five components (e.g., five cells in the case of landfills). Each component is 350 feet wide by 600 feet in length and has an effective area of about 4.8 acres.

The unit operating period for the landfill, and the storage and disposal surface impoundments is twenty years. In the case of the waste pile the unit operating period is thirty years. Final closure of each unit occurs at the end of each unit operating period. With the exception of the storage surface impoundment, from which the wastes are removed at closure, the post-closure care period is for thirty years after closure.

It should be noted that the presence of a leak detection system is not only for monitoring purposes, but also serves to collect and remove leachate. Unless otherwise noted, the operation of the leak detection and leachate collection systems are assumed to cease at the end of the post-closure care period. This is not meant to imply systems failure, but rather, the termination of pumping activities to remove collected volumes. Thus, an increase in head within these systems will result.

A discussion of facility-specific operating conditions is given in the following paragraphs. A comprehensive summary of operating conditions for each facility type is provided in Table 7.2-5.

## TABLE 7.2-5

## SUMMARY OF OPERATING CONDITIONS

**LANDFILL**

Cell Area - 4.8 acres
Cell Dimensions - 350 ft. X 600 ft.
Number of Cells - 5
Unit Operating Period - 20 years
Cell Operating Period - 4 years
Subcell Operating Period - 1 year with 3-month overlap on next subcell
Condition of Waste - moisture content at field capacity
Closure - All cells closed after 20 years
Post-Closure Care Period - Runs for 30 years after closure
Leachate Collection System - stops operating 30 years after unit is closed*
Leak Detection System - stops operating 30 years after unit is closed*

**SURFACE IMPOUNDMENT - DISPOSAL**

Surface Impoundment Area - 4.8 acres
Surface Impoundment Dimensions - 350 ft. X 600 ft.
Number of Surface Impoundments - 5
Average Depth of Liquid - 7 ft. during operating period
Unit Operating Period - 20 years
Closure - all impoundments closed after 20 years

- waste dewatered using cement-based process
- stabilized waste has minimum strength to support final cover system
- stabilized waste has moisture content at field capacity

Post-Closure Care Period - Runs for 30 years after closure
Leak Detection System - stops operating 30 years after unit is closed

**SURFACE IMPOUNDMENT - STORAGE**

Surface Impoundment Area - 4.8 acres
Surface Impoundment Dimensions - 350 ft. X 600 ft.
Number of Surface Impoundments - 5
Average Depth of Liquid - 7 ft. during operating period
Unit Operating Period - 20 years
Closure - all waste removed

**WASTE PILE**

Waste Pile Area - 4.8 acres
Waste Pile Dimensions - 350 ft. X 600 ft.
Number of Waste Piles - 5
Height of Waste Piles - 15 ft.
Unit Operating Period - 30 years
Closure - all waste piles closed as landfills
Post-Closure Care Period - runs for 30 years after closure
Leachate Collection System - stops operating 30 years after unit is closed

---

* As discussed in Section 7.3.3.1, under certain design cases the leachate collection and the leak detection systems were assumed to operate throughout the modeled period.

7.2.4.1 Landfills

As noted, the landfill facility is comprised of five (5) components (i.e., cells). Each cell is in turn composed of five sub-cells. Each sub-cell has an operating period of one year, three months of which overlap onto the next sub-cell. This equates to a four-year operating period for each cell and, hence, a total of twenty years for the entire unit. Placement of a final cover on each sub-cell occurs at the end of the sub-cell operating period (i.e., one year). The placement of the cover is assumed to occur immediately upon reaching that milestone date. Thus, after the first year of operation and until the end of the twenty-year unit operating period, the facility is in a partial closure mode. At any given point in time during this period the maximum area lacking a cover system is equivalent to about one and one-quarter sub-cells. Final closure of the facility occurs at the end of the last sub-cell operating period, that is, at the end of year twenty.

The post-closure care period runs for thirty years from the date of closure of each cell. Finally, it is assumed that for the entire duration of the model run the moisture content of the waste is at field capacity.

7.2.4.2 Disposal Surface Impoundments

Operation of the disposal surface impoundment facility begins on day one and runs continuously at full capacity through the end of year twenty at which time closure occurs. It is assumed that in all five lagoons, a constant depth of seven feet of liquid is maintained throughout the operating period. At closure, no lag time is assumed between the end of operation and the start of post-closure care. Also at closure, all five lagoons are dewatered by means of a cement-based mixing process and a final cover is emplaced. The stabilized waste has the minimum strength to support the cover system, and the moisture content of the waste is assumed to be at field capacity. The thirty-year post-closure care period runs through the end of year fifty. Where present, the leak detection system is assumed to stop operating at the end of the post-closure care period.

#### 7.2.4.3 Storage Surface Impoundments

During the unit operating period, conditions are identical to those described above for the disposal surface impoundment facility. However, at closure all of the waste is removed from the unit. As above, closure occurs instantaneously at the end of the twenty year operating period.

#### 7.2.4.4 Waste Piles

The waste-pile facility operates for thirty years, in contrast to the twenty-year operating period for the other three facility types. The facility runs at full capacity throughout the operating period, that is, each of the five 4.8-acre waste pile components maintains a constant pile height of fifteen feet throughout the operating period. At closure, the wastes cannot be removed and the facility is immediately closed as a landfill, including placement of a final cover system. The thirty-year post-closure care period runs through the end of year sixty at which time it is assumed that the leachate collection system stops operating. As before, the moisture content of the waste is at field capacity.

Some of the cap/liner designs for the different facility types (as discussed in Section 7.2.3) make use of a double barrier consisting of a flexible membrane liner (FML) underlain by clay. The permeabilities of the clays used in the barrier system are given (see Tables 7.2-1 through 7.2-4) and are assumed to remain constant throughout the modeling period. The seepage rate through the FML is a function of the mode of FML failure. The following failure modes were evaluated.

### FML Failure Modes for Landfills

1. No change in liner for 25 years after installation, then catastrophic failure
2. No change in liner for 25 years after installation, then 0 to 100% failure over next 25 years in a step function
3. No change in liner for 50 years after installation, then catastrophic failure
4. No change in liner for 50 years after installation, then 0 to 100% failure over next 50 years in a step function
5. No change in liner for 150 years after installation, then catastrophic failure
6. Fixed seepage due to installation/operational problems; 1% of the liner area has the same vertical permeability as the underlying bedding layer.
7. Fixed seepage due to installation/operational problems; 0.1% of the liner area has the same vertical permeability as the underlying bedding layer.

### FML Failure Modes for Surface Impoundments and Waste Piles

1. No change in liner for 25 years after the start of operation, then catastrophic failure.
2. No change in liner for 25 years after the start of operation, then 0 to 100% failure over the next 25 years in a step function.
3. No change in liner for 50 years after the start of operation, then catastrophic failure.

4. No change in liner for 50 years after the start of operation, then 0 to 100% failure over the next 50 years in a step function.

5. No change in liner for 150 years after the start of operation, then catastrophic failure.

6. Fixed seepage due to installation/operational problems; 1% of the liner area has the same vertical permeability as the underlying bedding layer.

7. Fixed seepage due to installation/operational problems; 0.1% of the liner area has the same vertical permeability as the underlying bedding layer.

An additional FML failure mode was assumed for the disposal surface impoundment; FML failure mode "0" assumes complete FML failure throughout the operating period. Thereafter it is assumed to exhibit the same response as FML failure mode 1.

The ranges in FML failure mode assumptions were based on currently available FML lifetime data as presented in Expected Life of Synthetic Liners and Caps (A.D. Little, 1983).

Additional HELP model input values used in the facility design analysis are presented in Tables 7.2-6 and 7.2-7.

### 7.2.5 Scenario Identification System

A coded system was developed by the EPA to identify each of the facility scenarios modeled. The codes are a function of facility type and level of waste control. For consistency, this approach was also used to reference scenarios for the clay cap/liner designs, addressed in Interim

Report I, and with some modification, for the subsequent ground-water fate and transport analysis.

The following format is used:

- The first two characters (i.e., letters) refer to the type of facility as follows:

  LF = Landfill
  SD = Surface Impoundment-Disposal
  SS = Surface Impoundment-Storage
  WP = Waste Pile

- The following one or two characters (i.e., Roman numerals) refer to the level of waste control (refer to Tables 7.2-1 through 7.2-4).

- If a letter (e.g., A or B) is present after the Roman numeral, this refers to one of the multiple cases of liner design given in Tables 7.2-1 through 7.2-4.

- If an Arabic number is present at the end of the code, this refers to the FML failure mode (i.e., 1 through 7) as listed in Section 7.2.4. Obviously, this applies only to those scenarios which employ an FML in addition to the clay layer in the final cover design.

For example, Code LFIIA identifies a landfill with level of waste control IIA as described in Table 7.2-1. Addition of the number "1" to the end of the code (i.e., LFIIA1) refers to the FML failure mode. Reference to the Operating Conditions (Section 7.2.4) describes failure mode 1 as "no change in liner for 25 years after installation then catastrophic failure."

## 7.3 RESULTS OF HELP SIMULATIONS

### 7.3.1 General

The following discussions summarize the results of the HELP simulations with respect to climate and facility type considerations. General trends of the seepage profiles and comparison with respect to design factors are addressed. It should be noted that the term "final mean seepage rate" refers to the average rate of seepage through the bottom barrier layer predicted to occur after the end of the post-closure care period.

### 7.3.2 Climatic Effects

In general, the three climatic conditions do not alter the trend of the facility release profiles but rather the magnitude of the seepage rates. This holds true for all of the facility types and operational conditions with the exception of surface impoundments during the operating period. For the latter cases, the climate has no effect on either the trend or the magnitude of the seepage rates. The reason for this is the assumption that the liquid level remains constant at seven feet during the operating period and, therefore, the driving force of seepage production is independent of rainfall quantities. After closure, the climate effects the magnitude of seepage production without altering the trend of the release profile.

In light of the above, discussion herein shall focus on the landfill facility design cases to exemplify general climatic trends.

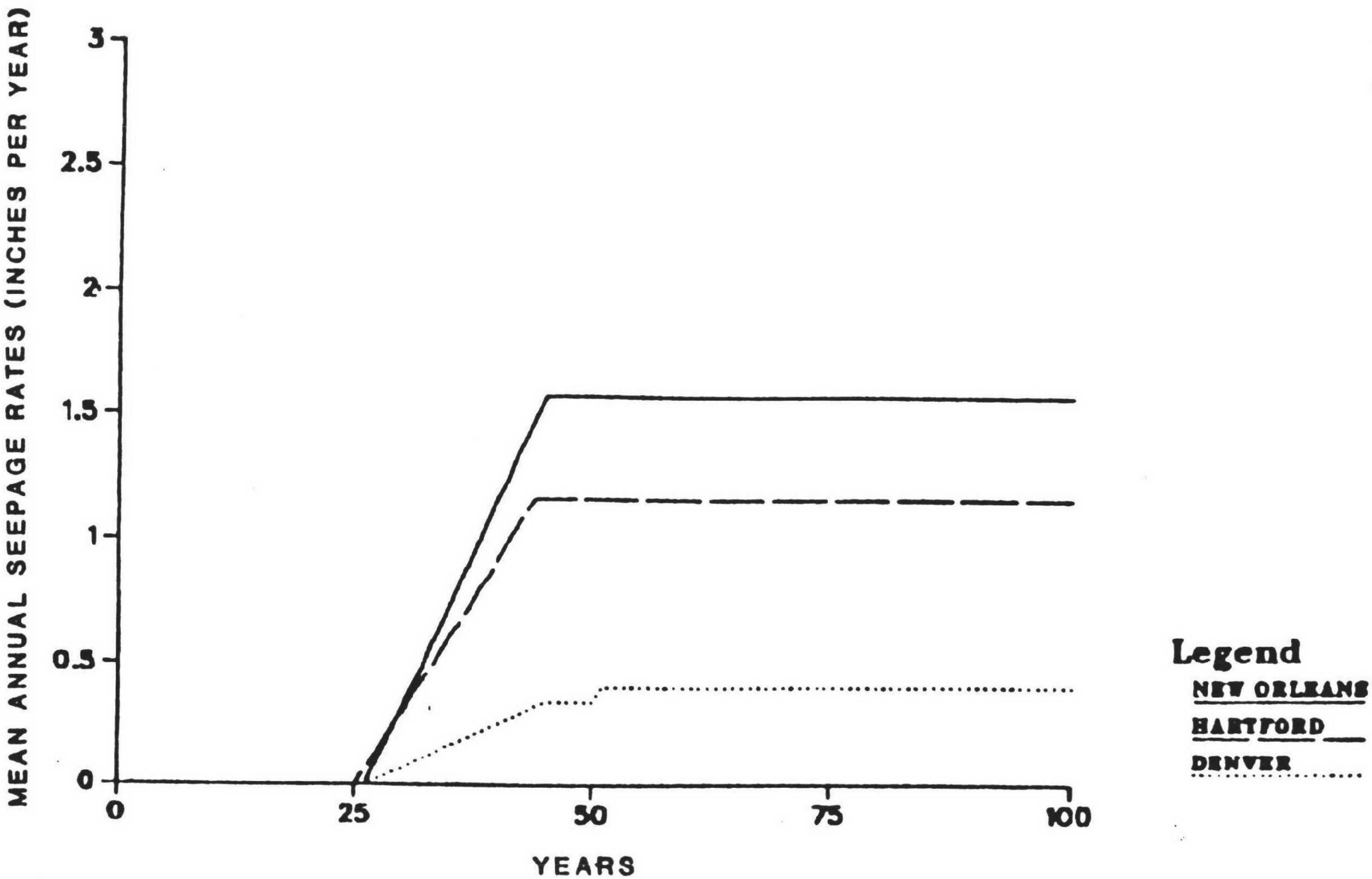
Figure 7.3-1 graphically compares the release profiles for the three climate types for landfill design case LFI1. The figure shows the change in seepage rates over time, where seepage rates refer to the percolation of leachate through the bottom liner or barrier layer. The trends exhibited by the design cases will, of course, vary dependent upon FML failure mode. However, for a given design case with the same FML failure, the trends will be similar.

Table 7.3-1 summarizes the seepage rates for each landfill design case at select model years for the three climates.

The Denver climate generally yielded the lowest simulated seepage rates for each design case after FML failure, when compared with the Hartford and New Orleans climates. Hartford generally yielded the next lowest rates, followed by New Orleans, as expected. This is shown by comparing the seepage rates between climates for a given design and FML failure mode (see Table 7.3-1). Of course, prior to FML failure the seepage rates for all of the climates would be zero. It is interesting to note that for cases LFI and LFII the seepage rates are always about equal under a given climate type. When making comparisons to the above Table, the reader should note that for design case LFIIA1 under the Hartford and Denver climates, the assumption has been made that post-closure care activities are continued throughout the modeled period. This is in contrast to case LFI1 for all three climates, and LFIIA1 for the New Orleans climate where it is assumed that post-closure care activities end at year 50.

FIGURE 7.3-1

## LANDFILL CLIMATE COMPARISONS
## LEVEL 11




SOURCE: EPA

TABLE 7.3-1

SUMMARY OF MEAN SEEPAGE RATES
BY LANDFILL DESIGN
FOR SELECTED MODEL YEARS
(NEW ORLEANS CLIMATE)

| YEAR | MEAN SEEPAGE RATE (INCHES/YEAR) | | | | | | |
|---|---|---|---|---|---|---|---|
| | LFI1 | LFI2 | LFI3 | LFI6 | LFIIA1 | LFIIA3 | LFVI |
| **NEW ORLEANS CLIMATE** | | | | | | | |
| 12 | 0.000 | 0.000 | 0.000 | 0.453 | 0.000 | 0.000 | 9.527 |
| 20 | 0.000 | 0.000 | 0.000 | 0.015 | 0.000 | 0.000 | 13.328 |
| 37 | 0.904 | 0.232 | 0.000 | 0.015 | 0.808 | 0.000 | 13.328 |
| 50 | 1.561 | 0.966 | 0.000 | 0.015 | 1.280 | 0.000 | 13.328 |
| 75 | 1.566 | 1.561 | 1.566 | 0.012 | 1.280 | 1.579 | 13.328 |
| **HARTFORD CLIMATE** | | | | | | | |
| 12 | 0.000 | 0.000 | 0.000 | 0.396 | 0.000 | 0.000 | 7.021 |
| 20 | 0.000 | 0.000 | 0.000 | 0.011 | 0.000 | 0.000 | 9.984 |
| 37 | 0.732 | 0.172 | 0.000 | 0.011 | 0.405 | 0.000 | 9.984 |
| 50 | 1.151 | 0.719 | 0.000 | 0.011 | 0.641 | 0.000 | 9.984 |
| 75 | 1.151 | 1.151 | 1.151 | 0.012 | 0.641 | 1.153 | 9.984 |
| **DENVER CLIMATE** | | | | | | | |
| 12 | 0.000 | 0.000 | 0.000 | 0.150 | 0.000 | 0.000 | 0.850 |
| 20 | 0.000 | 0.000 | 0.000 | 0.005 | 0.000 | 0.000 | 0.947 |
| 37 | 0.196 | 0.051 | 0.000 | 0.005 | 0.148 | 0.000 | 0.947 |
| 50 | 0.338 | 0.210 | 0.000 | 0.005 | 0.229 | 0.000 | 0.947 |
| 75 | 0.400 | 0.338 | 0.400 | 0.038 | 0.229 | 0.321 | 0.947 |

With the exception of FML failure modes 6 and 7, which assume a fixed seepage rate (see Section 7.2.4), the final seepage rates for all LFI and LFII scenarios were about equal for a given climate type. A brief summary of the final seepage rates under the three climates for selected designs are shown below:

FINAL SEEPAGE RATES (INCHES/YEAR)

| | New Orleans | Hartford | Denver |
|---|---|---|---|
| LFI3 | 1.56 | 1.15 | 0.40 |
| LFIIA3 | 1.57 | 1.15 | 0.32 |
| LFVI | 13.32 | 9.98 | 0.97 |

As shown above, the variability between the design cases for a given climate is insignificant. The release rates observed for the Hartford and New Orleans climates were similar, with the New Orleans rate about 35 percent higher. The release rates for the Denver climate were about 4.3 times lower than the New Orleans rates. The lower seepage rate observed for the Denver climate results from the lower precipitation and higher evapotranspiration (ET) rate.

Perhaps, the scenario which best illustrates the significance of climate in reducing seepage rates is design LFVI. This case represents "free infiltration" and, as can be seen above, the variability between climate types is significant. It is interesting to note that the final seepage rate of case LFVI for the Denver climate was lower than the final seepage rates for all case LFI and LFIIA scenarios (assuming post-closure care activities end at year 50 and excluding scenarios with FML failure modes 6 and 7).

### 7.3.3 Effects of Facility Design and Operating Conditions

#### 7.3.3.1 Landfills

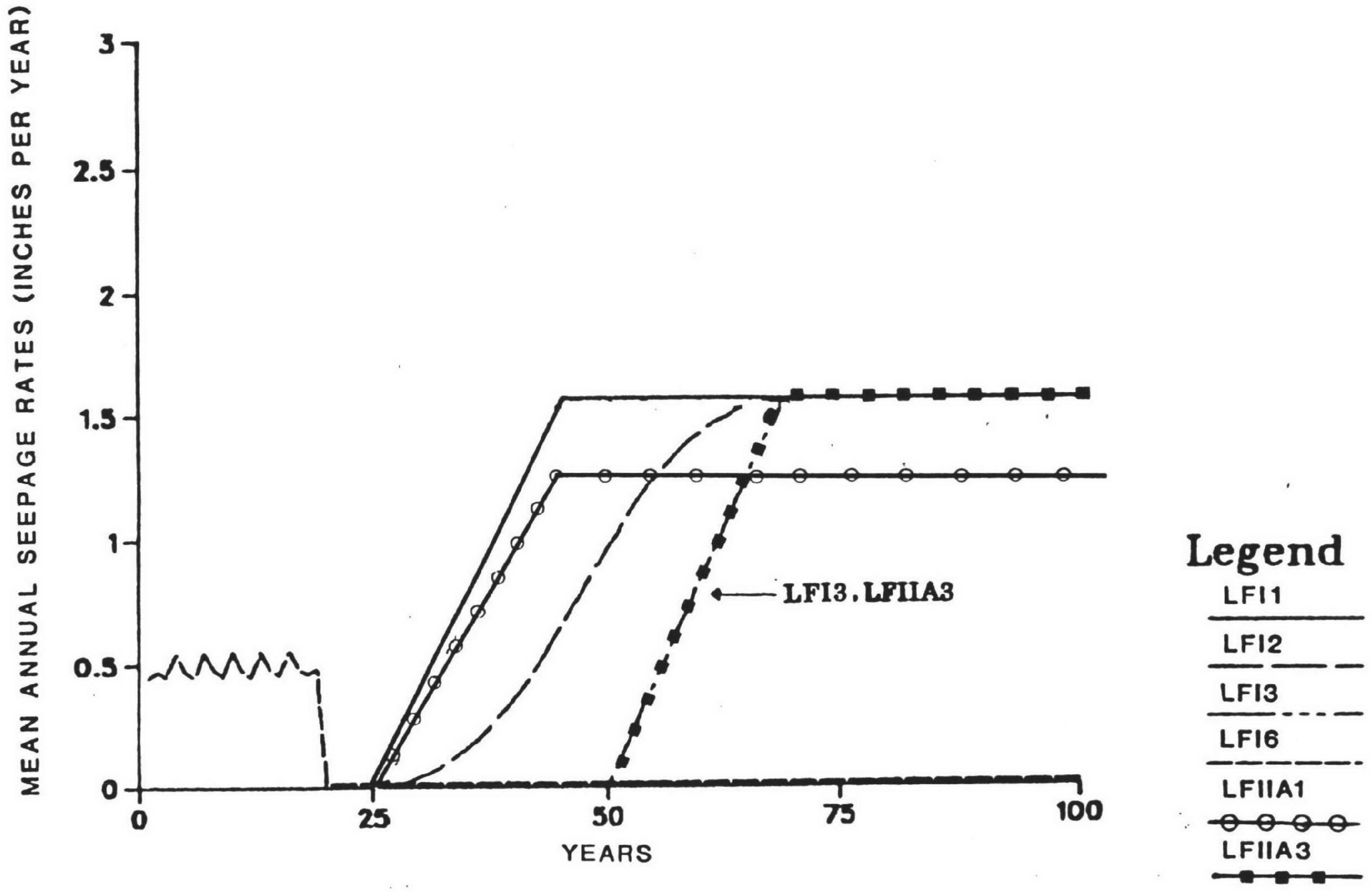
Three landfill designs were evaluated in this study. Design cases LFI and LFIIA are identical except for the bottom liner design. Design LFI has a double 30-mil FML liner system; design LFIIA has a double bottom liner consisting of an upper 30-mil FML underlain by two feet of clay. For comparison, as a worst-case scenario, design LFVI does not have a cap or liner and is considered to represent a "free infiltration" case.

Assuming that the FML failure mode is the same, similar trends were generally observed for the release profiles of a given design regardless of climate type. The climate affects the magnitude of the seepage rates, as discussed in the previous section. The timing of the release rates are a function of the FML failure mode. Figures 7.3-2, 7.3-3 and 7.3-4 plot the mean annual seepage rates (in inches per year) for the various design cases for the New Orleans, Hartford and Denver climates, respectively. Table 7.3-1 summarizes the mean annual seepage rates for the design cases for select model years. The years were selected to afford comparison of seepage rates under a range of operating conditions, as follows:

- o Year 12 - mid-way through the operating period;
- o Year 20 - end of the operating period;
- o Year 37 - mid-way through the post-closure care period;
- o Year 50 - end of the post-closure care period; and
- o Year 75 - final seepage rates.

FIGURE 7.3-2

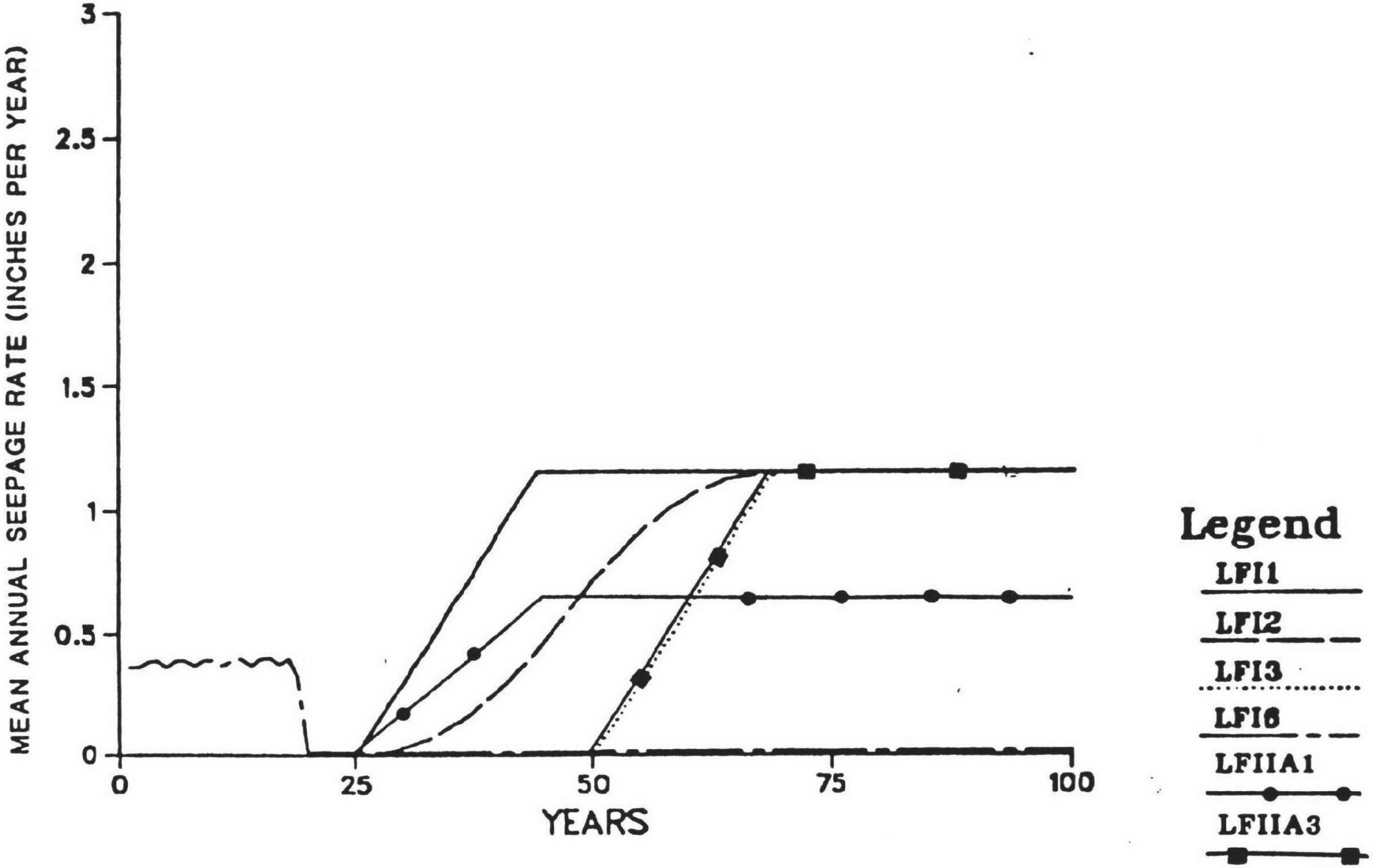
# COMPARISONS OF LANDFILL DESIGN AND SEEPAGE NEW ORLEANS CLIMATE




SOURCE: EPA

FIGURE 7.3-3

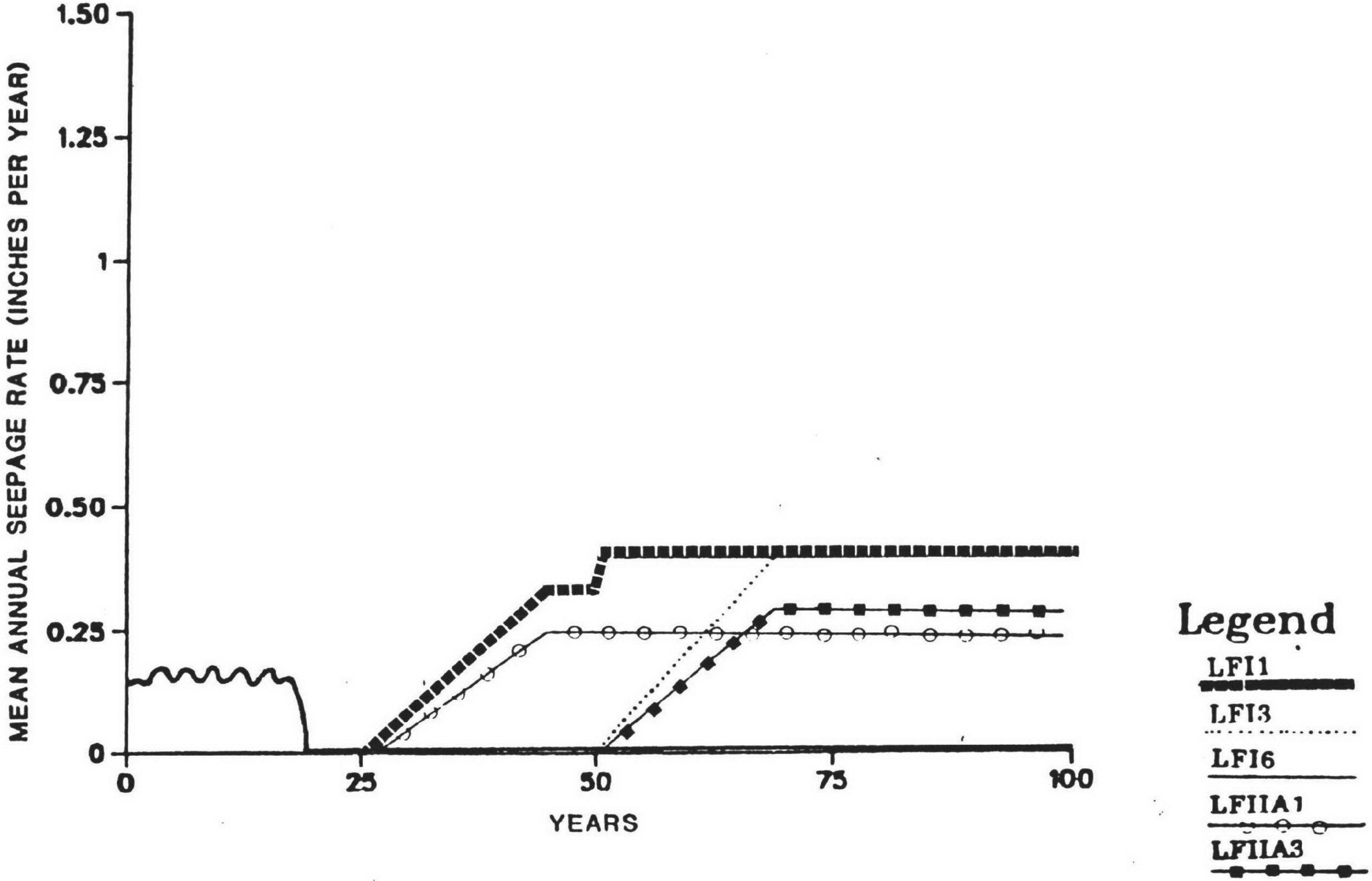
## COMPARISONS OF LANDFILL DESIGN AND SEEPAGE
## HARTFORD CLIMATE




SOURCE: EPA

FIGURE 7.3-4

# COMPARISONS OF LANDFILL DESIGN AND SEEPAGE DENVER CLIMATE




SOURCE: EPA

The timing of the release rates are a function of the FML failure mode assumption employed (see Section 7.2.4). FML failure modes 1, 3 and 5 undergo catastrophic failure at model years 25, 50 and 150, respectively. The trends for the release rates are similar; only the timing varies. Similar trends are also exhibited between FML failure modes 2 and 4 which undergo complete failure in a step function starting at model years 25 and 50, respectively. Finally, FML failure modes 6 and 7 exhibit fixed seepage rates over the model period. Each FML failure type shall be addressed with duplication kept to a minimum.

It is assumed that seepage is not produced until FML failure occurs. In the case of LFI1, seepage production began at year 25 and increased at a sharp and steady rate until stabilizing at year 45. Generally, this rate remained constant for the balance of the model run and there was no change in the seepage rate in response to termination of post-closure care activities at year 50.

As with case LFI1, case LFIIA1 also did not show any seepage production until year 25 when catastrophic failure occurred. However, case LFIIA1 showed post-closure seepage rates about 1.2, 1.8 and 1.5 times lower than comparable case LFI1 post-closure care seepage rates for the New Orleans, Hartford and Denver climates, respectively. As all other design variables are the same, the lower rates are believed to be related to the greater efficiency of leachate collection resulting from the presence of a clay component in the LFIIA bottom liner design. Under normal operating conditions (see Table 7.2-5), the operation of the leachate collection and leak detection systems is terminated at the end of the post-closure care period. Given this assumption, the seepage rates for case LFIIA1 should show a sudden increase after year 50 prior to achieving a stable final seepage rate. For example, case LFIIA1 under the Hartford climate would yield a final seepage rate of about 1.2 inches/year, as exhibited by case LFIIA3. However, in contrast to the normal operating conditions, the operation of the leachate collection and leak detection systems is assumed to continue throughout the modeled period for the case LFIIA1 scenarios. As such, they maintain the same seepage rates as during the post-closure care period; that is, about 1.2, 0.6 and 0.2 inches/year for the New Orleans, Hartford and Denver climates, respectively.

The release profile for FML failure mode 2 shows a more gradual and variable increase than for the catastrophic failure modes. Seepage production begins at about year 27 and eventually stabilizes at about year 70. Due to the presence of a clay component in the LFIIA2 design, a slightly lower rate of increase would be expected during the post-closure care period as compared with LFI2. This would be due to a more effectively operating leachate collection system in the former case. Both scenarios would achieve about the same final seepage rates about year 70.

FML failure modes 6 and 7 represent the only scenarios which showed seepage production for the first 25 model years. Both failure modes call for a fixed seepage rate. FML failure modes 6 and 7 assume that 1.0 percent and 0.1 percent of the liner area has the same vertical permeability as the underlying bedding layer. The trend exhibited by both failure modes will be the same with the latter significantly lower than the former. Discussion herein shall refer to FML failure mode 6. Basically, a "saw-tooth" pattern emerges over the 20-year operating period. This pattern is a result of the sequential manner in which the landfill sub-cells are closed (see Section 7.2.4). At final closure (year 20), the seepage rates decrease sharply to virtually a zero rate and generally remain constant thereafter. A reduction of about 10 percent was observed in design case LFIIA6 as compared with case LFI6 during the operating period (see Appendix G of the aforementioned Ertec memorandum). This is a result of the presence of the clay bottom liner component for case LFIIA.

With the exception of FML failure modes 6 and 7 and the assumption that post-closure care continues for any of the LFIIA scenarios after year 50, all of the design cases eventually achieve about the same final seepage rate for a given climate. These final rates are about 1.5 inches/year for New Orleans, 1.1 inches/year for Hartford, and between 0.3 to 0.4 inches/year for Denver. As noted earlier, if post-closure care activities are continued for the duration of the modeled period for applicable cases under design LFIIA, the seepage rates would appear to be roughly one-half of those shown above. For design scenarios assuming FML failure modes 6 and 7, the post-operating seepage rates are essentially zero.

Design LFVI represents a "free infiltration" scenario. A detailed evaluation of the seepage trend of this scenario is addressed in the companion report for clay containment systems. Comparison of the final seepage rates for the LFI and LFIIA designs with those of LFVI indicate a significant degree of leachate containment for each climate type.

### 7.3.3.2 Disposal Surface Impoundments

The surface impoundment liquid depth is the main driving force for seepage production during the operating period, rather than precipitation. This is the critical period for leachate production. As the effect of climate is negated, the following discussion is limited to the New Orleans climate.

Table 7.3-2 summarizes the mean annual rates for the various design cases for select model years. These years were chosen to allow comparison of seepage rates by design case under the range of operating conditions,as follows:

- Year 20 - last year of operating period;
- Year 21 - start of post-closure care period;
- Year 37 - mid-way through post-closure care period; and
- Year 51 - final seepage rates.

Figure 7.3-5 graphically displays the mean annual release rates for the various design cases over the first 100 years modeled.

The two disposal surface impoundment designs are similar to those discussed in the previous section for landfills. However, for the impoundments there is no leachate collection system. Both designs have a double bottom liner system; Design SDI uses two 30-mil FMLs, while SDII uses a 30-mil FML underlain by two feet of clay.

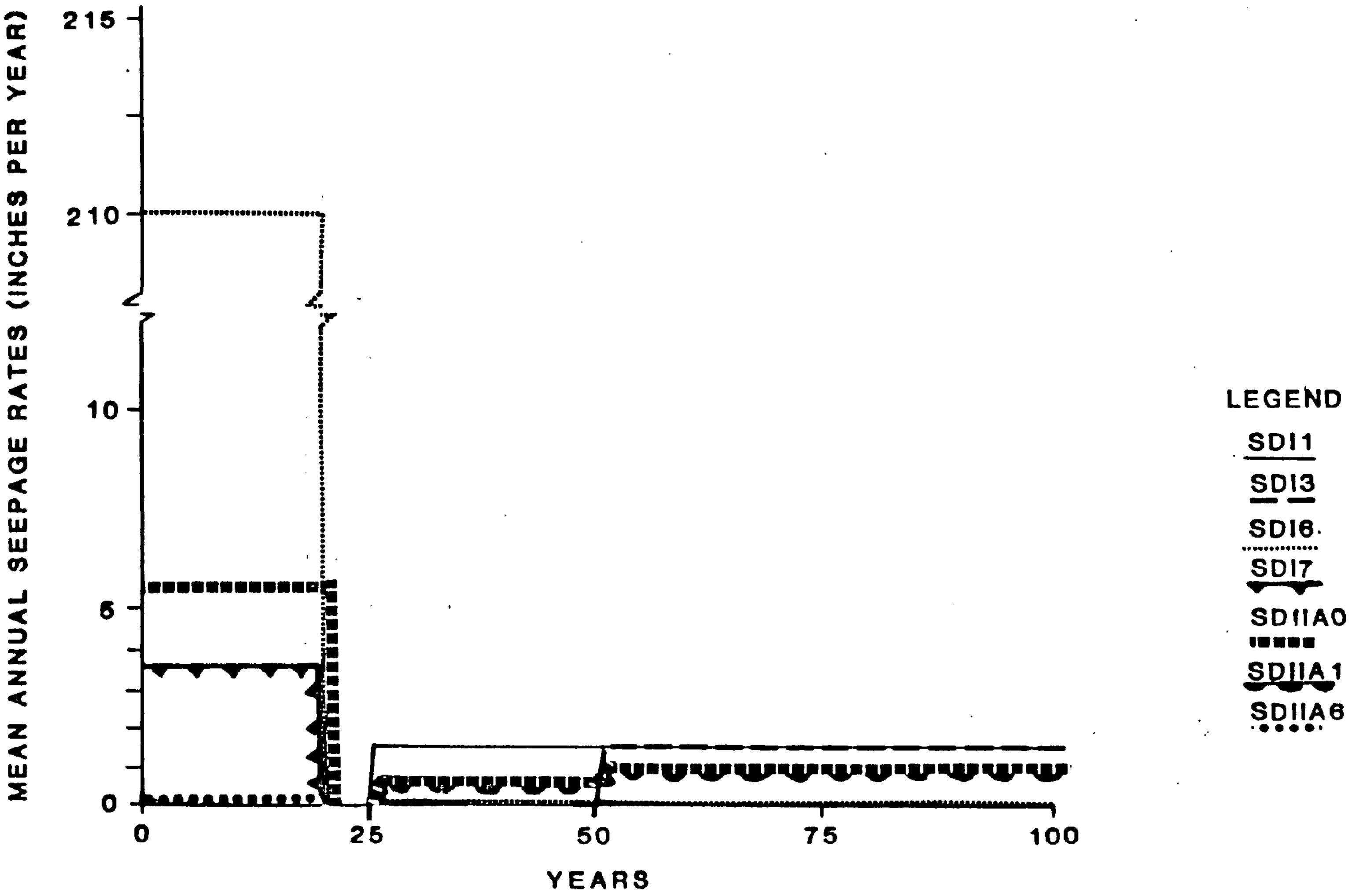
TABLE 7.3-2

SUMMARY OF MEAN SEEPAGE RATES
BY DISPOSAL SURFACE IMPOUNDMENT DESIGN
FOR SELECTED MODEL YEARS
(NEW ORLEANS CLIMATE)

| | MEAN SEEPAGE RATE (INCHES/YEAR) | | | | | | |
|---|---|---|---|---|---|---|---|
| YEAR | SDI1 | SDI3 | SDI6 | SDI7 | SDIIA0 | SDIIA1 | SDIIA6 |
| 20 | 0.000 | 0.000 | 210.000 | 3.400 | 5.580 | 0.000 | 0.060 |
| 21 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 37 | 1.562 | 0.000 | 0.024 | 0.000 | 0.755 | 0.755 | 0.000 |
| 51 | 1.564 | 1.564 | 0.023 | 0.000 | 1.365 | 1.365 | 0.000 |

FIGURE 7.3-5

# COMPARISONS OF DISPOSAL SURFACE IMPOUNDMENT DESIGN AND SEEPAGE NEW ORLEANS CLIMATE




SOURCE: EPA

The timing of the release rates are a function of the FML failure mode. As the critical period for leachate production is the 20-year operating period, the timing of the release will also indirectly determine the magnitude of release. With the exception of FML failure modes 6 and 7, all of the scenarios for designs SDI and SDIIA show zero seepage production during the operating period. This is because the FMLs did not fail until after the operating period was over. In contrast, FML failure modes 6 and 7 were subject to a fixed seepage rate throughout the modeled period, including the operating period. Under the constant seven-foot liquid depth assumed during facility operation, design cases SDI6 and SDI7 yielded constant seepage rates of about 210 and 3.4 inches/year, respectively. Design cases SDIIA6 and SDIIA7, by comparison, only established seepage rates of about 0.06 inches/year and essentially zero, respectively. The disparity in seepage production between design cases SDI6 and SDI7 and those of SDIIA6 and SDIIA7 reflect the different bottom double-liner systems. The lower values for the latter cases result from the presence of the clay component in the bottom liner system. To further illustrate the benefit of a clay component in the double bottom liner, an additional FML failure mode was assumed, that is, SDIIA0. Under this scenario, the FML is assumed to completely fail throughout the operating period. The resulting seepage rate (about 5.6 inches/year) was still significantly less than for case SDI6.

At closure, the liquid waste is solidified and the main driving force for seepage production now becomes precipitation. In response to catastrophic FML failure, case SDI1 shows a marked increase at year 25, before stabilizing at a final seepage rate of about 1.5 inches/year. There was no change in the seepage rate in response to the termination of post-closure care activities at year 50. The same final rate was achieved for case SDI3; only the timing of the release varies.

Case SDIIA1 also showed an increase at year 25 in response to catastrophic FML failure. However, the seepage rate yielded during the post-closure care period was about 0.75 inches/year. This is roughly one-half the seepage rate for case SDI1. The reason for the lower seepage rate for case SDIIA1 is the presence of the clay component in the bottom liner system. At the end of the post-closure care period, the seepage rate for SDIIA1 increases to a final level of about 1.4 inches/year. This is in response to the termination of the leak detection system operation. Although not presented in Table 7.3-2, case SDIIA3 would result in the same final seepage rate as for SDIIA1.

At closure, the design cases exhibiting FML failure modes 6 and 7 essentially achieve zero final seepage rates. These sudden (and for case of SDI6, dramatic) decreases in seepage rates are a result of the decrease in the head from the constant seven-foot liquid depth during operation, and the placement of the final cover system. For case SDIIA0, the seepage rate also decreases at closure to zero. Thereafter, it is assumed to exhibit FML failure mode 1. Thus, beginning at year 25, case SDIIA0 is identical to case SDIIA1, as described above.

7.3.3.3 Storage Surface Impoundment

As with the disposal impoundment facility, the driving force for seepage production during the operating period is the constant seven-foot liquid depth. The climatic conditions were not observed to alter the magnitude or trend of seepage during the operating period. As such, discussion will be limited to the New Orleans climate type.

Table 7.3-3 summarizes the mean annual seepage rates for cases SSI6 and SSI7. Model year 20 represents the last year of operation. Model year 21 reflects the final seepage rate. Figure 7.3-6 displays the seepage profiles for these cases.

Only one design was selected by the EPA for evaluation herein. This design incorporates a single 30-mil FML in the bottom liner. There are no leachate collection or leak detection systems.

As with the disposal impoundment facility, the critical period for leachate production is during facility operation. At closure, the waste and liner are assumed to be removed; thus, the seepage rates shown after year 20 are not reflective of leachate rates.

Cases SSI1 through SSI5 had zero seepage production during the operating period as the FML was functional for at least 25 years. Only cases SSI6 and SSI7, which assume fixed seepage rates, are of concern. The operating seepage rates for cases SSI6 and SSI7 were about 186 and 18.6 inches/year, respectively. Although not specifically addressed for this facility type, the presence of a clay liner below the FML liner would reduce the rate of seepage production to about 0.06 inches/year and zero, as observed in cases SDIIA6 and SDIIA7, respectively.

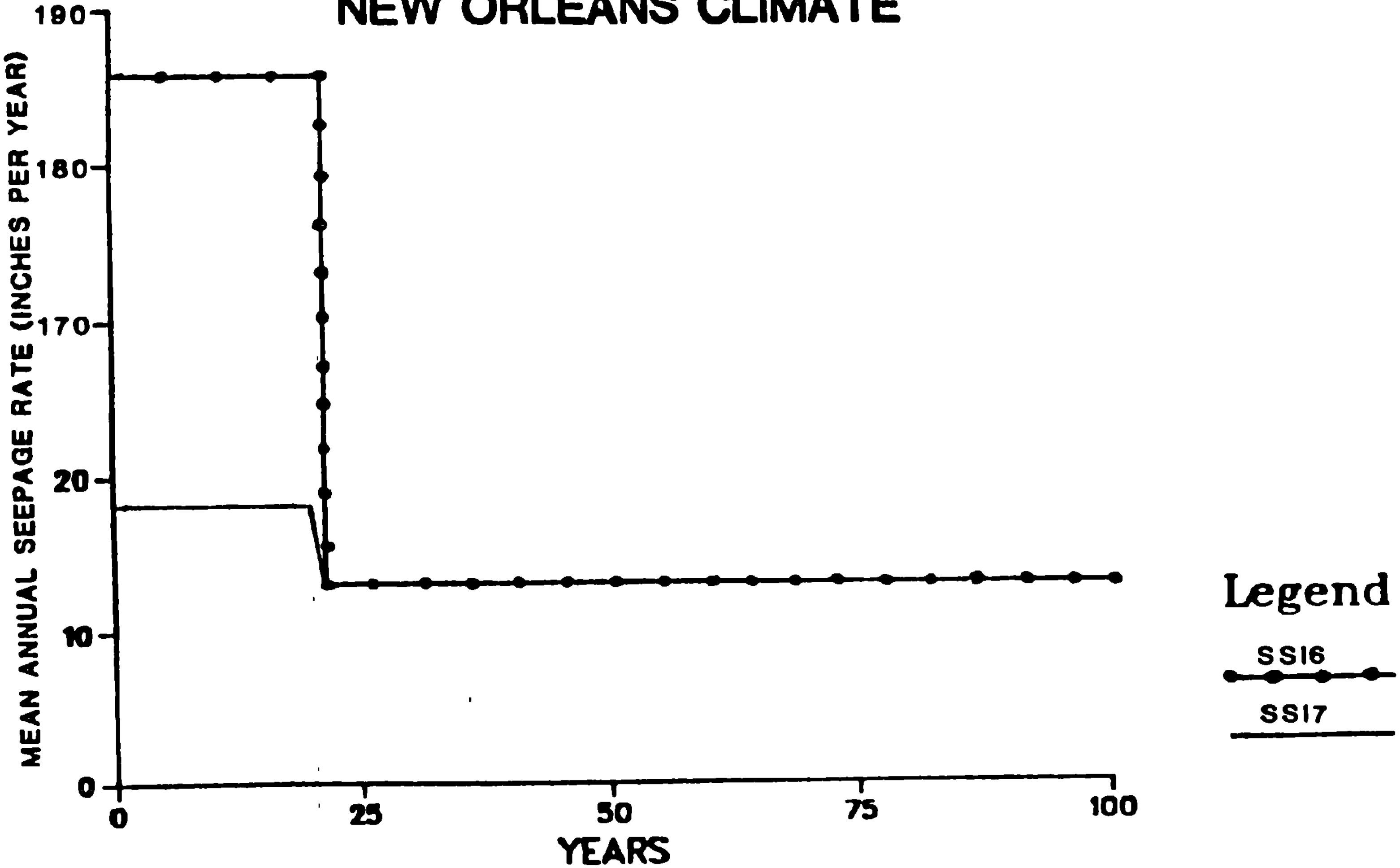
TABLE 7.3-3

SUMMARY OF MEAN SEEPAGE RATES
BY STORAGE SURFACE IMPOUNDMENT DESIGN
FOR SELECTED MODEL YEARS
(NEW ORLEANS CLIMATE)

| | MEAN SEEPAGE RATE (INCHES/YEAR) | |
|---|---|---|
| YEAR | SSI6 | SSI7 |
| 20 | 186.000 | 18.600 |
| 21 | 13.238 | 13.238 |

FIGURE 7.3-6

# COMPARISONS OF STORAGE SURFACE IMPOUNDMENT DESIGN AND SEEPAGE NEW ORLEANS CLIMATE




SOURCE: EPA

At closure, the waste and liner are removed and final seepage rates stabilize at about 13 inches/year. These seepage rates are included to represent free-drainage infiltration, consistent with the rates observed in LFVI. Again, these rates are not leachate rates.

7.3.3.4 Waste Piles

Only one waste pile design was evaluated in this study. Design WPI is similar to design LFI with the exception of a single FML liner and lack of a leak detection system in WPI.

As with the landfill scenarios, climate was not found to affect the seepage trends but, rather, the magnitude of the seepage rates. The effects of climate were discussed in Section 7.3.2. Discussion herein shall be limited to the New Orleans climate for illustration. Table 7.3-4 gives a summary of seepage rates for select model years, as follows:

- Year 30 - last year of operating period;
- Year 31 - start of post-closure care period; and
- Year 61 - post-care final seepage rates.

Figure 7.3-7 plots the mean annual seepage rates for the design cases discussed herein over time.

In preface, FML failure modes 1 and 2 (see Section 7.2.4) were not considered applicable for this analysis as closure does not begin until after year 30, and FML failure modes 1 and 2 are assumed to occur at year 25. This

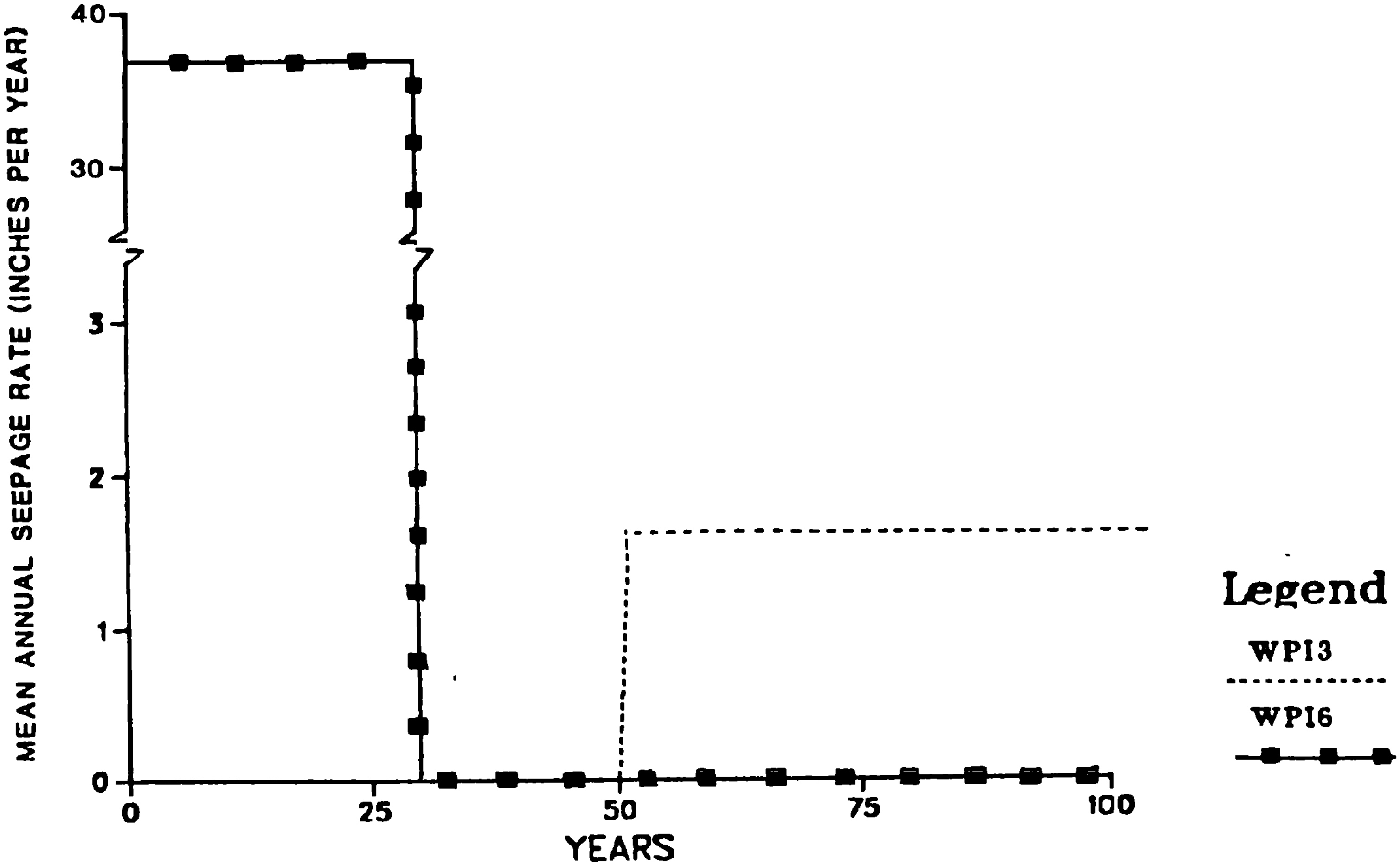
TABLE 7.3-4

SUMMARY OF MEAN SEEPAGE RATES
BY WASTE PILE DESIGN
FOR SELECTED MODEL YEARS
(NEW ORLEANS CLIMATE)

| | MEAN SEEPAGE RATES (INCHES/YEAR) | |
|---|---|---|
| YEAR | WPI3 | WPI6 |
| 30 | 0.000 | 37.295 |
| 31 | 0.000 | 0.012 |
| 61 | 1.565 | 0.012 |

FIGURE 7.3-7

# COMPARISONS OF WASTE PILE DESIGN AND SEEPAGE NEW ORLEANS CLIMATE




SOURCE: EPA

evaluation shall focus on FML failure modes 3 and 6, reflective of catastrophic FML failure at year 50, and fixed seepage throughout the modeled period, respectively.

During the 30-year operating period, cases WPI6 and WPI7 yielded significantly higher seepage rates than those yielded by comparable landfill cases LFI6 and LFI7, respectively. For example, the operating seepage rate for WPI6 was about 37.3 inches/year, as compared with about 0.453 inches/year for LFI6. This is a result of the different operating conditions assumed. That is, the five waste pile components are assumed to operate concurrently rather than sequentially as for the landfills. Thus, during the operating period, all five waste piles are open and contributing seepage. At closure, the seepage rates for WPI6 and WPI7 decreased sharply to about zero seepage as a result of final cover placement. This is the same trend as was observed for the comparable landfill scenarios.

Case WPI3, by definition of the FML failure mode, does not produce seepage until year 50. At this time, in response to catastrophic FML failure, the seepage rate increases sharply and stabilizes with a final seepage rate of about 1.5 inches/year. This is the same final seepage rate as yielded for LFI and LFIIA designs (with the exception of FML failure modes 6 and 7).

## 7.4 CONCLUSIONS

### 7.4.1 Landfills

In general, designs LFI and LFIIA effectively contain the rate of seepage production during the modeled period. This is shown by comparing the seepage rates for these designs with those seepage rates reflecting free infiltration under design LFVI. Refer to Table 7.3-1 for comparison.

The trends of the seepage profiles for designs LFI and LFIIA are generally similar for a given FML failure mode assumption. A notable exception to this general rule regards cases LFIIA1 and LFI1 during the post-closure care period. During this period case LFIIA1 yielded seepage rates approximately 1.2, 1.8 and 1.5 times lower than comparable seepage rates for case LFI1 under the New Orleans, Hartford and Denver climates, respectively. This is a result of the more efficiently operating leachate collection and leak detection systems for design case LFIIA1.

The efficiency of the leachate collection and leak detection systems to collect and remove leachate is determined by comparing the post-closure care period seepage rates with the final seepage rates for each design. As previously noted, it was assumed that post-closure care activities (i.e., leachate collection system and leak detection system operation) continued throughout the modeled period for case LFIIA1. Therefore, to properly assess the effectiveness for leachate collection under design LFIIA, it is necessary to compare the post-closure care period seepage rates for case LFIIA1 with the final seepage rates for case LFIIA3 (see Table 7.31). The results indicate that the post-closure care period seepage rates are about 20, 45 and 30 percent lower than the final seepage rates for design LFIIA under the New Orleans, Hartford and Denver climates, respectively. In contrast, there was no change observed when comparing the post-closure care period seepage rates and final seepage rates for case LFI1. This implies that the leachate collection and leak detection systems are ineffective in reducing seepage rates for design LFI.

The data implies that the efficiency of the leachate collection and leak detection systems is largely controlled by the bottom liner system. For case LFI1 the double FMLs had failed and, as such, did not inhibit vertical percolation. On the other hand, the clay component in the double bottom liner for case LFIIA restricted downward percolation, thereby allowing the leachate collection and leak detection systems to operate more effectively. This illustrates an advantage to incorporating both synthetic and clay barriers in the bottom liner design. This also suggests that the effectiveness of the leachate collection and leak detection systems is interrelated to the permeability of the underlying barrier liner.

The increase in seepage production after post-closure care activities are terminated underscores an additional implication. That is, the continuation of the leachate collection system and leak detection system operation beyond the post-closure care period for LFIIA1 will reduce the final seepage rates. As noted above, the HELP results indicate that a reduction in seepage rates ranging from 20 to 45 percent was achieved for LFIIA1 depending on the climate type.

The final seepage rates for all of the LFI and LFIIA designs which assume complete FML failure and for which post-closure care activities end after year 50, were about equal for a given climate type. In the case of the New Orleans climate the final seepage rate was about 1.5 inches/year. The con-trolling factor for the final seepage rates is the final cover system. As complete FML failure is assumed, the final cover system essentially consists of a 24-inch vegetated layer, a 12-inch drain layer and a two-foot clay barrier. Thus, the presence of the clay component in the bottom liner for design LFIIA does not appear to be a significant factor in reducing the rate of seepage production (providing post-closure care activities have ended).

The ability to limit leachate production is a function of the FML failure mode assumption used. Obviously, design cases which assume a longer FML operational life expectancy are relatively more desirable. With the possible exception of FML failure mode 5 which assumes zero seepage through year 150, cases which assume FML failure modes 6 and 7 probably reflect the second and first best scenarios for seepage containment, respectively. Whereas specific assumptions were made regarding the behavior of FMLs in this analysis, many factors can effect an FML's effectiveness and life expectancy. The reader should refer to A.D. Little (1983) for a more comprehensive assessment of these factors.

The significance of the different design scenarios in terms of limiting seepage production would appear to be greater for the New Orleans and Hartford climates rather than for the Denver climate. The final seepage rate produced under the "free infiltration" case LFVI for Denver was less than that yielded by the best design case for the other climates. Thus, consideration must be given to what level of control is needed based on locational factors. The data suggest that a less stringent design would be required to effect an adequate level of leachate control for a semi-arid region, such as Denver. However, consideration must also be given to the relatively high value of the ground-water resources in such a region.

### 7.4.2 Disposal Surface Impoundments

The results strongly demonstrate the benefit of a bottom double liner design which incorporates an FML component underlain by a clay component, as compared with a design which uses two FMLs. During the critical operating period, design SDI6, which represents the former case described above, resulted in a very high seepage rate of about 210 inches/year. In contrast, design SDIIA6, which represents the latter case described above, had a seepage rate of less than 0.1 inches/year. In effect, the fixed seepage rate assumed for the FMLs, in conjunction with the considerable head exerted by the liquid level in the impoundment, essentially negated the effectiveness of the leak detection system to collect and remove leachate. In contrast, the presence of a low permeability ($1 \times 10^{-7}$ cm/sec) clay liner under the "leaky" FML liner effectively inhibits vertical percolation and allows the leak detection system to collect and remove the great majority of the seepage produced. To underscore the value of the bottom clay component, design case SDIIA0 was simulated to show the maximum seepage rate which would result from complete FML failure during operation. This seepage rate was about 5.6 inches/year; that is, still significantly below the operating seepage rates for SDI6. This suggests that surface impoundment designs should incorporate a combination FML/clay double bottom liner in conjunction with a leak detection system to effectively contain leachate migration through the bottom liner.

After closure, the facility follows similar seepage trends, and establishes similar seepage rates as described for the landfill scenarios in the previous section. As such, post-closure seepage rates will not be addressed herein.

As the operating period is the most critical stage for leachate production, and as the designs appear to yield similar final seepage rates, locational factors associated with climate do not appear to have a significant impact on design considerations.

### 7.4.3 Storage Surface Impoundments

The only storage impoundment design considered by the EPA had a single FML bottom liner and did not include leachate collection or leak detection systems.

As shown in Table 7.3-3, the operating seepage rate for case SSI6 (about 186 inches/year) was an order-of-magnitude greater than the operating seepage rate for case SSI7 (about 18.6 inches/year). This is directly proportional to the order-of-magnitude differences assumed for the respective FML failure modes (see Section 7.2.4). These results suggest that a single FML design is inadequate to contain leachate production during the critical operating period. In light of the negligible effect of the leak detection system for double FML design case SDI6, as discussed in the previous section, the presence of such a system for case SSI6 will not improve leachate containment. The data imply that incorporation of a double bottom liner system using a combination of FML/clay barriers and a leak detection system (as assumed for design SDIIA) is warranted to effectively control seepage production during operation.

The post-closure seepage rates are not leachate rates and, therefore, are not significant.

### 7.4.4 Waste Piles

The only waste pile design simulated in this study had a single FML bottom liner and a leachate collection system. The high seepage rates for case WPI6 (about 37 inches/year) during the operating period suggests that this design may not provide effective leachate containment. As the final cover is not placed on the facility until after year 30, the factor controlling seepage production during the operating period is the single FML bottom liner. The single FML liner does not inhibit vertical percolation sufficiently to permit effective leachate collection and removal. This design would provide a reasonably good degree of leachate containment under landfill operating conditions, as final cover placement is assumed to occur in a sequential manner for the sub-cells during facility operation. However, the lack of a cover during the waste-pile facility operating period permits a much greater infiltration rate and, in turn, a greater seepage rate.

As the presence of the clay component (with a permeability of $1 \times 10^{-7}$ cm/sec) in design LFIIA was found to increase the effectiveness of leachate collection and removal, a similar effect would be expected for the waste pile scenarios. Thus, it appears that use of a clay bottom liner (with a permeability of 1 X $10^{-7}$ cm/sec, or less) may be more effective in reducing seepage rates than would the single FML previously noted.

At closure the seepage rate for WPI6 decreased below 0.1 inches/year. This emphasizes the value of the final cover in reducing seepage production.

As suggested for the landfill scenarios, the significance of the various designs for seepage reduction would be expected to be greater for the humid climates as opposed to the Denver climate. This would imply that a less stringent design may be adequate to contain seepage for a semi-arid region.

# 8.0 SUMMARY AND CONCLUSIONS

The Environmental Protection Agency issued Interim Final Land Disposal Regulations on July 26, 1982. In response to these regulations the EPA received several comments regarding the recommended use of synthetic liner and cap materials. This report provides a summary of the initial EPA investigation of the anticipated performance of synthetic liners in hazardous waste environments. The synthetic material investigation represents one element of a broad technical investigation conducted by the EPA into the current hazardous waste containment practices and technology. The program was directed by the EPA Office of Solid Waste and Office of Research and Development (Municipal Environmental Research Laboratory). The technical investigation was performed primarily by Arthur D. Little, Incorporated and TRW, Incorporated. Coordination and consolidation of the technical material obtained was conducted by the Earth Technology Corporation (ERTEC) with support from E.C. Jordan, Incorporated.

## 8.1 INTRODUCTION

The synthetic liner investigation was initiated by EPA to consolidate available information regarding the suitability of synthetic materials for hazardous waste containment. The resulting technical data base will be used by EPA to support further synthetic liner studies, to develop technical guidance for the design and installation of synthetic barrier systems and to support further revision of the land disposal regulatory program. The project was designed by the EPA to address significant comments received following publication of the Interim Final Land Disposal Regulations.

### 8.1.1 Study Objectives

The EPA initiated the investigation of synthetic liners and caps in order to establish the technical adequacy of the Interim Final Land Disposal Regulations in light of the technical comments received. The specific goals identified to achieve the project objectives are as follows:

- Establishment of a complete base of currently avail-able information regarding synthetic liner systems.
- The development of specific recommendations for rregulatory reform regarding the use of synthetic liners at hazardous waste facilities.
- The identification of further technical guidance materials required to assist synthetic liner system operators, designers and constructors, and synthetic material manufacturers.
- Provide recommendations for further EPA research to improve the available synthetic material and liner system data base.
- Assess the ability of synthetic materials to contain hazardous waste leachate on a short- and a long-term basis.
- The development of a basic modeling approach for use in evaluating the relative performance of synthetic-lined facility design options.

The research effort was performed under the direction of the EPA Office of Solid Waste.

### 8.1.2 Approach

The EPA reviewed the various technical comments received following publication of the Interim Final Land Disposal Regulations to determine the most significant areas of concern identified by the commentors. The synthetic liner investigation was designed to gather the necessary information to respond to the technical issues defined and to provide an assessment of the need for further research and regulatory reform.

The approach selected by the EPA was designed to consolidate available information along the five principal areas of concern:

- o Physical and chemical properties of synthetic liner materials and appropriate testing methods.
- o Chemical resistivity of synthetic liners with respect to hazardous waste streams, and available testing methods.
- o Synthetic liner installation and field inspection procedures and unique problems.
- o Typical synthetic cap and liner failure modes, which have been experienced at existing facilities.
- o Synthetic liner and cap performance modeling.

The evaluation of the physical and chemical attributes of synthetic-lined facilities was conducted using standard data search techniques and personal interviews. The personal interview approach was employed due to the fragmented nature of the existing synthetic system data base and as a means to overcome the reluctance of some facility operators and design firms to divulge sensitive information. The evaluation of appropriate testing methods utilized a similar approach, relying primarily on information available from research facilities and engineering testing laboratories.

A detailed investigation of existing facilities which have experienced synthetic liner failure was conducted in order to identify the most common causes of liner failure and corrective actions required. Due to the sensitive nature of this effort, most of the information was obtained through direct communication with facility operators and their consultants as well as interviews with government inspectors familiar with the facility under evaluation.

The approach used to develop design performance modeling capability relied primarily on the extension of previously tested and verified computer modeling techniques. The principal effort was expended in the generalization of previously developed special purpose models to facilitate their use in evaluating typical hazardous waste disposal facility designs and liner installation options. The technique developed was designed specifically to provide a relative assessment of design suitability.

In developing the overall study approach, the EPA recog-nized the fragmented nature of the existing information base regarding synthetic materials used as liners and therefore emphasized the data collection effort. The result of this additional planning ensured that the resulting information base represented a consolidation of available data from various divergent sources. This approach necessitated additional effort during the evaluation phase in order to provide a common basis for subsequent data comparison. The additional attention afforded by this approach ensured that the resulting synthetic material data base would prove useful as a basis for the subsequent technical evaluation of regulatory options. Technical guidance material and further synthetic liner material research efforts.

## 8.2 CONCLUSIONS RELATIVE TO OVERALL SYNTHETIC BARRIER PERFORMANCE

Based on the results of this research project, several conclusions were reached regarding the problems with, and anticipated performance of, synthetic liner and cap systems at hazardous waste disposal facilities. The study results are organized into five general areas, which correspond to the principal concerns identified regarding synthetic liner system performance. These areas were identified as follows: general synthetic liner performance; chemical resistance of synthetic materials to hazardous waste leachate; synthetic cap and liner installation; failure modes; and, alternative design performance results based on the HELP analysis. Generally, the study results indicate that properly manufactured synthetic liners will minimize leakage from hazardous waste facilities, if the facilities are properly designed, maintained and routinely inspected. However, small amounts of leakage will occur, due to vapor transport through synthetic materials. Therefore, synthetic liners do not meet the performance goal established in the regulations. Modification of the regulatory goal to allow "de minimus" leakage is recommended. The principal issues associated with the use of synthetic liners are the present lack of a long-term synthetic liner data base, the lack of detailed design and installation guidance and the lack of a comprehensive approach toward the determination of the chemical resistance of specific liner materials to multi-component waste leachate. Additional research is recommended to determine the significance of these issues in terms of synthetic liner performance at hazardous waste facilities.

## 8.2.1 General Performance of Synthetic Barrier Materials

The use of synthetic materials as containment barriers can effectively minimize, but not entirely prevent leakage from hazardous waste facilities. In order to achieve optimum performance, synthetic barrier materials should be specifically selected on the basis of a consideration of facility design, regional evnironment and the type of waste material to be contained. The design of such a facility must incorporate all aspects of leachate control within the overall facility design scenario. The facility's regional environment must be incorporated into the design concept to reflect intensity of sunlight, amount of precipitation and regional hydrology. The synthetic liner must be selected as an integral component of facility design, incorporating anticipated subsidence, chemical components of the waste material and liner exposure considerations. Finally, a comprehensive quality assurance program is required to insure attainment of design specifications and proper facility maintenance. A suitably designed and installed facility using synthetic barriers will effectively minimize leakage from a hazardous waste facility.

### 8.2.1.1 Optimal Synthetic Liner Performance

The common perception that synthetic liners are impervious to leachate is not entirely correct. Synthetic barriers can be impermeable to hydraulically driven liquid flow, but they cannot eliminate vapor transport of volatile material. Vapor transport is a material diffusion phenomenon. Essentially, the volitized component of a liquid in contact with a barrier will be absorbed by the barrier, moving through the barrier in the vapor state, in response to the concentration gradient across the barrier. Upon reaching the low concentration side of the barrier (the outside) the vapor will desorb and return to the liquid state (further discussion is provided in Section 3). Effectively, this results in some leakage from the facility. Thus, synthetic barriers cannot meet the regulatory performance objective of preventing leachate penetration through the facility liner during the operating life of the facility. However, if synthetic materials are selected appropriately, total vapor trans-port during the operating life of the facility can be held to very small amounts. It appears that the regulatory performance goal should be modified to allow "de minimus" effective leakage during the operating life of the facility.

8.2.1.2 Advantages and Disadvantages of Synthetic Liners

Synthetic cap and liner systems have several advantages over natural soil barriers which should be considered in designing hazardous waste facilities. The following provides a brief list of the most significant advantages of synthetic liners:

- Leachate migration through intact synthetic barriers occurs through gaseous diffusion only. Based on the characteristics of the liner material and the waste leachate, effective leakage can be minimized. Non-volatile materials can be completely contained.
- Since synthetic materials are manufactured, they can be formulated to exhibit uniform properties under proper quality assurance control of the manufacturing process.
- Synthetic materials can be selected to provide flexibility, strength and chemical resistance properties to meet specific hazardous waste facility design requirements.

- Leachate leakage through synthetic materials is not hyudraulically driven and is not dependent on the hydraulic pressure exerted by the waste material and leachate.

- The formulation and manufacturing of synthetic liner materials is well understood, and the technology required to produce uniform liner materials is available. Liner installation technology is less advanced; but if proper precautions are taken, the present technology is capable of successful liner installation.

- Synthetic materials can be reinforced to provide sufficient tensile strength to prevent failure due to minor subsidence or soil movement.

- In service testing methods are available to allow monitoring of synthetic liner materials during the operational life of the facility. Monitoring tests can be defined to reasonably approximate actual liner conditions.

Synthetic materials also have several disadvantages which must be considered in the design of hazardous waste facilities. The most significant disadvantages of synthetic liners with respect to their use in containment of hazardous waste leachate are:

- Synthetic barriers are relatively thin membrane liners which are susceptible to puncture, tearing and other types of penetration damage.

- Synthetic materials lose tensile strength if stressed over long periods of time.

- Material properties may be effected by exposure to sunlight, ozone, fluctuating temperature extremes and fluctuating loads and pressures.

- The long-term effects of liner exposure to hazardous waste leachate connot be specifically determined using current technology. Laboratory testing has shown that exposure to pure chemicals can result in alteration of the physical and chemical properties of synthetic liner materials.

- The short experience base available for synthetic liner materials (10 years for hazardous waste applications) does not allow verification of liner life projections and long-term performance goals.

#### 8.2.1.3 Quality Assurance Requirements

The single most important recommendation which was provided by all investigators on this project is the need for a comprehensive Quality Assurance program to insure attainment of design specifications. The need for a mandatory program was expressed by the groups charged with the evaluation of existing facility failures, installation techniques and chemical resistance of synthetic materials. The results of this project clearly establish the need for such a program. An acceptable quality assurance program must incorporate at a minimum the following broad categories of quality control to insure the integrity of liner systems:

- Project description;
- Organization and responsibility;
- Design evaluation;
- Complete design specifications for field installation and facility operation;
- Training and minimum personnel experience requirements;
- Methods and procedures;
- Equipment and materials certification and testing;
- Testing and data interpretation procedures;
- Internal quality control inspections;
- External quality assurance audits;
- Procedures for resolving identified deficiencies; and,

- o Complete project design, installation and operation documentation.

#### 8.2.1.4 Importance of Regional Factors to Liner Design

Precipitation and regional hydrogeology provide the principal hydraulic driving mechanisms which determine the ultimate performance of hazardous waste facility caps and liners. Regional precipitation essentially determines the amount of leachate available for ultimate release from the facility in the event that liner failure occurs. Precipitation also provides the driving mechanism for "bathtub effect" facility failures, which have been documented at some existing facilities. Regional hydrology is important because it determines the ultimate fate of leachate which is released from the facility. The overall importance of regional factors lies in the fact that if any containment system failure occurs, regional factors will determine the progression of the failure event and the ultimate distribution of contaminants in the environment. In addition, regional hydrology and climate essentially act to increase the significance of any design, installation or operating flaws which are incorporated into the facility inadvertantly.

### 8.2.2 Chemical Resistance of Synthetic Material to Hazardous Waste Leachate

The chemistry of synthetic liner materials is primarily based on the specific polymer used and the particular formulation of the base polymer. Beyond basic polymer chemistry, liner materials are amended with various additives and reinforcing materials, to increase the desireable attributes of the resulting liner material. As with all long chain organic chemistry, the possible combinations are almost unlimited. This problem is complicated by the fact that most manufacturers regard their formulations as proprietary and retain specific information as industrial secrets. The situation regarding leachate chemistry is even more complicated. Leachate from relatively simple waste streams can contain hundreds or even thousands of chemical components as the raw waste materials mix and decay into the leachate soup. The complex chemistry of synthetic polymers and the cornucopia of leachate components can combine in essentially a limit-less array of potential reactions and counter reactions. Standard single chemical testing of liner materials cannot hope to analyze a fraction of the potentially available reactants. Yet, field data, although available only for the past 10 years, indicates that well designed and installed synthetic liners are remarkably stable, even in rather harsh environments.

In response to this apparent dilemma, researchers have developed various laboratory and field testing methods designed to determine the resistivity of classes of synthetic materials to various industrial waste streams. The techniques monitor the change in chemical and physical properties of liner materials which occurs with time after exposure of the material to hazardous waste leachate or to pure chemicals. The results are far from complete, and the testing procedures used are not standardized, but the results thus far form the framework needed to assess chemical resistance of synthetic materials. The following provides a brief summary of the results of chemical resistance testing and identifies the major problems which exist regarding the interpretation of these results.

8.2.2.1 Synthetic Liner Service Life

The procedures available for testing the chemical reactivity of synthetic liner materials to attack by various chemicals were largely developed by liner manufacturers during product development. Recently, independent researchers have adopted these techniques for hazardous waste facility testing. Essentially, all current methods rely on the same basic principal. The chemical and physical properties of the liner material are determined prior to leachate exposure. Changes in these parameters are recorded as a function of time after material exposure to the leachate. The results are generally accepted for determining short-term resistance, but several researchers have ex-pressed reservations when the results are extended to the long-term case. Part of the problem is verification of long-term results. Short-term tests are accepted, since they have been verified in the field. Since synthetic liners have been used in hazardous waste applications for only 10 years, long-term resistivity has not yet been directly verified.

In general, current liner testing research is hampered by the lack of specific guidance regarding the essential difference between the concept of long and short-term resistance, and by the lack of any specific definition of chemical resistance or reactivity. The Interim Final Land Disposal Regulations introduced the concept of short- and long-term liner resistance, but failed to provide any guidance regarding the definition of these periods. Similarly, the concept of chemical resistance requires further definition. The current procedures monitor changes in chemical and physical properties. However, the specific properties monitored and the level of change which should be regarded as significant has not been defined. In order for further meaningful progress to be made in this area, further standardization of the reactivity concept and the definition of the interpretation of long- and short-term chemical resistance must be established.

### 8.2.2.2 Physical and Chemical Properties Used in Chemical Resistance Theory

The identified protocol used for testing the chemical resistance of synthetic materials essentially utilizes the monitored change of the chemical and physical properties of the liner material during exposure to hazardous waste leachate. There are no standards established which specify the particular properties used in the resistance assessment or the degree of change which should be regarded as a "significant" change. However, most facilities which test chemical resistance of liner materials report the following material change parameters:

- Weight change;
- Dimensional stability; and,
- Strength properties.

Other properties which are reported sometimes include: analytical properties (ash content, volatile fraction, etc.), hardness, and occasionally CED (cohesive energy density). Permeability of the liner to water is sometimes reported, and visual observations are generally included in the laboratory report.

Weight change appears to provide a good method of indicating liner reactivity. Unfortunately, the lack of any weight change by itself does not provide conclusive evidence of chemical resistance. In general, weight gains observed range from 2 to 50 percent of the original synthetic material weight. Generally accepted industry practice indicates that weight change of over 10 percent indicates poor chemical resistance.

Dimensional stability refers to the amount of swelling or contraction observed in a liner sample after exposure. There is no generally accepted range of dimensional change associated with acceptable chemical resistance of the liner. Acceptability of the liner material is determined on a subjective basis only.

The strength of the synthetic material and its' change during exposure are viewed as important resistance monitoring parameters, since the liner strength essentially provides a measure of its resistance to mechanical stress in the facility environment. Liner strength may increase due to the loss of plasticizers within the material, or strength may decrease indicating a softening of the liner. Softening of liner materials is generally associated with weight gain, swelling and an increase in liner permeability. There are no standards established to indicate the level of change in liner strength associated with chemical resistance or reactivity.

The results of a visual inspection are used to document the appearance of cracks or holes in the material, and to document evidence of delamination or discoloration. Most researchers do not subject the material to microscopic analysis, although this would appear to be warranted. The results of any visual inspection performed are subjectively treated in establishing liner acceptability, as no specific guidance for quantifying the results exists at this time.

8.2.2.3 Chemical Resistance Testing Procedures

Several procedures have been introduced as a means of testing chemical resistance of synthetic liner materials. Each procedure has specific advantages and disadvantages but all suffer from three common problems. Standard sample preparation and exposure protocols have not been established. Liner properties are used to indicate acceptability of liner materials, but parameters used vary by laboratory and the degree of change associated with material acceptance has not been standardized for any parameter. Finally and probably most important, there are no well defined procedures regarding preparation of the test leachate used to determine the chemical resistance of the liner material. The most commonly used laboratory test procedures and their advantages and disadvantages are discussed in the following sections.

<u>Pouch Test</u> - A pouch of liner material is constructed and filled with a test leachate solution. The pouch is immersed in water and the quality of the water bath is monitored to determine leak rates and liner deterioration.

Advantages:

- o Allows measurement of volume of chemical waste liquid which permeated the barrier materials; and,
- o Exposure of barrier materials to waste liquids on one side is comparable to field exposure.

Disadvantages:

- o Does not allow estimation of maximum permeability rates because test conditions do not simulate the driving force for vapor transport through the material;
- o Waste liquids contained in the inner pouch are not readily rejuvenated or replaced; and,

- Application of test is limited to thermoplastic and crystalline materials.

Immersion Test - A sample coupon of the liner material is immersed directly into a test leachate. Several procedures exist including the EPA Method 9090 which represents a first attempt at testing standardization.

Advantages:

- Exposes both sides of barrier material to waste liquids, thereby providing a more aggressive environment than field conditions;
- Applicable to all barrier materials; and,
- Waste liquids can be rejuvenated or replaced.

Disadvantages:

- Does not directly measure permeability

Tub Test - A tub of synthetic liner material is constructed, partially filled with waste and exposed to the environment. The level of waste is allowed to fluctuate to simulate surface impoundment conditions.

Advantages:

- Material is subject to the effects of the air/waste interface;
- The tub is exposed to normal climate conditions including temperature variation, sunlight, etc.

Disadvantages:

- The method does not provide a direct measurement of liner permeability;
- The method is most useful to simulate surface impoundment conditons. However, it can be used to simulate leachate sump conditions.

In-Service Tests - Several procedures are available, including sample coupon immersion and the construction of liner tubes which are partially filled with sand and placed in the leachate sump or direct-ly into the surface impoundment.

Advantages:

- o In-service tests provide a measure of liner resistance to the actual leachate produced within the facility;
- o The methods provide a direct measure of liner decay within a given facility, allowing the identification of significant liner problems before liner failure.

Disadvantages:

- o The technique cannot be used to simulate facility operation prior to facility construction.

The most advanced testing method at the present time is the immersion test. Several "standard" techniques are available including the following:

- o EPA Method 9090 Compatability Testing of Membrane Liners (draft)
- o National Sanitation Foundation Recommended Test Method for Determining Long-Term Performance of Membrane Liners in a Chemical Environment (proposed)
- o ASTM D471-79 Rubber Property-Effect of Liquids
- o ASTM D543 Resistance of Plastic to Chemical Reagents
- o Matrecon Test Method 3 Immersion of Membrane Liner Materials for Compatibility with Wastes

The EPA method represents a first step toward testing procedure standardization. However, further work is warranted. The EPA procedure does not provide standards for leachate preparation or immersion bath level maintenance.

### 8.2.2.4 Comparability and Applicability of Resistance Test Results

The present lack of standardization regarding sample preparation and analysis procedures precludes direct comparison of test results obtained from different laboratories. At the present time, chemical resistance determination is largely a subjective determination made by the researchers involved in performing the test. Since the attitude and motivation of the personnel involved in making this subjective evaluation may vary significantly, the results obtained are not likely to be directly comparable.

Synthetic liner selection must be based on quantifiable evidence of chemical resistance testing results. However, due to the broad range of materials available, it is not practical to test all synthetic material options. A definite need exists for a conceptual framework which would narrow the range of material options for specific leachate types. Solubility theory has been used by the chemical industry for this purpose in other applications. Essentially, solubility theory states that materials with similar chemical bonding energies will tend to dissolve each other. Materials with very different bonding energies would not affect one another. Solubility parameter theory can be used as a preliminary screening test to identify barrier material and hazardous waste combinations which should not be used because they are likely to dissolve each other. Additional research is needed to determine if the theory can be used to improve the identification of candidate materials for chemical resistance testing.

The results of the testing methods discussed are considered to accurately portray chemical resistivity of liner materials in the short-term. Long-term resistance is projected on the basis of these procedures. However, there is no formal justification for this extrapolation. Further research is required to justify this assumption through the development of a long-term chemical resistance data base.

8.2.2.5 Chemical Resistance Monitoring

The current chemical resistance testing procedures are not sufficiently advanced to be totally reliable, although they have been successfully compared to short-term (10 years) field experience. However, the critical importance of liner integrity to overall facility performance suggests that actual field monitoring of liner stability should be conducted. As mentioned, several in-service testing procedures have been proposed in order to provide a suitable mechanism for liner monitoring. Based on the information obtained during the course of this investigation, it would appear prudent to require field monitoring of liner stability.

The results of such a program would add to the limited data base available regarding long-term liner stability, and would provide an early warning of impending liner failure. Should liner decay be indicated, remedial action could be taken to repair the problem before contamination escaped the facility. This represents significant advantages over the current monitoring requirements, which identify the problem after leachate has entered the site environment.

### 8.2.3 Synthetic Cap and Liner Installation

The results of this study indicate that current techniques are available to adequately design and install synthetic liner systems. Unfortunately, these techniques are not always applied in a uniform manner to assure the integrity of the liner system. Field investigations revealed that certain aspects of the design and installation were accomplished using appropriate techniques in most cases. However, other aspects were poorly treated or ignored. The problem may be due to the lack of awareness of the importance of long-term liner integrity on the part of facility designers, constructors and operators. Improved design and construciton monitoring along with further technical guidance regarding acceptable synthetic cap and liner designs and installation procedures is required to correct this situation.

#### 8.2.3.1 Field Preparation

A number of specific field procedures and protocols have been identified to ensure that the installed components of a facility correspond closely with the design. Consideration should be given to the possibility of including some of the most critical procedures in the relevant guidance documents. Activities for which critical procedures have been identified include:

- Foundation preparation and bedding material selection
- Material stockpiling and handling
- Liner placement and seaming techniques
- Synthetic material storage and handling

- Construction of leachate collection system
- Sterilization of all soils used in providing liner support or protection
- Cap placement and compaction
- Quality Assurance/Quality Control activities

8.2.3.2 Quality Assurance and Quality Control

The results of the investigation of existing facilities uniformly indicate the need for the development of comprehensive quality assurance procedures to ensure the integrity of designed hazardous waste facilities. Most, if not all, of the problems encountered at existing facilities could have been readily avoided if a properly integrated quality assurance program was applied during facility construction. The required quality assur-ance program must address all aspects of facility design, operation and maintenance jointly to ensure adequate performance of the facility. Based on the investigative effort performed under this project, the development of an integrated quality assurance program is critically important to ensure the integrity of all waste facilities, in particular those with synthetic barrier systems.

Quality assurance/quality control necessarily involves formulation and approval of a comprehensive installation/construction plan, together with specified quality control inspections and confirmatory testing. The field testing of synthetic liner seams and the verification of the use of proper bedding materials is particularly important to facility performance.

8.2.3.3 Selection and Installation of Bedding Materials

Bedding materials above and below the synthetic membrane must be smooth in order to avoid damage to the liner during subsequent construction and operation of the facility. Coarse aggregate material should be avoided since it may puncture or stress the liner material. Specific guidance regarding the depth of bedding material or a suitable grain size is not specifically available. Most researchers agree that almost any sand or filtered soil would be suitable as bedding material. The minimum bed depth has not been established. However, a minimum base of approximately 6 inches of bedding material should be sufficient to protect the liner. Further technical guidance regarding the use of particular bedding materials and minimum layer depths may be justified.

8.2.3.4 Storage and Handling of Synthetic Materials

Liner materials must be properly stored and handled in order to avoid damage prior to field installation. Materials should be stored in a secure area to avoid damage by vandals. Synthetic materials are subject to blocking if exposed to sunlight (liner material bonds to itself if rolls are left exposed to sunlight). Therefore, materials should only be stored in covered areas. Finally, materials should not be excessively handled prior to placement. Repeated bending or folding, particularly in cold weather, results in the possible fracture and reduced tensile strength of the material.

#### 8.2.3.5 Sterilization of liner Support and Cover Soils

Organic material present in the soil layers in contact with the synthetic liner may result in penetration of the membrane. It is essential that soil sterilant be applied to all soil layers and subbase materials in the facility. Sterilant application should be performed in strict accordance with the manufacturer's specifications. Facility design specifications should include the specification of the maximum allowable organic content for all facility soil layers.

The facility cap should be constructed in order to minimize damage to the liner from burrowing animals and root penetration. The use of a layer of gravel or coarse sand above the liner and bedding material has been effective in reducing animal damage. The vegetative cover on the facility cap should be properly maintained to avoid in-migration of deep rooted plant species. A properly defined quality assurance program should be developed to insure proper design, installation and maintenance of the various liner protection mechanisms identified. If a suitable quality assurance program is provided, liner performance can be greatly enhanced.

#### 8.2.3.6 Liner Seaming Operations

Liner seams represent the weakest point of the synthetic liner material, if the seams are not constructed properly. Factory and field seams must be subject to thorough testing and inspection if liner integrity is to be assured. Synthetic liner seaming techniques vary depending on the specific liner material used. However, all seaming operations have the following components:

- o Cleaning the material to be seamed;
- o Applying solvent, heat or adhesive;
- o Applying pressure; and,
- o Providing sufficient time for curing.

During the factory seaming process, environmental conditions can be effectively controlled. However, field seaming is subject to the external environment at the site. Effective field seaming cannot be accomplished during periods of adverse weather, including windy conditions, precipitation events and cold periods. Adverse weather conditions have been responsible for weak seams at several locations. However, most poor field seams have resulted from the use of the wrong solvents and adhesives for the particular liner material. The critical nature of the seaming operation requires rigid qulaity assurance control. A comprehensive quality assurance testing and inspection program should include the following items:

- o Material certification and testing procedures;
- o 100 percent seam testing in the field;
- o Documentation of weather conditions during seaming; and,
- o Complete laboratory testing of sample seam sections.

Particular attention must be afforded when seaming new material to older liner material which has been exposed to the environment. Acceptable seams can be accomplished, but more intensive cleaning of the old material is required to remove any damaged surficial material prior to seaming. Similarly, the seaming of two different types of liner material require special procedures to insure compatability of seaming techniques.

Under a proper field inspection and testing program, synthetic liner seaming can be accomplished without jeopardizing liner performance. However, the operation should only be conducted under strict quality assurance supervision.

8.2.3.7 Subsidence

Subsidence occurs either due to poor compaction of sub-liner materials or, in the case of cover systems, due to the decay of waste materials. In the latter case, approximately 90 percent of the total settlement of the cover will occur within five years of site closure. Poor subsurface compaction and the resulting settlement was the most prevalent form of cover system failure documented during this investigation.

Some subsidence can be expected at all waste sites due to waste decay. However, through proper design, installation and operating procedures, settlement can be minimized. The facility design must incorporate a thorough geotechnical evalution of the facility foundation material and the facility installation must be monitored closely to ensure attainment of design specifications.

Some subsidence of the facility cap can be expected within any waste disposal facility. Synthetic liners can be reinforced to support the facility cap in order to accomodate this settlement. However, the added stress on the synthetic liner may weaken the liner with time. It has been suggested that the final facility cap be installed following the period of significant settlement. This approach would expose the facility to precipitation and weathering during the interim period between the end of facility operation and final closure. An alternative approach which appears more reasonable, is the installation of a temporary cap which is maintained until settlement diminishes. The temporary cap is then regraded and the final cap can be installed.

The study results indicate that more comprehensive facility design studies, along with more substantial quality assurance and quality control procedures during facility installation, are required to minimize settlement problems.

### 8.2.4 Synthetic Cap and Liner Performance

The overall performance of a hazardous waste facility throughout the operational and post-closure period is largely dependent on the performance of the synthetic barrier systems integrated within the facility. The synthetic barriers represent only one component of the entire facility. To a large extent, the performance of the synthetic liner system is dependent on the performance of other facility components. Essentially, the synthetic liner must be evaluated as a significant part of the total facility design concept. Due to the importance of the barrier system, it is necessary to view the other facility components in terms of their effect on the synthetic liner. The following section provides a summary of the attributes of synthetic liners and their relationship to other facility components.

#### 8.2.4.1 Period of Performance for Synthetic Liners

Better definitions of "long-term" (as used in the 40 CFR Part 264) and "service life" are needed to accurately assess synthetic cap and liner system performance. Physical and chemical properties of synthetic barriers change with time. Consequently, their performance must be assessed over a specified period of time. A definition of long-term should consider the time over which hazardous wastes retain their characteristics. A definition of service life should consider synthetic material properties. Preliminary definitions of these terms which should be further developed are:

> "Long-term is equal to or greater than the period of time that hazardous waste constituents migrate to the liner in amounts which result in their presence in ground water and surface water, at concentrations greater than background or National Interim Primary Drinking Water Standards"; and
>
> "Service life is that period of time over which synthetic materials retain physical and chemical properties and provide containment of hazardous wastes which prevent migration of hazardous waste constituents to the ground water and surface water at concentrations greater than background or National Interim Primary Drinking Water Standards."

8.2.4.2 Projected Service Life of Synthetic Liners

Synthetic materials have been available for a relatively short period of time. Actual synthetic liner field experience extends back over only 25 years, and field experience with synthetic liners used for hazardous waste containment extend over only 10 years. Therefore, the available experience base cannot be used to establish the anticipated period of performance of synthetic liners. Liner experts and researchers have developed various procedures to estimate liner life based on the rate of liner degradation over short test periods. The degree to which these procedures simulate actual liner decay cannot be verified using actual field data at this time.

The methods used to project service life vary. But all rely on the measured rate of change of the physical and chemical properties of liner materials over specified time periods. The procedure is similar to the chemical resistance testing discussed previously and suffers the same lack of standardization. Specific tests have indicated liner service life up to 150 to 200 years, which appears to be unduly optimistic. There is general agreement that high quality synthetic liners should last approximately 40 to 45 years in a hazardous waste environment. A more direct determination of synthetic liner service life is not available at present due to the lack of longer term field data.

### 8.2.4.3 Synthetic Liner Permeability

The effective permeability of a synthetic liner refers to the liner's ability to prevent migration of materials through the barrier system. Synthetic liners have been shown to effectively prevent specific leachate materials from migrating, except for "de minimus" leakage amounts due primarily to vapor transport through the liner. The analytical techniques required to predict the synthetic liner's performance with respect to specific leachate over time is presently available. However, the specification of the chemical components of a hypothetical leachate from a mixture of known hazardous wastes is not possible at this time. Similarly, it is not possible to specify with assurance which particular liner material is the optimum choice for containment of a specific leachate. Essentially, chemical testing procedures are far too time consuming to allow testing of a significant fraction of synthetic material and specific leachate combinations. However, specific testing of a suitable liner type and a class of leachate material can be performed using current techniques. Therefore, proper testing of a selected liner and a representative leachate can be performed to confirm basic facility design concepts.

8.2.4.4 Facility Design Considerations

A hazardous waste facility consists of a number of systems and subsystems. Cap and liner systems contain drainage and barrier subsystems. The integrated performance of all subsystems determines the ability of the facility to meet the general performance goal. A fault-effect analysis to determine the effect on the subsystems and overall facility performance, of failure of one subsystem, is necessary during design. Design should include at least the following fault-effect analyses:

- Clogging of leachate removal system and effect on barrier;
- Crushing of leachate drain pipe and effect on barrier;
- Hole in barrier and effect on leak detection and leachate removal system; and,
- Effect on liner of greater permeability in cap (resulting from holes or other causes) than in liner.

Worst-case conditions are typically used for such analyses. The design should be adjusted where a deficiency in specific subsystems is identified.

Greater confidence in the performance of cap systems can be provided by placing the final barrier component after subsidence has occurred. This may be accomplished, depending on waste characteristics, by installing a temporary cap until the rate of subsidence diminishes and then installing the final facility cap. An appropriate period of time for delayed placement of the permanent barrier may be determined by monitoring the rate of consolidation using settlement markers or by calculating consolidation for certain uniform wastes. Because waste liquids would still be produced, the leachate collection and removal system would have to operate during this extended closure period. The extended closure period may range from several months to several years.

Confidence in synthetic material performance may be increased by providing thick bedding material layers, particularly where bulky or sharp objects are placed in the facility. The current regulations require a 30 cm maximum leachate head above the barrier. The <u>Guidance Documents</u> place a dimensional and permeability limitation on the bedding material where it is to be used as the leachate drain layer. More cost-efficient leachate collection systems may be designed with negligible effect on performance if the 30 cm head is increased to 60 cm. This modification would not result in substantially increased leakage through synthetic liners because synthetic materials are not affected by minor changes in hydraulic pressure.

Synthetic barriers can be designed to resist stresses of anticipated minor differential subsidence or to elongate and conform to the dislocation. The amount of stress should be minimized by proper compaction and filling of the waste materials. Additional strength and higher confidence in long-term strength properties of the barrier can be accomplished using fabric reinforced liners. The design of good waste placement procedures should minimize subsidence. However, the increased stress on the synthetic liner may result in the eventual weakening of the liner system over time.

### 8.2.5 Failure Modes

Two primary failure modes have been identified for synthetic liner materials, the first is referred to as liner holes and the second is the "bathtub effect" failure mode. Some investigators refer to the vapor transport mechanism as a third failure mode. However, since vapor transport is an inherent property of synthetic materials, it should not be associated with any material failure of the liner itself. Rather, it should be viewed as a property of synthetic liners much as permeability is viewed as a property of soil liners.

#### 8.2.5.1 Liner Holes

Liner holes have been detected in most in-service liners, which have been tested. Essentially, liner holes range from pinholes resulting from poorly controlled manufacturing processes to holes caused by liner tears and punctures due to poor installation techniques. Based on the information available, it appears that liner holes can be minimized through the use of effective quality control programs throughout the manufacturing and installation process. However, it is unlikely that holes can be entirely eliminated from installed synthetic liners.

The significance of holes in the liner system with respect to liner performance is generally quite small if proper precautions were taken to minimize the number of holes present. For example, the presence of a one square meter hole or 25 million pinholes per acre of liner material would result in the same net leakage as an optimum clay liner syustem. This number of holes is far greater than that which would be expected in a good quality liner system. The study results indicate that with the implementation of a comprehensive quality assurance program the number of holes present in a synthetic liner can be minimized. The required quality assurance program must include a manufacturers' quality control program as well as a quality assurance evaluation of field installation techniques.

#### 8.2.5.2 Bathtub Effects

The "bathtub" or tarmac effect results from the gradual filling of a landfill unit with liquid due to the presence of a cap system with a higher permeability than that of the liner. Essentially, precipitation percolates into the facility through the cap at a higher rate than it can move through the bottom liner. The unit then fills with leachate which eventually escapes over the facility sidewalls. Bathtub effect problems have been noted in several existing landfill facilities, and are invariably the result of poor cap design and the lack of an effective leachate removal system.

The installation of a properly designed cap system is the most important design feature in eliminating bathtub effect problems. The second principal design feature is the leachate collection system. Essentially, the leachate collection system can remove leachate before a significant leachate buildup can occur, and thus avoid the bathtub problem. A third system, which is recommended, is the monitoring of leachate levels in the operating or closed landfill unit. The leachate level monitor would provide an early warning of potential problems in the event that the leachate collection system was not functioning properly. In the event of a rise in the leachate level, excess leachate could be pumped from the facility to allow sufficient time to repair the facility cap system. Based on the results of this investigation, it appears that "bathtub effect" failures can be avoided through proper design of the facility cap, the lechate collection system, and a leachate level monitoring system.

### 8.2.6 Performance Modeling

Basically, the results of the HELP simulations verified the expected seepage trends relative to climatic and design factors. Climate is the most important factor controlling the rate of seepage production. Low precipitation/high evapotranspiration climates, such as Denver, will result in lower seepage production. As expected, the more conservative the engineering design, the lower the seepage rate. Because of the limitations in the assumptions and operation of the HELP model, the simulation results cannot be considered to have absolute validity, but their utility lies in providing comparisons of differing release rates resulting from a range of differing design factors and climatic conditions.

The HELP simulation results imply that use of a double bottom liner system which incorporates both an FML and an underlying clay barrier (with a permeability of $1 \times 10^{-7}$ cm/sec or less) provides an advantage over either a single FML or double FML bottom liner system. The combination FML/clay system and FML-only systems all assume that complete seepage containment is achieved provided FML failure has not occurred. When FML failure occurs, the clay component in the combination FML/clay system serves as a "second defense". The value of the combination bottom liner system is most notable during the operating period before final cover is emplaced.

An added benefit of the clay component in the combination FML/clay double bottom liner system is the reduction in the seepage rate for as long as the leachate collection and leak detection systems are operated. In contrast, the failure of the FML-only bottom liner systems essentially negates the effectiveness for leachate collection. This implies that continued operation of the leachate collection and leak detection systems beyond the post-closure care period for functioning bottom liner systems will result in reduced final seepage rates.

## 8.3 RECOMMENDATIONS

The following provides a summary of recommendations which resulted from this investigation of synthetic liner and cap systems. Recommendations are provided for regulatory reform, additional technical guidance materials and for further research efforts. Some of the recommendations provided for regulatory reform and additional technical guidance materials should be viewed as long-term objectives, since further research will be required before the changes required can be completely specified.

### 8.3.1 Regulatory

The results of the study indicate that regulatory action is required to correct certain deficiencies in the current regulations to reflect an improved understanding of synthetic liner performance. The current regulation requires that liners must contain all leachate throughout the active life of the facility and minimize leakage thereafter. Synthetic liner systems cannot achieve total containment during the active life of the facility, due to their ability to transport vapor, and due to the presence of some liner leaks. They can, however, achieve minimal leakage of waste leachate, if properly designed and installed. The following regulatory recommendations assume that the total containment restriction will be modified to allow the use of synthetic barrier systems at hazardous waste facilities.

8.3.1.1 Quality Assurance and Quality Control

The results obtained from the investigation of failures at existing facilities strongly indicates the need for a formal quality assurance program to verify the achievement of design specifications at hazardous waste facilities. It is recommended that a comprehensive quality assurance and quality control program be established to control all aspects of the waste facility as part of the final land disposal regulations. The recommended program should include installation verification procedures as well as operational testing and maintenance provisions. The program envisioned should include requirements necessary to verify the following elements of facility design construciton and operation:

- A geotechnical evaluation of the site prior to preparation of design specifications, including soil samples, boring logs and soil testing results;
- Synthetic liner placement, and bedding material selection in accordance with design specifications for grain sizes and sterilization of subsurface materials;
- Chemical resistivity testing of proposed liner material and sample waste leachate;
- Inspection procedures to verify waste placement, cover requirements and compaction;
- Final cap liner placement, bedding layer placement and the installation of animal barrier and

vegetative drainage layers according to design specifications for grain sizes and sterilization of subsurface materials;

- o Verification of material composition for all liners, soils and barrier materials;
- o Verification of all synthetic liner seams;
- o Verification of waste composition prior to disposal;
- o Inspection and maintenance of liners, caps, surface vegetation and surface grades of all active and inactive waste units; and,
- o Inspection and maintenance of the leachate control system before and after waste placement.

#### 8.3.1.2 Synthetic Liner Service Life

The present regulations do not provide a working definition for "long-term" or "period of performance". Consequently, determining the ability of synthetic barriers to meet these requirements is not possible. Suggested definitions for these terms are provided in Section 8.2.4. It is necessary that the definition be sensitive to mobility characteristics of different hazardous wastes. It is recommended that a definition of "long-term" be included in the regulations.

#### 8.3.1.3 Closure Period Extension

Greater confidence in performance and increased design and operating flexibility may be gained by extending the closure period. Subsidence of cap systems can be kept to a minimum in some cases by delaying completion of the final cap system placement (especially the barrier component). Use of consolidation theory for high moisture soils, or observations of settlement markers can be used to determine the appropriate time to place the final barrier layer. It is recommended that regulations be modified to provide a longer closure period to allow the installation of a temporary soil cap system during the period of maximum subsidence. The method of subsidence monitoring should be included in the facility plan. Leachate collection and removal should be continued until final cap placement occurs.

8.3.1.4 Leachate Depth Limitation

Chemical seepage through a synthetic barrier material is not dependent on hydraulic head, unless there are holes in the barrier. The requirement for a maximum of 30 cm of leachate head is therefore not appropriate for synthetic barriers. It is recommended that the limitation on leachate head be increased to 60 cm to allow a thicker leachate collection layer to provide more protection to the synthetic liner.

8.3.1.5 Cap Maintenance and Leachate Control

As previously discussed, the HELP analysis results indicate that further attention to the design of facility caps and leachate control systems is warranted. It is recommended that leachate level and quality monitoring be instituted within the facility during operation and the post-closure care period. Leachate-level monitoring provides a practical means of monitoring cap and leachate collection system performance. Should a problem occur in either system, a rise in leachate levels would be detected allowing correction of the problem before groundwater contamination occurred.

### 8.3.2 Guidance Materials

The results of the synthetic liner study indicate that further technical guidance is warranted in several areas related to the use of synthetic liner systems at hazardous waste facilities. Recommendations regarding the preparation of additional guidance material are provided in the areas of quality assurance of hazardous waste facilities and the specification of standard chemical resistance testing procedures.

#### 8.3.2.1 Quality Assurance and Quality Control

An integrated quality assurance program is required to ensure that all aspects of the hazardous waste facility are properly designed, installed and operated. A technical guidance document specifying the minimum requirements of a hazardous waste facility quality assurance program should be developed. The guidance material should provide a well documented quality assurance approach designed to verify the proper design, installation, operation, and maintenance of the following facility components:

- Facility foundation preparation;
- Bottom liner installation and maintenance;
- Liner material specification and testing;
- Leachate collection system design, installation and maintenance;
- Cap liner;
- Water quality monitoring system, including internal facility water levels;
- Waste composition;

- o Waste compaction and cover; and,
- o Facility unit management.

The development of such detailed technical guidance material is a significant undertaking. The task could be reduced significantly by adopting one of EPA's other quality assurance programs as a model for the hazardous waste program. The EPA has well established quality assurance programs associated with the Prevention of Significant Deterioration (PSD) program under the Clean Air Act and similar programs under other environmental regulations. While it would appear that an air-related program could not be modified to suit these requirements, it should be noted that a well designed quality assurance program provides a formal framework to verify attainment of technical specifications. The technical specifications are not actually incorporated into a quality assurance program per se. Further, the permit process under the PSD program is similar to the hazardous waste facility process.

8.3.2.2 Chemical Resistance and Projected Service Life Testing

A comprehensive chemical resistance testing protocol should be developed and included as guidance material. EPA Method 9090 provides a good starting base and should be improved by providing specific time and temperature conditions for immersion and material property testing, guidance on data interpretation, procedures for obtaining waste liquids for use during immersion, procedures for controlling waste liquid quality, and quality control procedures. Correlation of chemical resistance test results with field performance data should also be added to the Guidance Documents as the data becomes available.

Other chemical resistance testing procedures, which should be developed further and standardized include:

- o Pouch Test
- o Tub Test
- o In-Service Test

The standardization process should include the definition of standard liner properties used to determine chemical resistance and projected service life. In addition, the degree of change which constitutes acceptable chemical resistance should be specified for each testing method. Finally, the results of all chemical resistance and service life testing should be incorporated into a synthetic material data base, accessible to all liner research programs.

### 8.3.3 Future Research

Successful performance of synthetic barriers is dependent on their proper manufacturing and installation. Research can improve performance by identifying and developing techniques to monitor the quality of barrier materials during manufacture. Quality assurance procedures are currently available for seam testing, but more efficient methods would improve the quality and reduce the costs for barrier installation. Priority should be given to methods that reduce the level of expertise required to perform the test. Protocols should be developed for different polymer types since some testing procedures are not applicable to all polymers.

A centralized data base of chemical resistance testing and long-term field performance data should be developed. This data base would allow comparison of polymer formulations and waste combinations, and would also allow comparison of field data with chemical resistance testing data. The data base would be a valuable resource for new facility design and barrier material design, as well as a reference source for permit application review purposes.

The solubility parameter theory should be developed and tested to supplement its current capability to identify incompatible waste/barrier material combinations, with the capability to identify compatible barrier material candidates. Specific areas requiring investigation include:

- Provide more sensitive indicators of chemical resistance;
- Effect on solubility parameter resulting from interactions of polymer constituents and interactions of waste constituents;
- Long-term stability of solubility parameter under exposure conditions;

Continued development of the immersion test, the pouch test and in-service tests are needed to determine appropriate temperature conditions, methods to reduce volatile losses, and appropriate rate of stress application and relaxation during strength tests. Integral to both tests is the use of representative waste liquids. Procedures are needed to describe how waste liquids are obtained for the purpose of barrier material selection. A rigorous method to project performance from chemical resistance testing is needed.

Vapor permeation theory should be investigated to determine its significance with currently available barrier materials and materials currently under development. A consensus standard method for directly measuring the permeability of barrier materials is needed for improved barrier material selection and product development. Various wastes should be evaluated to more accurately assess the barrier permeability to aqueous and pure solutions of chemicals and to identify those chemicals which are most effectively contained by specific barrier materials.

A comprehensive evaluation of the significance of holes in barrier materials is needed to provide criteria for use in manufacturing and installation quality assurance programs. The evaluation should consider the size of holes, surface tension of barrier materials, hydraulic characteristics of underlying materials and characteristics of wastes and liquids which migrate through the holes. The influence on barrier performance should be evaluated on the basis of volumetric seepage rates as well as chemical mass transport rates.

The HELP model proved to be a very powerful tool in evaluating a variety of landfill design and failure conditions. The model should be further developed to assess its ability to incorporate barrier specific properties such as vapor permeation of specific compounds (e.g. hazardous constituent and water). Sensitivity analysis and field testing of the model to obtain correlation of predictions and actual performance are needed to provide permit officials and designers with accuracy and precision information needed to assess the significance of the model's performance predictions.