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EBASCO WORK ASSIGNMENT NO. 168-1L16

EPA CONTRACT NO. 68-01-7250

EBASCO SERVICES, INCORPORATED

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TECHNICAL MEMORANDUM CHEMICAL COMPATIBILITY EVALUATION OF THE PROPOSED CHARLES GEORGE LANDFILL COVER SYSTEM

CHARLES GEORGE LAND RECLAMATION TRUST LANDFILL SITE

TYNGSBOROUGH, MASSACHUSETTS

MARCH 1989

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EXECUTIVE SUMMARY

This document was prepared in response to Work Assignment No. 168-1L16 for the Charles George Landfill. The specific subject of this task is the evaluation of chemical resistance characteristics of the flexible membrane (high density polyethylene) and soil cover system as designed for the Charles George Landfill. This cover system was specified in a Record of Decision signed by the United States Environmental Protection Agency (EPA) in July 1985. Construction of the flexible membrane cap with associated systems for leachate collection, surface water diversion, and gas collection and venting is anticipated to begin in 1989. Chemical constituents of concern are those detected in gas and leachate generated at the Charles George Landfill site. This evaluation is based on a review of liner chemical resistance literature and data from the Charles George Remedial Investigation (Ebasco, 1988).

The literature concerning high density polyethylene (HDPE) and clay liner compatibility with landfill leachate has been comprehensively reviewed for the U.S. Environmental Protection Agency (Shafer, 1988). The review is appended to this report to provide more detailed information.

Chemical compatibility testing has not been performed for the proposed HDPE liner with the specific mixture of chemicals present in the Charles George Landfill gas and leachate. Without site-specific information, conclusions drawn are based solely upon the existing literature. The literature review performed for this study indicates several of the chemicals present at the Charles George Landfill can potentially affect the proposed cover system if present in high concentrations in the landfill gas or leachate. These chemicals, however, were detected in low concentrations during the Remedial Investigation and subsequent sampling, and are not believed to be concentrated enough to adversely affect the HDPE liner. Therefore, it is our opinion that the proposed use of the HDPE in the cover system for the Charles George Landfill is appropriate and we support its use. It is important to note, however, that if significant post-closure settlement of the landfill occurs, significant physical stresses to the HDPE membrane could result. These stresses could make the liner more susceptible to chemical aggression. The potential for post-closure settlement is being reviewed concurrently.

1.0 INTRODUCTION

The design of the Charles George Landfill site closure cap incorporates a minimum 6-inch layer of select common fill between the preliminary grade and the HDPE membrane. In locations where significant quantities of fill material will be placed to attain design grades, the HDPE membrane will be as much as 10 feet above the landfilled waste.

A leachate drain will be installed above the water table at the toe of the landfill slope to collect leachate seeping from the waste material. A drainage net layer will be installed directly beneath and, where slopes are less than 4H to 1V, above the HDPE membrane to transport leachate to the toe drain and surface water to the collection system, respectively. The subgrade fill material, 6-inch bedding layer, and drainage net are anticipated to transport and limit direct exposure of the HDPE membrane to the leachate. However, because the toe drain trench will be lined with the HDPE flexible membrane liner (FML), leachate accumulated in the toe drain will be in direct contact with the liner and could potentially affect it.

The recommended approach to designing a FML cover system is to perform chemical compatibility testing with the materials to which it will be exposed (EPA, 1983; H.E. Haxo, Jr., et al., 1985; McAneny, et al., 1985; Schwope, et al., 1985). In these tests, FML test specimens are exposed to the leachate and gas emissions and can be tested for changes in physical or mechanical properties. Based on the results of these tests, the liner is deemed compatible or incompatible with the landfill emissions.

This report first provides an overview of FML chemical compatibility. The discussion is then narrowed to those chemicals detected at the Charles George Landfill. A short discussion concerning the chemical compatibility of soil-based covers is then presented before conclusions are made.

The literature reviewed is listed in the references section of this report. A report prepared by the Army Corps of Engineers, which comprehensively reviews much of the literature on this subject, is appended.

2.0 CHEMICAL COMPATIBILITY OF FLEXIBLE MEMBRANE LINERS

The chemical resistance of an FML is evaluated by its behavior after exposure to waste materials. Generally, FML behavior is categorized by changes in specific physical properties. These changes can be caused by a number of reactions with the waste which can be affected by physical and environmental conditions (Tratnyek et al., 1985).

Chemical reactions can involve degradation of the polymer chain by a reagent in the leachate. These reactions alter the molecular chain and affect the properties of the material. The three most common chemical reactions are solvation, plasticization, and hydrolysis.

- **Solvation is a reaction in which organic solvents dissolve the FML by breaking the molecular bonds that hold the polymer chain together. Solvation can cause a polymer to swell when the solvent enters the polymer structure.**

- Plasticization is similar to solvation, except that the attacking solvent is not fully soluble in the polymer. The chemical concentrations will affect chemical reaction rates. This can affect the response time of a FML to waste material.

- Hydrolysis (i.e., the reactivity of a material with water) can also affect chemical reactions and is a problem with FMLs when substances such as aggressive ionic compounds and organic chemicals are present and contact a polymer. These compounds can be transported through the water to the polymer chain where a reaction can occur.

Chemical reactions can also be affected by the environment. Environmental conditions can accelerate liquid sorption and chemical reactivity. Environmental conditions of concern include temperature changes, exposure to sunlight (ultraviolet irradiation), and dimensional distress. A dimensionally distressed membrane is susceptible to environmental stress-cracking. Environmental stress cracking involves chemical attack on a stressed polymer by chemicals that have little effect on the polymer in its unstressed state.

2.1 HIGH DENSITY POLYETHYLENE LINERS

HDPE is the designed FML for the Charles George Landfill cover system. Currently HDPE membranes are generally produced without the addition of plasticizers and fillers which can be attacked by a variety of organic solvents. HDPE is manufactured by a low-pressure polymerization process that yields a linear chain. HDPE exhibits a high degree of resistance to oils, solvents, microorganisms, permeation by water vapor and gases, and ultraviolet light when carbon black is added to it. HDPE materials have been in field service for approximately 25 years; however, there is a general lack of definitive performance information concerning HDPE or other FMLs (Lyman et al., 1983).

HDPE is highly resistant to acids and alkalis, with the exception of oxidative agents. It exhibits a good resistance to other chemicals, but is susceptible to attack by some organic solvents. For example, in the presence of chlorinated hydrocarbons, HDPE can swell and lose strength. At elevated temperatures (i.e., approximately 160°F), it can become soluble in the presence of chlorinated hydrocarbons (e.g., carbon tetrachloride) (Richardson et al., 1987). HDPE is not soluble in acetone, carbon disulfide, aliphatic alcohols, glycerine, or ether.

HDPE materials have a higher coefficient of thermal expansion than other FML materials because HDPE is a crystalline polymer and HDPE sheets are normally thermally extruded. During installation, large-magnitude temperature fluctuations can create significant stresses at the seams. These stressed areas could be potentially exposed to reactive chemicals (i.e., soaps, surfactants, oils, detergents, or organic substances) and environmental stress-cracking could occur.

A study by Nelson et al. (1985) showed that in a specific application, physical properties of an HDPE FML were altered after 4.75 years of service in the presence of high concentrations (greater than 50 parts per million [ppm]) of aqueous organic chemicals (e.g., chloroform, ethylbenzene, methylene chloride, tetrachloroethane, trichloroethane, toluene, 1,1,1-trichloroethane, and 1,2-dichlorobenzene) known to be aggressive to HDPE. The study data, however, also indicated little effect on the HDPE at lower concentrations of these compounds.

2.2 COMPATIBILITY OF HIGH DENSITY POLYETHYLENE WITH CHARLES GEORGE LANDFILL CHEMICALS

Existing literature, FML manufacturer brochures, and data sheets were compiled and reviewed by Schwope et al. (1985). This reference provided the most comprehensive data gathered for the chemical resistance evaluation of HDPE. The information obtained from this document and two HDPE FML manufacturers was compared to the surface water and gas vent emissions monitored at the Charles George Landfill site. Leachate and vent gas data were presented in the "Remedial Investigation (RI) and Feasibility Study (FS) Reports, Charles George Land Reclamation Trust Landfill Site, Tyngsborough, Massachusetts" (Ebasco, 1988). Table 1 identifies the compounds detected in the leachate and vent gas that were considered for compatibility evaluation.

TABLE 1

CHARLES GEORGE LANDFILL
VENT GAS AND LEACHATE CONSTITUENTS

Compound	Vent Gas Constituent	Leachate Constituent
Acids		
benzoic acid		X
Halogen Compounds		
1,1-dichloroethane		X
trans-1,2-dichloroethene		X
methylene chloride[1]	X	X
chloroform[1]	X	X
bromoform[1]	X	
vinyl chloride	X	X
1,2-dichloroethane	X	
trichloroethene	X	X
tetrachloroethane	X	
1,1,2,2-tetrachloroethane	X	X
1,1-dichloroethene	X	
carbon tetrachloride	X	
1,1,2-trichloroethane	X	X
chlorobenzene	X	
bromomethane	X	
heptachlor		X
Inorganic Gases		
hydrogen sulfide	X	
Hydrocarbons		
toluene[3]	X	X
ethyl benzene		X
xylene	X	X
benzene	X	X
Ketones		
4-methyl-2-pentanone[1]		X
2-butanone		X
acetone[2,1]	X	X
Hydroxl Compounds		
4-methylphenol		X
phenol		X

TABLE 1 (continued)

CHARLES GEORGE LANDFILL
VENT GAS AND LEACHATE CONSTITUENTS

Compound	Vent Gas Constituent	Leachate Constituent
Sulfur Compounds		
carbon disulfide	X	
ethyl mercaptan	X	
hydrogen sulfide	X	
Additional Organic Compounds		
tetrahydrofuran		X
ethyl ether		X

Ratings by Schwope, et al., 1985.

[1] **Schwope, et al., 1985; Table 13.**
[2] **At <30% acetone aqueous solution data available inferring good resistance.**
[3] **At <30% toluene aqueous solution data available inferring good resistance.**

There is a lack of data concerning the chemical compatibility of HDPE with 18 of the compounds listed in Table 1. Of the 14 compounds where qualitative or quantitative data does exist, five of the compounds are qualitatively rated as compatible with HDPE (benzoic acid; 1,1-dichloroethene; hydrogen sulfide; 2-butanone; acetone); two of the compounds are qualitatively rated as incompatible (bromomethane, carbon disulfide); and seven of the compounds (chloroform, 1,2-dichloroethane, carbon tetrachloride, chlorobenzene, toluene, xylene, benzene) are qualitatively and quantitatively rated as incompatible with HDPE when it is exposed to pure compound.

The results of this compatibility analysis appear to indicate that the HDPE liner is not chemically compatible at the Charles George Landfill. This is not necessarily true. The majority of the test data is from experiments conducted using pure chemicals. The use of this compatibility rating system for determining the compatibility of an FML material to a specific leachate is strongly cautioned by the authors (Schwope, et al., 1985). They state that the intention of this rating system is to provide a reasonable basis on which to make a preliminary selection of the FML type. With respect to the HDPE cover system for the Charles George Landfill, the HDPE liner is expected to be compatible with the vent gas.

It is also expected to be compatible with the leachate even in areas of direct contact (toe drain). Table 2 presents the compounds detected in the leachate during three different rounds of sampling; Phase I RI sampling (1984), Phase II RI sampling (1988), and post-RI sampling (1988). This table illustrates that contaminant concentrations in the leachate have decreased since 1984. Except for the maximum concentrations detected in the Phase I RI sampling, the low-level concentrations in the leachate are expected to have little effect on the HDPE liner. In addition, three of the major contaminants (acetone, 2-butanone, and benzoic acid) are compatible with HDPE.

It is expected, however, that the leachate will decrease in volume and increase in concentration following installation of the HDPE cover. Under this scenario, the leachate may approach the maximum concentrations detected in the Phase I RI sampling. If this occurs, the potential exists for the leachate to alter the physical properties of the HDPE liner in the toe drain system. This scenario is considered unlikely; however, periodic leachate sampling could be performed to assess changes in leachate concentration with time. If potentially harmful concentration levels are reached, liner sampling and/or replacement may be required.

To summarize, the HDPE liner is expected to be compatible with the Charles George Landfill vent gas and leachate for the following reasons:

TABLE 2
CHARLES GEORGE LANDFILL

SUMMARY OF ORGANIC COMPOUNDS IN THE LEACHATE SAMPLING EVENTS

ORGANIC COMPOUND	PHASE I RI[1] SAMPLING MAXIMUM	PHASE I RI[1] SAMPLING AVERAGE	PHASE II RI[2] SAMPLING	POST-RI[3] SAMPLING
Acetone	22,000	17,000	520	2,000
2-Butanone	21,000	16,429	38	1,600
4-Methyl-2-pentanone	1,800	1,185	--	76
Toluene	700	631	--	230
Benzene	--	--	--	88
Ethylbenzene	140	61	--	56
Total Xylenes	160	143	41	140
1,1,2,2-Tetrachloroethane	310	310	--	--
1,1,2-Trichloroethane	25	25	--	--
1,1-Dichloroethane	83	64.67	--	--
Trichloroethene	24	24	--	--
Trans-1,2-dichloroethene	290	211	--	--
Vinyl chloride	250	152	--	--
Chloroform	20	20	--	--
Methylene chloride	7,200	2,960	--	13
Benzoic acid	38,000	22,050	--	7,300
Phenol	3,000	2,075	1,200	650
4-Methylphenol	12,000	9,587	1,800	2,600
Heptachlor	0.12	0.09	--	--
Tetrahydrofuran	--	--	--	1,500
Ethyl ether	--	--	--	200

Note: All concentrations are μg/ℓ.

[1] Data from NUS 1984-1985 sampling
[2] Data from E.C. Jordan sampling (landfill well JLF-1)
[3] Data from EPA 1988 sampling (maximum of west lagoon sample #55661 or east lagoon sample #63343)

- the compounds in the leachate and vent gas are not pure and exist in lesser concentrations than those commonly used in compatibility tests;

- the HDPE liner, used as a cap, will have minimal contact with contaminated leachate and landfill gas because of the drainage net system and 6-inch bedding layer; and

- the HDPE liner, used as a toe drain, will have direct contact with the leachate; however, three of the major constituents in the leachate are compatible with HDPE. In addition, the present and future leachate concentrations are not expected to achieve levels that would have a deleterious effect on the HDPE liner in the toe drain.

3.0 SOIL-BASED COVERS

Natural soil covers are another type of commonly implemented cover system and have been in service for many decades. Although research indicates that the permeability of clay soils is known to be affected by pure solvents and commercial petroleum products in high concentration (Shafer, 1988), no information was found in the literature to suggest that dilute aqueous solutions (e.g., leachate or landfill vapors) detrimentally affect clay soil liners.

The United States Corps of Engineers (COE) produced a report entitled "Compatibility of Liner Systems with New Bedford Harbor Dredged Material Contaminants". This report presents an excellent comparison of the compatibility of both FML and natural soil liners with concentrated wastes and low-strength wastes. Based on the information presented in this report, it appears that a clay liner would also be compatible with the leachate and landfill gas at the Charles George Landfill. This report is included in the appendix of this technical memorandum.

4.0 CONCLUSIONS

The Nelson et al. study (1985) indicated that, at low concentrations, the organic compounds found in aqueous lagoon wastes had little effect on an HDPE liner. Organic compounds, including those that are potentially incompatible with HDPE, have been detected in leachate from the Charles George site, but at significantly lower concentrations than those cited in the study. These detected concentrations at the Charles George Landfill indicate that the HDPE membrane should be compatible with the leachate.

There is a lack of literature data on the effect of chemical vapors on FMLs. Without specific chemical compatibility testing of HDPE with the vapor to which it would be exposed, a definitive evaluation of the compatibility with vapor constituents cannot be made. However, in view of the relatively low chemical vapor concentrations measured in the emissions from the landfill and the incorporation of a venting system in the cover, the proposed HDPE membrane is expected to be compatible with the landfill gases.

The report by the USCOE indicates that a compacted clay liner, if properly installed, would also be expected to be compatible with the leachate and landfill gas at the Charles George Landfill. Therefore, compacted clay could be a viable alternative cover material for use during post-closure landfill maintenance.

Based on these findings, it is our opinion that the Charles George Landfill HDPE cover system appears qualified to provide service in this type of application. The HDPE liner is not expected to be exposed to concentrations of either the leachate or landfill gas constituents that could adversely affect the integrity of the liner. However, landfill settlement could physically stress the liner, thus making it more vulnerable to chemical degradation.

REFERENCES

Agranoff, J. (Editor). Modern Plastics Encyclopedia; McGraw-Hill, Inc.; Vol. 59; October 1983.

Bass, J.M., W.J. Lyman, and J.P. Tratnyek. "Assessment of Synthetic Membrane Successes and Failures and Waste Storage and Disposal Sites"; Arthur D. Little, Inc.; EPA-600/2-85/100; Hazardous Waste Engineering Research Laboratory; Cincinnati, Ohio; August 1985.

Ebasco Services, Inc. "Remedial Investigation Report Charles George Landfill Reclamation Trust Landfill Site, Tyngsborough, Massachusetts"; prepared by E.C. Jordan Co.; December 1987.

Haxo H.E., Jr., R.S. Haxo, N.A. Nelson, P.D. Haxo, R.M. White, and S. Dakessian. "Liner Materials Exposed to Hazardous and Toxic Wastes"; EPA-600/2-84/169; Hazardous Waste Engineering Research Laboratory; U.S. Environmental Protection Agency; Cincinnati, Ohio; 1985.

Kao, Y. "Effects of Gases/Vapors Permeability on Flexible Membrane Liners Used as Cover Systems"; Final Report; Hazardous Waste Engineering Research Laboratory; Cincinnati, Ohio; May 1985.

Lord, A.E., Jr. and R.M. Koerner. "Fundamental Aspects of Chemical Degradation of Geomembranes"; Proceedings of the International Conference on Geomembranes; Denver, Colorado; published by IFAI; St. Paul, Minnesota; pp. 293-298; June 1984.

Lyman, W.J., K.R. Sidman, J.P. Tratnyek, M. Damani, J.H. Ong, A.D. Schwope, and J.M. Bass. "Expected Life of Synthetic Liners and Caps"; Draft Final Report; Arthur D. Little, Inc.; Municipal Environmental Research Laboratory; U.S. Environmental Protection Agency; Cincinnati, Ohio; 1983.

McAneny, C.C., P.G. Tucker, J.M. Morgan, C.R. Lee, M.F. Kelley, and R.C. Horz. "Covers for Uncontrolled Hazardous Wastes Sites"; EPA-540/2-85/002; Hazardous Waste Engineering Research Laboratory; U.S. Environmental Protection Agency; Cincinnati, Ohio; 1985.

Nelson, N.A., H.E. Haxo, Jr., and P. McGlew. "Recovery and Testing of a Synthetic Liner from a Waste Lagoon after Long-term Exposure"; Proceedings of the Eleventh Annual Research Symposium on Land Disposal of Hazardous Waste; EPA-600/9-85/013; Hazardous Waste Engineering Research Laboratory; U.S. Environmental Protection Agency; Cincinnati, Ohio; 1985.

Richardson, G.N. and R.M. Koerner. "Geosynthetic Design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments"; EPA-600/2-87/097; Hazardous Waste Engineering Research Laboratory; Cincinnati, Ohio; 1987.

Schwope, A.D., P.P. Costas, and W.J. Lyman. "Resistance of Flexible Membrane Liners to Chemicals and Wastes"; Arthur D. Little, Inc.; EPA-600/2-85/127; Hazardous Waste Engineering Research Laboratory; U.S. Environmental Protection Agency; Cincinnati, Ohio; 1985.

Shafer, R.A. "Upper Achushnet River Estuary Engineering Feasibility Study of Alternatives for Dredging and Dredged Material Disposal, Compatibility of Liner Systems with New Bedford Harbor Dredged Material Contaminants"; Draft Final Report; U.S. Environmental Protection Agency Region I; Boston, Massachusetts; January 1988.

Tratnyek, J., P. Costas, and W. Lyman. "Test Methods for Determining the Chemical Waste Compatibility of Synthetic Liners"; Arthur D. Little, Inc.; EPA-600/2-85/029; Hazardous Waste Engineering Research Laboratory; Cincinnati, Ohio; 1985.

U.S. Environmental Protection Agency. "Lining of Waste Impoundment and Disposal Facilities"; EPA SW 870; Municipal Environmental Research Laboratory, Office of Research and Development; Washington, DC; March 1983.

NEW BEDFORD HARBOR SUPERFUND PROJECT
ACUSHNET RIVER ESTUARY ENGINEERING FEASIBILITY STUDY
OF DREDGING AND DREDGED MATERIAL DISPOSAL ALTERNATIVES

Report No. 8

Compatibility of Liner Systems With New Bedford Harbor Dredged Material Contaminants

by

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Contaminated dredged material disposal	Liners

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

New Bedford Harbor sediments contain substantial amounts of both organic and inorganic contaminants. Leaching studies with this sediment indicate that the leachate generated from the disposal of these sediments may contain significant amounts of the same contaminants.

This investigation examined the available literature and data pertaining to the chemical compatibility of synthetic and natural liners with both organic and inorganic contaminants. Although compatibility testing with various liner materials and leachate with contaminant concentrations exactly like New Bedford Harbor sediment leachate is not available, testing with contaminant mixtures similar to and with higher concentrations has indicated no significant compatibility problems. Lining experience has shown that, with low contaminant-concentration mixtures such as the leachate generated from disposal of New Bedford Harbor sediments, problems with installation may be of more concern than liner compatibility.

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PREFACE

This study was conducted as a part of the Acushnet River Estuary Engineering Feasibility Study (EFS) of Dredging and Dredged Material Disposal Alternatives. The US Army Corps of Engineers (USACE) performed the EFS for the US Environmental Protection Agency (USEPA), Region 1, as a component of the comprehensive USEPA Feasibility Study for the New Bedford Harbor Superfund Site, New Bedford, MA. This report, Report 8 of a series, was prepared by the US Army Engineer Waterways Experiment Station (WES) in cooperation with the New England Division (NED), USACE. Coordination and management support was provided by the Omaha District, USACE, and dredging program coordination was provided by the Dredging Division, USACE. The study was conducted between January and June 1987.

Project manager for the USEPA was Mr. Frank Ciavattieri. The NED project managers were Messrs. Mark J. Otis and Alan Randall. Omaha District project managers were Messrs. Kevin Mayberry and William Bonneau. Project managers for the WES were Messrs. Norman R. Francingues, Jr., and Daniel E. Averett.

This report was prepared by Mr. Richard A. Shafer, Water Supply and Waste Treatment Group (WSWTG), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

The study was conducted under the general supervision of Mr. Norman R. Francingues, Jr., Chief, WSWTG; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL.

COL Dwayne G. Lee, EN, was the Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

This report should be cited as follows:

Shafer, Richard A. 1988. "New Bedford Harbor Superfund Project, Acushnet River Estuary Engineering Feasibility Study of Dredging and Dredged Material Disposal Alternatives; Report 8, Compatibility of Liner Systems with New Bedford Harbor Dredged Material Contaminants," Technical Report EL-88-15, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimetres
mils	0.0254	millimetres
pounds (force) per inch	175.1268	newtons per metre
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms

NEW BEDFORD HARBOR SUPERFUND PROJECT, ACUSHNET RIVER ESTUARY ENGINEERING FEASIBILITY STUDY OF DREDGING AND DREDGED MATERIAL DISPOSAL ALTERNATIVES

COMPATIBILITY OF LINER SYSTEMS WITH NEW BEDFORD HARBOR DREDGED MATERIAL CONTAMINANTS

PART I: INTRODUCTION

1. In August 1984, the US Environmental Protection Agency (USEPA) reported on the Feasibility Study of Remedial Action Alternatives for the Upper Acushnet River Estuary above the Coggeshall Street Bridge, New Bedford, MA (NUS Corporation 1984). The USEPA received extensive comments on the proposed remedial action alternatives from other Federal, state, and local officials, potentially responsible parties, and individuals. Responding to these comments, the USEPA chose to conduct additional studies to better define available cleanup methods. Because dredging was associated with all of the removal alternatives, the USEPA requested the Nation's dredging expert, the US Army Corps of Engineers, to conduct an Engineering Feasibility Study (EFS) of dredging and disposal alternatives. A major emphasis of the EFS was placed on evaluating the potential for contaminant releases from both dredging and disposal operations.

2. The technical phase of the EFS was completed in March 1988. However, as part of Task 8 of the EFS, the results of the study were compiled in a series of 12 reports, listed below.

- a. Report 1, "Study Overview."
- b. Report 2, "Sediment and Contaminant Hydraulic Transport Investigations."
- c. Report 3, "Characterization and Elutriate Testing of Acushnet River Estuary Sediment."
- d. Report 4, "Surface Runoff Quality Evaluation for Confined Disposal."
- e. Report 5, "Evaluation of Leachate Quality."
- f. Report 6, "Laboratory Testing for Subaqueous Capping."
- g. Report 7, "Settling and Chemical Clarification Tests."

h. Report 8, "Compatibility of Liner Systems with New Bedford Harbor Dredged Material Contaminants."

i. Report 9, "Laboratory-Scale Application of Solidification/Stabilization Technology."

j. Report 10, "Evaluation of Dredging and Dredging Control Technologies."

k. Report 11, "Evaluation of Conceptual Dredging and Dredged Material Disposal Alternatives."

l. Report 12, "Executive Summary."

This report is Report 8 of the series. The results of this study were obtained from conducting EFS Task 6, element 10 (see Report 1).

3. When contaminated dredged material is placed in a confined disposal facility (CDF), contaminated leachate may be produced. The leaching potential for New Bedford Harbor sediment has been investigated under another element of the EFS and is discussed in Report 5 of the series. Final results from the leaching studies and a detailed evaluation of disposal alternatives will determine if leachate control measures are considered necessary for all or a part of the contaminated sediment from the Acushnet River Estuary proposed for placement in a CDF.

4. Lining a disposal facility used to contain contaminated New Bedford Harbor dredged material is one potential contaminant control measure for preventing the escape of contaminants into adjacent surface water and underlying ground water. Both soil and synthetic membrane liners have been used to prevent contaminant migration from landfilled wastes. With the realization that highly contaminated wastes can have deleterious effects on liner materials, concern has grown in recent years over the compatibility of liner materials and contaminants. Because waste-liner compatibility is a relatively new concern in the disposal of hazardous waste and contaminated dredged materials, the data base available to properly evaluate a waste-liner system is limited and is based primarily on qualitative short-term studies. The ability to properly select a liner material for a specific disposal site is limited further by the fact that most compatibility studies to date have been conducted with concentrated, neat chemicals that, in most cases, do not represent the real-world disposal scenario of a low-concentration mixture of several different contaminants.

5. Compatibility testing of the proposed liner material with the waste or leachate that will be in contact with the liner has been suggested as a

method to evaluate the effects of contaminants on liner systems. The aerobic and anaerobic leaching data obtained from contaminated New Bedford Harbor dredged material indicate that the leachate that will contact the liner system has low contaminant concentrations (less than 10 ppm in most cases). This is particularly true of the polychlorinated biphenyls (PCBs) (<5 ppm) and other organics, which present most concern when evaluating waste-liner compatibility. The results of compatibility testing with low-level contamination are limited, in some cases contradictory and inconclusive, and generally based on short-term tests (USEPA 1983, 1986; Peirce and Peel 1985).

6. The extrapolation of short-term test results to predict long-term effects is suspect. Recent studies have also indicated that leakage resulting from installation and construction of liner systems may exceed any problems caused by waste-liner contaminant incompatibility (Bass, Lyman, and Tratnyek 1985). For these reasons, conducting an intensive, short-term, laboratory waste-liner compatibility program does not appear to be justified for evaluating liners for proposed confined disposal of New Bedford Harbor sediment.

7. This report will present available data on liner-contaminant compatibility and a review of problems associated with construction and installation of liner systems. A review of the contaminants being leached from contaminated New Bedford Harbor dredged material will also be presented.

PART II: COMPATIBILITY OF LINERS WITH CONCENTRATED WASTES

8. The chemical compatibility or resistance of a liner material refers to its ability to withstand two primary types of chemical attack: reaction of chemicals with the liner and absorption of chemicals by the liner. A liner material with good resistance to a particular chemical will neither react readily with nor absorb significant amounts of the chemical while in contact with it. If a liner material has poor resistance, reaction with or absorption of the chemical will occur, with resulting degradation of the desirable physical properties of the liner. Failure of the liner material may then follow (Stewart 1978). Liner materials considered as having applicability for lining a contaminated dredged material disposal site include flexible membrane liners (FML) and natural soil (clay) liners.

9. The purpose of a liner in a waste disposal site is to prevent transport of contaminants from the impounded waste into adjacent ground water or surface water systems. Liners may prevent contaminant transport by two mechanisms:

- a. Low-permeability materials may impede the flow of leachates and thereby limit the movement of contaminants into the subsoil and ground water.
- b. Liner materials may absorb or attenuate suspended or dissolved pollutants and reduce their concentrations so that they fall within acceptable limits set by regulatory agencies. This absorptive or attenuative capability is dependent largely upon the chemical composition of the liner material and its mass.

Most liner materials function by both mechanisms, but to different degrees depending on the type of liner material and the waste liquid and its constituents. Membrane liners are the least permeable of liner materials but have little capacity to absorb contaminants from the waste. They can absorb organic materials but, due to their small mass, their total absorption capacity is small. As stated earlier, this absorption of waste constituents may lead to incompatibility problems. Soil liners can have a large capacity to absorb materials of different types, but they are generally considered to be more permeable than synthetic membranes. However, the greater the thickness of a soil liner, the lower the flux through the liner (USEPA 1983).

Flexible Membrane Liner Compatibility

Testing methods

10. Flexible membrane liners are produced from mixtures of one or more base polymers with additives that may facilitate processing, provide desired physical properties, and/or protect the base polymer(s) from the effects of exposure to weather and soil burial. Except for highly compounded FMLs such as polyvinyl chloride, the base polymer is the main determinant of chemical resistance of a FML. The chemical resistance of any polymer is principally a function of its chemical structure, molecular weight, crystallinity, and degree of cross-linking. Each of these factors also influences a polymer's physical properties. Base polymers most commonly used for FMLs include the following.

a. Chlorinated polyethylene (CPE).
b. Chlorosulfonated polyethylene (CSPE).
c. High-density polyethylene (HDPE).
d. Polyvinyl chloride (PVC).

11. A flexible membrane liner may deteriorate by chemical interaction that reduces the physical properties of the FML to a point where failure occurs under the stresses present at the waste site or by permeation of the waste or its components through the FML. The latter may occur with little or no noticeable effect on the physical properties of the liner material (Schwope, Costas, and Lyman 1985). The determination of chemical resistance relies heavily on the results of physical property testing of liner materials following short-term immersion in neat chemicals, wastes, or leachates. The results are then compared with the properties of an unexposed specimen. An example of one compatibility test is the EPA Method 9090 immersion test (USEPA 1987). Although a consensus has not yet evolved, significant changes in one or more of the physical characteristics listed below are believed to be indicative of a lack of chemical resistance.

a. Weight.
b. Dimensions.
c. Tear strength.
d. Tensile strength.
e. Percent elongation at break.

f. Modulus of elongation.

g. Hardness.

In addition, semicrystalline polymers such as polyethylenes may also exhibit stress cracking as a sign of poor chemical resistance. Correlations between changes in these physical properties and changes, if any, in the barrier effectiveness of the FML have not been developed. Also, the long-term effectiveness correlation with short-term testing has not been developed or verified with field experience.

12. In addition to the above physical property tests, the chemical resistance of FML materials can also be measured by permeation testing. Studies have determined the following principles (Schwope et al. 1983, Surprenant et al. 1984):

a. Chemicals used to make polymeric materials will readily permeate similar polymeric materials.

b. For any given chemical, the permeation rate is a function of the polymeric material.

c. Permeation rates for certain chemicals/FML pairs can greatly exceed the minimum performance levels required for the clay-type liners.

13. The movement of a chemical through a nonporous polymeric sheet occurs by a three-step process.

a. The sorption of the chemical at one surface of the sheet.

b. The diffusion of the chemical through the sheet.

c. The desorption of the chemical into the medium in contact with the other surface of the sheet.

This process takes place on a molecular basis in contrast to bulk flow through porous media such as soils (Schwope et al. 1983, Haxo et al. 1984).

14. Several tests have been used in recent years to determine liner-waste compatibilities. The immersion, tub, and pouch tests have been found most useful in assessing the effects of the wastes upon lining materials. Procedures and equipment requirements for these tests are given in USEPA (1983).

15. In the immersion test, specific membrane liner samples are immersed in the waste, and the effects of the immersion on physical properties are measured as a function of immersion time. By immersing the samples totally in the waste fluid, a somewhat accelerated test is generated. Additional acceleration can be effected by increasing the temperature of the waste. However, it is believed that the closer the temperature is to actual field conditions,

the more reliable the results will be (USEPA 1983). Also, longer test periods result in a better prediction of field performance. An exposure period of 12 months or longer is desirable. Samples can be withdrawn at 1, 2, 4 (or more) months to assess the effects as a function of time.

16. In the tub test, a piece of the liner material is placed in a tub, and a sample of the waste is added. The tub is then exposed to the environment, and additional waste is added as required. The purpose of this test is to evaluate a FML under conditions that simulate those that occur in actual service. The effects of exposure to the waste and environmental conditions (sun, temperature, ozone, and other weather conditions) can be evaluated. The fluctuation of the waste level is particularly significant in that a section of the liner is subjected to both the waste and weather. This alternating of conditions is especially harsh on liner materials and may be typical of conditions encountered in the field.

17. The pouch test was developed to determine the permeability of a polymeric membrane liner material to water and dissolved constituents of the wastes. This test is limited to thermoplastic and crystalline membranes. A small pouch of the liner material is fabricated, within which a sample of the waste is sealed. The pouch is then placed in distilled or deionized water. Measurements are then taken periodically to determine the extent of leakage of the waste into the water or movement of water into the membrane and waste. Changes in the liner materials and their properties are observed and measured.

18. The cost of compatibility testing can be significant. The complete set of tests to measure changes in physical properties, such as weight, dimension, tear and tensile strength, elongation, and hardness, may cost $1,000. In addition, the waste fluid that will contact the liner must be obtained from the project site or generated in the laboratory. Depending on the length of time the compatibility test is run, the number of replicates used, and how often physical properties are measured, the costs for compatibility testing for one material may escalate rapidly. To run a 120-day compatibility test on one material in triplicate and measure physical properties four times would cost in excess of $15,000.

Tests results

19. As discussed previously, most compatibility studies have been conducted with concentrated neat chemicals. A recent study prepared for the USEPA compiled known data on the resistance of FMLs to waste chemicals

(Schwope, Costas, and Lyman 1985). The study attempted to develop a data base of all available qualitative and quantitative information on chemical resistance of FML-waste chemical pairs. Ratings were then developed for each chemical-material pair for which data were available. This included approximately 550 chemicals and 23 types of FMLs. As stated in the report, "the ratings are not appropriate, however, as a basis for selection or rejection of an FML since they do not take into account the intended application, nor have they been substantiated in field experience" (Schwope, Costas, and Lyman 1985). These ratings should be used only as a preliminary indication of the suitability of a particular liner material for a waste material. The data are presented in tabular form in Schwope, Costas, and Lyman (1985). The most noticeable factor of FML-chemical compatibility presented in this study is the lack of data and the number of gaps in the data base, which emphasizes that liner compatibility studies are currently in the developmental stage. Also of interest in these data is the amount of testing that has been performed on HDPE compared with other FML materials.

Natural Soil Liner Compatibility

Testing methods

20. The current state of knowledge on clay-chemical interactions is complicated by the dilemma of how to measure the permeability changes that appear to be caused by clay-chemical interactions. The question of what types of permeameters give valid measures of clay-chemical compatibility remains an important and controversial issue. Because permeability studies with different fluids have been carried out with various test protocols, test devices, and clays, quantitative data comparisons cannot be made. Only qualitative statements can be made regarding the behavior of certain clays in the presence of several types of fluids (USEPA 1986). A constant elevated pressure method that is considered suitable for performing comparative studies to evaluate the potential influence of waste leachates on the permeability of compacted clay soils that are candidates for use as liners is presented in USEPA (1983).

21. It has been known for many years that the permeability of clay soils may be drastically altered by chemicals present in the permeating liquid. Much of this knowledge was based on decades of experience resulting from the study of various chemicals on agricultural soils or on geological formations

important for oil production. The potential effects of certain organic fluids on clay permeability were recognized as early as 1942, when Macey's experiments with fireclay showed that the rates of flow for certain organic liquids through clay were "of an enormously higher order than for water" (Macey 1942). Since Macey's experiments, many researchers have investigated the effects of organic and inorganic fluids on clays in an effort to explain and predict the causes and changes in permeability.

22. Changes in the permeability of clay soils due to chemical interactions may result from a number of phenomena:

- a. Alterations in soil fabric stemming from chemical influences on the diffuse double layer surrounding clay particles.
- b. Dissolution of soil constituents by strong acids or bases.
- c. Precipitation of solids in soil pores.
- d. Soil pore blockage due to the growth of microorganisms.

The permeability of a soil may also be affected by the pore fluid velocity; for example, high velocities can displace small particles in the soil matrix. The fluid flow velocity can also influence chemical interactions that depend on the time of contact between the soil and chemical components of the permeating fluid. Thus, permeability and fluid flow velocity are interrelated characteristics of a soil-permeant fluid system (USEPA 1986).

23. Chemical influences on clay particles are the result of absorbed water within the clay particles being displaced by a fluid with a different dielectric constant or electrolyte concentration. This may lead to a change in the interlayer spaces of the clay. Such changes can cause the clays to shrink and crack, resulting in the formation of large conducting channels through the soil along with drastic increases in permeability. Desiccation of clays by certain organic fluids has also been reported by Anderson (1981).

24. Both strong organic and inorganic acids and strong bases will react with and dissolve aluminum, iron, and silica in the lattice of clay minerals. This dissolution can result in a release of mineral fragments that may migrate from their original position and leave enlarged pore spaces for conducting the permeant fluid through the clay. The increase in conducting pore size may give rise to an increased permeability if the particles migrate through the clay mass. If the particles lodge in a pore constriction, clogging the conducting pore spaces, a decrease in permeability may result (Anderson and Jones 1983). Studies have shown that sulfuric acid dissolves 3, 11, and 89 percent

of the aluminum present in kaolinite, illite, and smectite, respectively (Pask and Davies 1945). Other studies also suggest that kaolinite is less soluble than smectite in strong acids (Grim 1953).

25. The precipitation of solids in the soil-water system is controlled by ionic concentration and equilibrium solubility. Gypsum or jarosite may precipitate if the concentration of certain ions exceeds the solubility limits. A decrease in permeability may result if the formation of these precipitates clogs the pore spaces in the soil matrix (Shepard 1981, Dunn 1983).

26. The presence of microorganisms can affect the mobility of fluids through the soil. The attenuation of contaminants in soils may also be affected by microorganisms. Apart from the benefits of attenuation, the physical presence of the microorganisms as well as the gases produced by processes involving the microorganisms can cause blockage in the conducting pore spaces within soils, reducing the area for flow and decreasing permeability. This is particularly true when the permeant fluid is conducive to the growth of microorganisms (Fuller 1974).

<u>Test results</u>

27. Numerous studies have been performed to assess the effects of chemicals on clay soils. Among the classes of compounds that have been tested are aliphatic hydrocarbons, chlorinated aliphatics, aromatic hydrocarbons, alcohols, glycols, ketones, carboxylic acids, amines, and aromatic nitro compounds. Traditional clay-chemical compatibility studies have focused on concentrated, single-compound test solutions, although many studies have recently been conducted using complex chemical mixtures. Also, some tests have involved actual wastes or leachates. The results of some of the most significant permeability tests involving organic solvents are presented in Table 1. The results of permeability tests involving wastes are presented in Table 2.

28. As stated previously and seen in Tables 1 and 2, most clay-chemical compatibility studies to date have used pure, concentrated wastes. These studies have shown that certain pure, concentrated organics can drastically alter the permeability of clay soils under the conditions of the laboratory test. It should be emphasized that clay liners in disposal facilities are most often in contact with leachate having much lower organic solvent concentration than the test solutions associated with the drastic permeability increases seen in most laboratory studies to date. Laboratory studies

performed with less concentrated test solutions (either actual wastes or leachates or dilutions prepared in the laboratory) do not appear to produce large increases in permeability (Brown, Thomas, and Green 1984). Clay-chemical compatibility with low-concentration waste will be discussed in more detail in the sections that follow.

PART III: COMPATIBILITY OF LINERS WITH LOW-STRENGTH WASTES

Flexible Membrane Liner Compatibility

29. Flexible membrane liner-chemical compatibility data are primarily for concentrated, neat chemicals. Information on the resistance of liners to solutions or mixtures is available from Kays (1977), USEPA (1978), and August and Tatzky (1984). Quite often, these data are referred to in the literature as miscellaneous chemicals. In most cases, few details on the chemical composition of these types of waste are available, with only general descriptions such as "toxic pharmaceutical waste" or "rubber and plastic waste" provided.

30. Some permeation data for well-defined, multicomponent solutions have been reported (August and Tatzky 1984). The results of measured permeation rates for each component of an equipart, six-component solution through 1-mm-thick HDPE is presented in Table 3. For comparison, the permeation rates of the same components in neat form are also presented. For the four chemicals with data for both neat and the multicomponent solutions, the rates associated with the multicomponent solutions are less than one sixth the rate for the neat chemical. It appears that for this multicomponent solution, the interactions among the chemicals reduce their individual aggressiveness toward chemical attack and permeation (Schwope, Costas, and Lyman 1985).

31. August and Tatzky (1984) also investigated the permeation of low-solvent concentration (<5 percent) aqueous solutions through several types of liner materials. The results for HDPE are presented in Table 4. As an example, the trichloroethylene permeation rate for a solution having 1/1,000 the concentration of the neat liquid is 1/25 of that for the neat liquid. Equal permeation rates would have been expected since the chemical activity gradient across the membrane is the driving force for permeation. In a saturated solution, the activity of a chemical at saturation is equal to the chemical activity of that chemical in neat form. Thus, the driving force for permeation should be the same for both a saturated and a neat solution. The lower rates for the saturated solution may be due to poor mixing of the solution, such that at the solution/polymer interface, the local concentration was less than saturated. The lower rates could also be the result of solids precipitation at the solution/polymer interface.

32. A large volume of compatibility data is available from the resin manufacturers. Most of these data are interpreted qualitatively and are based on EPA Method 9090 (USEPA 1987) for waste-liner compatibility. The EPA Method 9090 is an immersion test that evaluates the changes in physical properties of the liner specimen. Several laboratory studies by Gundle Lining Systems, Inc. (1986), tested liner compatibility with wastes containing contaminants similar to those expected from New Bedford Harbor sediments. These studies included a heavy metal leachate, a saturated salt solution with 10-ppm chlorinated hydrocarbons, a creosote emulsion, a 10-ppm PCB waste, and others. In all the immersion tests that were conducted for 120 days at 23° and 50° C, "no significant loss in physical properties" was detected. A significant loss was considered to be greater than 10 percent.

33. Liner materials are also permeable to water in varying degrees. Since water is present in the ground, leachate, or waste in most liner installations, resistance to water may be a factor in liner selection. Data that have been normalized for thickness are presented in Table 5 (Haxo et al. 1984). Generally speaking, the olefin-based liner materials (i.e., HDPE through EPDM (ethylene/propylene/diene terpolymer)) are one to two orders of magnitude better barriers to water (on a per unit thickness basis) than the common chlorine-containing liner materials (i.e., neoprene through PVC, with the exception of the polyester elastomer).

34. The interpretation of short-term compatibility testing and the extrapolation of such data to evaluate the effects of long-term exposure are difficult. However, exposure to low concentrations of various chemicals for materials such as HDPE has indicated only limited changes, if any, in the liner's physical properties. A recent study attempted to assess the effects of long-term exposure on an HDPE liner (Nelson, Haxo, and McGlew 1985). Samples of a 100-mil HDPE liner were recovered from a waste lagoon in the northeastern United States after 4.75 years of service. Samples exposed to the waste were removed from different depths and tested to determine effects of the exposure on the physical properties of the liner. The impounded waste liquid was predominantly aqueous and contained significant amounts of organics, particularly chlorinated hydrocarbons, which increased in concentration with depth.

35. Table 6 presents data on the physical and chemical properties of the impounded waste sediment in direct contact with the liner, while Table 7

presents components and characteristics of the aqueous waste that may be potentially aggressive to the liner. Minute amounts of the PCB Aroclor 1254 were also detected in two samples. Table 8 presents the properties of the exposed HDPE liner in comparison with an unexposed sample. The exposed liner sample from the lagoon bottom showed a small amount of swelling (about 3 percent) and a 10-percent loss in both tensile strength at yield and in the modulus of elasticity. These changes do not demonstrate incompatibility, but they do indicate that the waste at the lagoon bottom had the greatest impact on the liner. The liner showed no cracking indicative of environmental stress-cracking. The liner lost in tensile strength at yield and in ultimate tensile strength; however, it did not crack at folds or bends. No evidence was found to indicate that the HDPE liner lost its integrity. All visible seams appeared secure. The only evidence of liner degradation was mechanical damages in areas where the liner had been worked on with earth-moving equipment during removal operations (Nelson, Haxo, and McGlew 1985).

Natural Soil Liner Compatibility

36. Studies of clay liner compatibility with pure solvent chemicals, binary mixtures of pure solvents, commercial petroleum products, and solvent-rich industrial waste have resulted in permeabilities higher by several orders of magnitude when compared with water. However, studies of clay liner compatibility with low-concentration mixtures, although few in number, offer encouraging results for clay liner-chemical compatibility. A study conducted for the USEPA stated that "the higher permeability to polar organic liquids diminishes as the organics are diluted with water, such that mixtures of over 50% water behave like water" (Brown, Thomas, and Green 1984).

37. Conflicting results have also been reported regarding the compatibility of clay liners with organic liquids. Compatibility studies with organic acids (acetic acid) resulted in initial decreases in soil permeability (USEPA 1983). Another study with a neutral polar organic (acetone) resulted in the same initial decrease in permeability (Green, Lee, and Jones 1981). Later studies have indicated that these tests may not have been run long enough to pass a sufficient volume of permeant to observe how the waste quids will actually affect the permeability of the clay liner. This

indicates the importance of running long-term studies if the effects of chemical compatibility are going to be determined by laboratory procedures.

38. The data available for weak organic mixtures and clay liners are limited; however, the information available for inorganic wastes and clay liner compatibility may be even more limited. A few qualitative studies have determined the effects of inorganics on clays. One study tested the effects of electroplating wastes on the hydraulic conductivities of four clays: pure montmorillonite, pure vermiculite, pure kaolinite, and White Stone clay. An increase in hydraulic conductivity was observed for the pure montmorillonite, while all other clays exhibited a decrease (Coia 1981, as cited in Peirce and Peel 1985). Care should be taken in interpreting Coia's data since his equipment and procedures were not well refined. The effects of zinc chloride and chromic acid on processed bentonite and White Stone clays were studied, and no significant changes in hydraulic conductivity were observed (Monserrate 1982, as cited in Peirce and Peel 1985). Metal hydroxides were tested with four clays: Wyoming bentonite, Groleg kaolin, vermiculite, and White Stone clay. Test results showed an increase in hydraulic conductivity for the bentonite exposed to alkaline permeants, while the hydraulic conductivity of the kaolin decreased upon permeation with the basic solutions (Tulis 1983, as cited in Peirce and Peel 1985). Two silty clay soils were tested with a synthetic acidic lead-zinc tailings leachate. In all tests, a slow decrease in hydraulic conductivity was observed (Dunn 1983). Commercial laboratories reportedly have conducted a great number of tests on different clays and leachates. However, most of the test results are not available because of confidentiality concerns. The permeants are typically reported to be complex mixtures of chemicals. For example, D'Appolonia, Inc. (1983), has compiled a lengthy list of test results indicating a slight change in hydraulic conductivity in some cases; however, no drastic changes have been observed.

39. A more recent study determined the effects of ferric chloride (500 mg/ℓ) and nickel nitrate (50 and 300,000 mg/ℓ) on three field clays (White Stone, Hoytville, and Faceville) using both fixed- and flexible-wall permeameters (Peirce and Peel 1985). The hydraulic conductivity results from this study are presented in Table 9. Ninety-percent confidence intervals were determined for all the tests in which more than one replicate was performed. From Table 9 it can be seen that no significant changes in hydraulic conductivity occurred in any of the clays as a result of permeation of the chemical

solutions. The leachate passing through the clay soils was also analyzed to determine if chemical breakthrough had occurred. The analyses indicated that no breakthrough occurred for the 500-mg/ℓ ferric chloride or the 50-mg/ℓ nickel nitrate solutions; however, chemical breakthrough did occur with the 300,000-mg/ℓ solution of nickel nitrate. No breakthrough was expected or observed for the lower concentrations since the cation exchange capacities (CEC) of the clays were not exceeded. Several hundred pore volumes of the low-concentration liquids would have been necessary to exceed the CEC of the clays (Peirce and Peel 1985).

40. Salt concentrations may also influence the permeability of clay soils. Studies have shown that the effects may be dependent on the type of clay being used for the liner. One study examined the influence of high salt concentrations (3.1-percent NaCl + 3.6-percent Na_2SO_4) on the permeability of two simulated clay liners constructed of smectitic clays (sodium-saturated and organic polymer-treated) and a sandy soil. The permeability of the organic polymer-treated smectite was unaffected by the concentrated salt solution; however, the sodium-saturated smectite (natural bentonite) underwent a 100-fold permeability increase in 7 days (Hughes 1975). The salt concentrations used in the Hughes study were approximately twice the concentration found in the New Bedford site waters.

41. In conclusion, although the compatibility data available for clay liner and low-concentration waste are limited and while strongly concentrated leachates may increase a clay's permeability, no examples have been found in the literature where very dilute aqueous solutions caused substantial permeability increases in clay soil liners (Anderson and Jones 1983). One potential exception may be water that contains low concentrations of strong surfactants. These compounds could increase the (intrinsic) permeability of a soil by decreasing the surface tension of water (Letey, Osborn, and Valoras 1975).

PART IV: NEW BEDFORD HARBOR SEDIMENT/LEACHATE CHARACTERIZATION

42. Contaminant release tests conducted on New Bedford Harbor sediments have indicated the potential for the release of elevated concentrations of metals and some organics when compared with other contaminated dredged materials (see Report 5). Preliminary testing of the composite sample has produced leachates with total PCB concentrations (Aroclors 1242 and 1254) of 4.4 ppm for batch testing and 0.018 ppm for permeameter testing. Additional organic analyses have indicated that all polynuclear aromatic hydrocarbon concentrations were below detectable limits. Analyses of inorganic species have shown relatively high concentrations of some metals (e.g., cadium (Cd), chromium (Cr), and lead (Pb)) when compared with other dredged materials that have undergone similar testing. Preliminary results of anaerobic batch leach tests and permeameter tests are presented in Table 10.

43. Potential leachate contaminants for New Bedford Harbor sediments include PCB and some inorganic parameters (Cd, Cr, and Pb). Due to the developmental stage of the work with chemical and liner material compatibility, it was difficult to find a waste that has concentrations of contaminants similar to the New Bedford Harbor sediments and has been subjected to liner and waste compatibility studies. Also, the proprietary nature of most waste materials subjected to compatibility studies by liner manufacturers for their clients does not allow the publication of exact waste stream characterizations. Instead, descriptions such as "heavy metal leachate" or "pharmaceutical waste" are used in the compatibility product sheets of liner manufacturers. Laboratory reports by Gundle Lining Systems, Inc. (1986), have indicated that no compatibility problems result when HDPE liner material is exposed to 10-ppm PCB waste. Also, due to the intrinsic inert nature of HDPE to inorganic compounds, no compatibility problems would be expected with HDPE and inorganic compounds at concentrations of 50 ppm.*

44. Compatibility data for clay liners are even more limited, and waste streams that have contaminant concentrations similar to New Bedford Harbor sediment leachate and have been subjected to clay liner compatibility studies are not available. However, a study conducted by the USEPA indicated that

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* Personal Communication, 1987, M. W. Cadwallader, Chemist, Gundle Lining Systems, Inc., Houston, TX.

mixtures of organics with over 50 percent water had no effect on clay (Brown, Thomas, and Green 1984). A study for the Chemical Manufacturers Association by Daniel and Liljestrand (1984) was conducted to determine the effects of dilute waste mixtures on five clay soils. One of the permeants was a liquid from an industrial waste impoundment that had similar or greater concentrations of five inorganic species as measured in the New Bedford Harbor sediment leachate. These metals and concentrations (in parts per million) were Cr (1.0), Cu (5.3), Pb (0.36), nickel (Ni) (0.18), and zinc (Zn) (6.0). This same liquid was also spiked with chloroform (200 ppm) and trichloroethylene (200 ppm) to simulate a landfill leachate contaminated with chlorinated hydrocarbons. In all cases, test results indicated that these dilute mixtures are not capable of causing significant changes in the permeability of natural clay liners (Daniel and Liljestrand 1984).

45. Because of the resistance of HDPE and clay liners to dilute organic and inorganic waste mixtures, no compatibility problems would be expected with New Bedford Harbor sediment leachate. As will be discussed in the following section, installation and operational factors for FMLs and clay liners may be of more significance to liner failure and contaminant release than exposure of the liner to the leachate expected with disposal of contaminated New Bedford Harbor sediments.

PART V: OTHER PROBLEMS LEADING TO LINER FAILURE

46. Several potential problems concerning the installation of liner systems are common to both FML and clay liners. Problems leading to liner failure may result from the improper preparation of the foundation that will support the liner, placement of the liner, and placement of backfill as a protection for the liner (Ghassemi et al. 1983). A study prepared for the USEPA that assessed liner materials exposed to municipal solid waste leachate concluded that the modest effects of the exposure on the liner materials did not indicate a compatibility problem and "that difficulties, if they arise, are more likely to be caused by poor workmanship in the site preparation or in the fabrication, by damage to the liner during installation, or by improper care during the operation of the facility" (Haxo et al. 1984) A similar statement can be made about the expected leachate that would result from disposal of contaminated New Bedford Harbor sediments and a clay or membrane liner with chemical resistance and mechanical properties similar to HDPE.

47. The installation of a liner in a nearshore environment similar to the sites being considered for disposal of New Bedford Harbor sediments presents additional unique and difficult construction problems. Traditional methods used to construct liners to control contaminant migration may not directly apply or, at the very least, may require extraordinary and costly installation efforts. The installation of a membrane or clay liner may require dewatering of a nearshore site to ensure proper foundation construction, to provide a clean, dry environment for seaming with an FML, or to achieve the proper compaction with a clay liner. Dewatering costs of a nearshore site would be significant depending on size and site-specific conditions. Flexible membrane liners may be seamed on dry land or a barge and then placed in the nearshore disposal facility; however, depending on the size of the completed liner, this operation may require an extraordinary coordinated effort of man and machines to properly and safely place the liner.

48. Liners for dike faces have been seamed and installed from barges with varying degrees of success. One attempt to place a liner directly on a riprap-protected dike face from a barge resulted in the liner being punctured

by the riprap.* This experience illustrates the requirement for a carefully prepared subbase that may require dewatering of a nearshore site, regardless of how the membrane liner will be placed. The changing environment unique to the nearshore disposal site, such as fluctuating water levels, tidal pumping, and gas-producing, organically rich bottom sediments, may also place physical stresses on both clay and membrane liners that may jeopardize the liner's integrity. The following sections discuss additional potential problem areas and experiences with the installation of FMLs and clay liners in upland environments.

Flexible Membrane Liners

49. Failures of membrane liners may result from waste-liner incompatibility when concentrated organic liquids come in contact with the liner; however, many other mechanisms are more likely to lead to an FML failure in actual field installations. A study prepared for the USEPA attempted to assess the success or failure of FMLs installed at 27 sites constructed between 1971 and 1983 (Bass, Lyman, and Tratnyek 1985). Failures during the preoperational period were defined as any condition of the liner that required nonroutine corrective measures to make the liner suitable for planned operation. Failures during operations were defined as any condition of the liner that caused (or threatened to cause) ground-water contamination. Based on these definitions, the 27 facilities assessed had a total of 12 failures at 10 sites. Only one failure was the result of waste incompatibility with a membrane liner.

50. Other failure mechanisms of impoundments lined with FMLs may include failure of the FML because of manufacturing defects, weathering, or physical-mechanical stresses. Defective installations, due to improper storage, transportation, placement, or seaming of the FML, may also result in liner failures. Liner connections, appurtenances, and lack of or improper placement of cover materials on the liner may also lead to liner failures. Contact damage as a result of puncture, vegetation, or shocks may lead to a type of liner failure. Improper subgrade preparation is an example of this type failure.

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* Personal Communication, 1987, John Dorkin, US Army Engineer District, Chicago, Chicago, IL.

Gas and liquid damages to an FML may result from gas or liquid uplift and wind or wave action. Geotechnical problems leading to liner failures may be slope instability, cover material sloughing, subsidence, or differential settlement. Other failure mechanisms may result from vandalism or seismic activity. A summary of potential failure modes for a double-liner system is presented in Figure 1.

51. Problems related to the storage and handling of FML materials may result from improper storage in a nonsecured area; improper scheduling to reduce time between delivery and placement of the liner; unnecessary folding and unfolding; and lack of or improper inspection of materials to identify and correct problems.

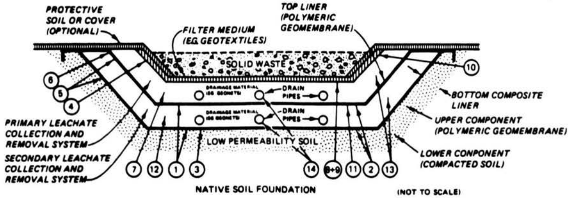
52. Problems associated with the placement of the liner include the following.

- a. Placement of panels in the wrong configuration (e.g., seams on side slopes oriented parallel rather than correctly perpendicular to the side).
- b. Placements that bridge a gap between two surfaces (e.g., at penetrations).
- c. Improper anchoring (e.g., backfilling anchor trenches before seaming is completed).
- d. Improper timing (for example, placement during inclement weather, including windy conditions).
- e. Placement of the liner with little clearance between it and the leachate collection pipes (this is often unavoidable per the requirements of the leachate collection system, but any ruptured pipe could potentially puncture the liner).

These problems may be avoided through the proper design and strict adherence to design specifications. Bridging may be avoided by ensuring complete liner contact with the supporting soil and proper compaction of the subgrade around connections. Anchoring the panel edges with sandbags before seaming and careful operation of equipment during anchor trench backfilling can reduce liner damage. Exact numbers of liners damaged during placement are not available; however, the problem of wind damage during placement operations is reportedly widespread (Ghassemi et al. 1983).

53. Seaming is the most critical operation in the installation of an FML. The following factors for good seaming practice may avoid common problems:

- a. Seaming procedures can vary for different liner materials and for the same material produced by different manufacturers. These



POTENTIAL FAILURE MODES OF GEOMEMBRANES:

1. PUNCTURE DUE TO SETTLEMENT OF COMPONENTS IN LEACHATE COLLECTION SYSTEM OR FROM IRREGULARTIES IN THE SUBGRADE.
2. ENVIRONMENTAL STRESS-CRACKING OF LINER AT BENDS AND CREASES.
3. BRIDGING CAUSED BY LOCALIZED SUBSIDENCE IN THE SUBGRADE.
4. SLOUGHING OF PROTECTIVE SOIL COVER DUE TO LOW COEFFICIENT OF FRICTION BETWEEN MEMBRANE AND SOILS.
5. TENSILE STRESS UNDER LOAD.
6. THERMAL CYCLING.
7. LOSS OF PROPERTIES DUE TO WASTE INCOMPATIBILITY.

POTENTIAL FAILURE MODES OF GEOTEXTILES:

8. LOSS OF PROPERTIES DUE TO WASTE INCOMPATIBILITY LEADING TO REDUCED FLUID FLOW.
9. CLOGGING OR BLINDING OF FILTER MATERIAL BY PARTICLES IN THE WASTE.
10. TENSILE STRESS UNDER LOAD.

POTENTIAL FAILURE MODES OF DRAINAGE NETS:

11. INTRUSION OF MEMBRANE INTO THE NET, LEADING TO CLOGGING.
12. LOSS OF PROPERTIES, LEADING TO REDUCED FLUID FLOW.
13. COLLAPSE OF THE MATERIALS UNDER WASTE LOAD.

POTENTIAL FAILURE MODES OF PLASTIC PIPE:

14. COLLAPSE OF PIPE UNDER LOAD, PARTICULARLY IF INCOMPATIBLE WITH WASTES.

Figure 1. Schematic diagram of a polymeric geomembrane/composite double-liner system and potential failure modes (after Haxo and Waller 1987)

differences should be carefully noted as plans for the seaming operation are devised.

b. Experienced labor, at least at the foreman level, is necessary to adequately address unexpected problems.

c. Weather conditions should be compatible with the seaming operations; in particular, excessive moisture, wind, and extremes in temperature should be avoided.

d. Solvents or adhesives, where these are used to make the bond, should be applied exactly as specified. Neither too little nor an excess provides adequate seam strength.

e. Likewise, pressure should be applied to the seam in accordance with specifications.

f. Slack and wrinkles should be removed, except those included intentionally to allow for thermal expansion/contraction.

g. Once completed, the seams should be allowed enough time to develop strength before being loaded.

h. Special attention should be given to making connections between the liner and structures.

i. Special precautions are required when new cap material is seamed to old liner material. These include ensuring that the bottom liner and cap are compatible when seamed, removal of the surface cure from the bottom liner using solvents and scrubbers, and repairing damage that the bottom liner suffers when uncovered.

The use of reputable installers, development of clear and concise specifications, and implementation of a comprehensive quality assurance program are essential to constructing adequate seams. A good quality assurance program should include checking to ensure proper positioning of the liner panels, cleaning of seam areas, proper overlaps, and suitable weather conditions. Test seams should be made and tested twice daily in shear and peel. All seams should be tested nondestructively over their full length. Samples of seams should also be tested destructively daily and the sampled areas properly patched and seamed.

54. All methods for the placement of backfill on a liner risk some damage to the underlying liner. Extra care must be taken when placing backfill on a liner to avoid damage to the liner. Construction survivability of the liner system has become an important consideration in recent years. The additional cost of using a thicker liner material such as a 100-mil* liner when compared with a 60-mil liner is small, and the added strength and protection against puncture during placement and backfilling operations is well worth the additional cost.** Additional strength against puncture may be obtained with the use of polyester fabrics used to underlay liner materials and may be required depending on the subbase provided. These fabrics also provide a cleaner environment for seaming the liner material and are well worth their extremely low cost. Proper design, use of clear and concise specifications, and an effective quality assurance program to ensure adherence to specifications are essential but not necessarily sufficient to install a properly functioning backfill without liner damage.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

** Personal Communication, 1987, Roy Leach, Civil Engineer, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

55. Although current knowledge and technology are believed to be sufficient to properly construct and install a flexible membrane liner system, many potential failure modes, other than chemical incompatibility, can jeopardize the integrity of an installed membrane liner system. When considering wastes with low contaminant concentrations, such as contaminated New Bedford Harbor sediments, experience indicates that leakage resulting from the construction and installation of the FML would far exceed any problems caused by liner-contaminant incompatibility.

Natural Soil Liners

56. Several potential problems, other than waste-liner compatibility, may lead to failure and leakage from a disposal site constructed with a clay liner. Problems with clay liner installation are primarily related to two areas. The first is the inability of laboratory permeability tests to accurately predict field liner permeability. The second problem area, which is partially responsible for the first problem area, is lack of proper inspection and quality assurance during liner installation.

57. Daniel (1984) alluded to a dozen cases in which the field hydraulic conductivity of clay liners used to retain fresh or salt water ranged from 10 to 1,000 times greater than anticipated even though, in most cases, the liner was designed using permeability tests performed with a permeant that was similar to the fluid in the field. In these cases, permeability tests with a permeant (fluid) representative of field conditions (compatibility testing) were not successful in predicting the performance of the liner. Daniel (1984) concluded that installation and construction methods may have far more impact on liner performance than liner compatibility with dilute waste streams. In this same study, features common to clay liner projects with high leakage rates were identified as follows.

- a. All of the liners were relatively thin (less than 24 in. thick).
- b. Liners were subject to some desiccation.
- c. Construction inspection was not as extensive as it might have been.

58. The details of construction of a clay liner are extremely important. Construction should be inspected to ensure that deleterious materials are not used, that compaction water content and compactive effort are correct, that

large clods of clay are properly hydrated and adequately broken down, and perhaps most importantly, that the liner is not allowed to dry out after construction has been completed. Without the proper inspection and construction practices to eliminate these problems, desiccation cracks, fissures, and other hydraulic defects may result, which could lead to leakage rates much greater than those resulting from compatibility problems between the clay liner and low-strength waste (Day and Daniel 1985). Additional problems may also exist where in situ clays are used. Failing to detect and remove discontinuities from the clay, such as sand or silt lenses, roots, and rocks, may lead to leakage of the liner. Similarly, where recompacted emplaced soil liners are used, inadequate protection of stockpiles from contamination may also result in leakage from the clay liner.

59. A number of shortcomings have been identified with regard to the use of clay liners, among which compatibility with low-concentration waste appears to be relatively minor. However, clay liners have several advantages:

- a. Fewer steps and parties are involved, and the procedures for completing installation are simpler.
- b. The state of the art is more developed due to considerable experience with other geotechnical projects.
- c. Favorable operating experience has been achieved with sanitary landfills sited on native clay deposits and from limited sites lined with recompacted clay.
- d. Fewer catastrophic failures have been experienced and, in addition, clay has the ability to attenuate pollutant migration in case of failure.
- e. Because of their greater thickness, clay liners have better ability to resist mechanical damage.

60. As with flexible membrane liners, many problems exist with the installation of a clay liner system. However, incompatibility with a low-contaminant concentration material such as leachate from New Bedford Harbor sediments does not appear significant when compared with other problems related to construction and installation of a liner system. As stated in a USEPA study assessing the failures and successes of lined waste sites (Bass, Lyman, and Tratnyek 1985), the "two main elements of success" at lined sites are considered to be:

- a. A proper philosophical and conceptual approach.
- b. The extensive use of quality assurance programs "in all facets and stages of a facility's operation."

PART VI: SUMMARY

61\. The characterization of New Bedford Harbor sediments and leachate indicates that only low concentrations of contaminants will come into contact with liner materials. This is particularly true of the organics, which are the contaminant of most concern when waste-liner compatibility is evaluated. Although some inorganic contaminants are elevated, experience has suggested that inorganic materials do not present a compatibility problem with clay or most FML materials. Waste-liner compatibility immersion tests (120 days) have been conducted by manufacturers and others, using HDPE and contaminants in concentrations similar to or greater than those expected in New Bedford Harbor sediments. These tests resulted in no significant change in the physical properties of the liner material.

62\. Although compatibility tests could be run on New Bedford Harbor sediments, there does not appear to be sufficient technical justification or need. Long-term compatibility tests would not provide additional beneficial data that are not available from the literature. Additional data generated by short-term compatibility tests would be of limited value in evaluating the long-term effects of contaminants on the liner.

63\. Many liner installations in upland environments have been plagued with foundation, fabrication, compaction, and protective cover problems that can lead to leaks and failures. Most of the problems associated with the construction of a liner system may be prevented or controlled with the proper design and extensive use of inspection and quality assurance/quality control (QA/QC) procedures. Liner installation in a nearshore environment would provide significant unique construction problems and physical stresses on the liner system during and after installation. Dewatering of the site would probably be required in a nearshore liner installation. All of these problems are far more likely to jeopardize the integrity of a liner system than the incompatibility of a liner material with a low-contaminant concentration material such as leachate from New Bedford Harbor sediments.

64\. If a liner system is to be considered for the proposed project, the design could incorporate either a clay or flexible membrane liner material. The decision to use natural soil or FML materials should be based on cost, availability, and practicality of installation depending on the type, location, and size of the proposed disposal site. The choice of a FML material should be based on available compatibility test results with the specific contaminant concentrations, as discussed earlier in this report. At a minimum, the strength of the FML material should be similar to or greater than 100-mil HDPE. If a natural soil liner material is used, the clay should be compatible with the saltwater environment. Bentonites are available that are resistant to saltwater environments; however, if native soils are used, short-term compatibility studies may be advisable.

65. Rigid specifications should be followed for installation of natural soil or flexible membrane liners. A diligent inspection and QA/QC program should be instituted, beginning with the fabrication, delivery, and storage of the material, whether FML or clay, and should continue through preparation of the subbase and installation of the liner. For a FML, the installation of the final protective cover should be conducted under the same strict inspection program.

REFERENCES

Acar, Y. B., Hamidon, A., Field, S., and Scott, L. 1984. "Organic Leachate Effects on Hydraulic Conductivity of Compacted Kaolinite," Symposium on Impermeable Barriers for Soil and Rock, American Society for Testing and Materials, Denver, CO.

Anderson, D. C. 1981. "Organic Leachate Effects on the Permeability of Clay Soils," M.S. thesis, Soil and Crop Sciences Department, Texas A&M University, College Station, TX.

Anderson, D. C., and Jones, S. G. 1983. "Clay Barrier-Leachate Interactions," National Conference on Management of Uncontrolled Hazardous Waste Sites, October 31-November 2, Washington, DC.

August, H., and Tatzky, R. 1984. "Permeabilities of Commercially Available Polymeric Liners for Hazardous Landfill Leachate Organic Constituents," Proceedings from International Conference on Geomembranes, June 20-24, Denver, CO.

Bass, J. M., Lyman, W. J., and Tratnyek, J. P. 1985. "Assessment of Synthetic Membrane Successes and Failures at Waste Storage and Disposal Sites," EPA-600/2-85-100, prepared by A. D. Little, Inc., for the Hazardous Waste Engineering Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Brown, K. W., Green, J., and Thomas, J. 1983. "The Influence of Selected Organic Liquids on the Permeability of Clay Liners," Proceedings of the Ninth Annual Research Symposium on Land Disposal of Hazardous Waste, EPA-600/9-83-018, Municipal Environmental Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Brown, K. W., Thomas, J. C., and Green, J. W. 1984. "Permeability of Compactd Soils to Solvent Mixtures and Petroleum Products," Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste, EPA-600/9-84-007, Municipal Environmental Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Buchanan, P. M. 1964. "Effect of Temperature and Adsorbed Water on Permeability and Consolidation Characteristics of Sodium and Calcium Montmorillonite," Ph.D. dissertation, Texas A&M University, College Station, TX.

Daniel, D. E. 1983. "Effects of Hydraulic Gradient and Field Testing on Hydraulic Conductivity of Soil," Progress Report, February-May 1983, US Environmental Protection Agency and the University of Texas, Austin, TX.

_________. 1984. "Predicting Hydraulic Conductivity of Clay Liners," Journal of Geotechnical Engineering, Vol 110, No. 2.

Daniel, D. E., and Liljestrand, H. M. 1984. "Effects of Landfill Leachates on Natural Liner Systems," report to the Chemical Manufacturers Association by the Department of Civil Engineering, University of Texas, Austin, TX.

D'Appolonia, Inc. 1983. "Data Compilation and Presentation for Column Testing Associated with Hazardous Waste Isolation," Project No. 83-1068, Research Triangle Institute, Research Triangle Park, NC.

Day, S. R., and Daniel, D. E. 1985. "Hydraulic Conductivity of Two Prototype Clay Liners," Journal of Geotechnical Engineering, Vol III, No. 8.

Dunn, R. J. 1983. "Hydraulic Conductivity of Soils in Relation to Subsurface Movement of Hazardous Waste," Ph.D. dissertation, Department of Civil Engineering, University of California, Berkeley, CA.

Everett, E. E. 1977. "Suitability of the Lacustrine Clays in Bay County, Michigan, for Land Disposal of Hazardous Waste," M.S. thesis, University of Toledo, Toledo, OH.

Foreman, D. E., and Daniel, D. E. 1984. "Effects of Hydraulic Gradient and Method of Testing on the Hydraulic Conductivity of Compacted Clay to Water, Methanol, and Heptane," Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste, EPA-600/9-84-007, Municipal Environmental Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Fuller, W. H. 1974. "The 'State of the Art' of Migration and Attenuation of Some Potentially Hazardous Polluting Trace and Heavy Metals, Asbestos, and Cyanide in Soil," University of Arizona, Tucson, AZ.

Ghassemi, M., Haro, M., Metzger, J., Powers, M., Quinlivan, S., Scinto, L., and White, H. 1983(Apr). "Assessment of Technology for Constructing and Installing Cover and Bottom Liner Systems for Hazardous Waste Facilities," Municipal Environmental Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Green, W. J., Lee, G. F., and Jones, R. A. 1979. "Impact of Organic Solvents on the Integrity of Clay Liners for Industrial Waste Disposal Pits--Implications for Groundwater Contamination," prepared for US Environmental Protection Agency, Ada, OK.

________. 1981. "Clay-Soils Permeability and Hazardous Waste Storage," Journal of the Water Pollution Control Federation.

Grim, R. E. 1953. Clay Mineralogy, McGraw-Hill, New York.

Gundle Lining Systems, Inc. 1986. "Chemical Compatibility Test Data," Laboratory Reports No. 671C, 1952, 1376, and 1824.

Haxo, H. E., Jr., and Waller, M. J. 1987. "Laboratory Testing of Geosynthetics and Plastic Pipe for Double-Liner Systems," Matrecon, Inc., Oakland, CA, presented at Geosynthetics '87 Conference, February 24-26, New Orleans, LA.

Haxo, H. E., et al. 1984. "Permeability of Polymeric Membrane Lining Materials," Proceedings from International Conference on Geomembranes, June 20-24, Denver, CO.

Hughes, J. 1975. "Use of Bentonite as a Soil Sealant for Leachate Control in Sanitary Landfills," Soil Laboratory Engineering Report Data 280-E, American Colloid Company, Skokie, IL.

Kays, W. B. 1977. Construction of Linings for Reservoirs, Tanks, and Pollution Control Facilities, John Wiley and Sons, New York.

Letey, J., Osborn, J. F., and Valoras, N. 1975. "Soil Water Repellency and the Use of Non-Ionic Surfactants," Contribution No. 154, California Water Research Center.

Macey, H. H. 1942. "Clay-Water Relationships and the Internal Mechanism of Drying," Transactions of the British Ceramic Society.

ichaels, A. S., and Lin, C. S. 1954. "Permeability of Kaolinite," Industrial and Engineering Chemistry, Vol 46, No. 6, pp 1239-1246.

Nelson, N. A., Haxo, H. E., Jr., and McGlew, P. 1985. "Recovery and Testing of a Synthetic Liner from a Waste Lagoon After Long-Term Exposure," Proceedings of the Eleventh Annual Research Symposium on Land Disposal of Hazardous Waste, EPA-600/9-85-013, Hazardous Waste Engineering Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

NUS Corporation. 1984. "Draft Feasibility Study of Remedial Action Alternatives, Acushnet River Estuary Above Coggeshall Street Bridge, New Bedford Site, Bristol County, Massachusetts," Pittsburgh, PA.

Olivieri, I. 1984. "The Effect of Organic Fluids on the Fabric of Compacted Clay," M.S. thesis, Department of Civil Engineering, Louisiana State University, Baton Rouge, LA.

Pask, J. A., and Davies, B. 1945. "Thermal Analysis of Clays and Acid Extraction of Alumina from Clay," Technical Paper 664, US Bureau of Mines, US Department of the Interior, Denver, CO.

Peirce, J. J., and Peel, T. A. 1985. "Effects of Inorganic Leachates on Clay Soil Permeability," Proceedings of the Eleventh Annual Research Symposium on Land Disposal of Hazardous Waste, EPA-600/9-85-013, Hazardous Waste Engineering Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Sanks, R. L., and Gloyna, E. F. 1977. "Clay Beds for Storing Solid Industrial Wastes--A Survey," Proceedings of the 32nd Industrial Waste Conference, urdue University, Lafayette, Indiana, Ann Arbor Science, Ann Arbor, MI.

Schramm, M. 1981. "Permeability of Soils to Four Organic Solvents and Water," M.S. thesis, Department of Hydrology and Water Resources, University of Arizona, Tuscon, AZ.

Schwope, A. D., Costas, P., and Lyman, W. 1985. "Resistance fo Flexible Membrane Liners to Chemicals and Wastes," EPA-600/2-85-127, Hazardous Waste Engineering Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Schwope, A. D., et al. 1983 (Mar). "Analysis of Flexible Membrane Liner Chemical Compatibility Tests," Draft Final Report, US Environmental Protection Agency, Washington, DC.

Shepard, T. A. 1981. "Geochemical Retardation Processes, Subsurface Contaminant Migration from Mine and Mill Waste Impoundments," Colorado State University, Fort Collins, CO.

Stewart, W. S. 1978. "State-of-the-Art Study of Land Impoundment Techniques," EPA-600/2-78-196, Municipal Environmental Research Laboratory, US Environmental Protection Agency, Cincinnati, OH.

Surprenant, N., et al. 1984. "Land Disposal Alternatives for Certain Solvents," Draft Final Report, Office of Solid Waste, US Environmental Protection Agency, Washington, DC.

US Environmental Protection Agency. 1978. "State of the Art Study of Land mpoundment Techniques," EPA-600/2-78-196, Cincinnati, OH.

US Environmental Protection Agency. 1983. Lining of Waste Impoundment and Disposal Facilities," EPA SW 870, Office of Solid Waste, Washington, DC.

__________. 1986. "Design, Construction, and Evaluation of Clay Liners for Waste Managment Facilities," EPA-530/SW-86-007, Office of Solid Waste and Emergency Response, Washington, DC.

__________. 1987. "Permitting Hazardous Waste Land Disposal Facilities - Seminar for Hazardous Waste Land Disposal Facility Permit Writers, Inspectors, and Operators," February 25-26, Research and Development Technology Transfer, Washington, DC.

van Schaik, J. C. 1970. "Soil Hydraulic Properties Determined with Water and with a Hydrocarbon Liquid," Canadian Journal of Soil Science, Vol 50, pp 79-84.

Table 1

Results of Permeability Tests with Organic Chemicals

Aliphatic and Aromatic Hydrocarbons

Heptane

Fixed-wall permeameter tests at high gradient with four clays showed rapid permeability increases and breakthrough. The increase in permeability was more than 3 orders of magnitude in an illite clay. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution. (Anderson 1981)

Benzene

The flow rate of benzene through fireclay was of an enormously higher order of magnitude than the flow rate for water. (Macey 1942)

In a column test under a head of 701 cm, signs of full penetration throughout the clay material were observed after 36 days; in a similar column with water as the permeant fluid, the liquid level dropped less than 2.54 cm over a 100-day period. Samples were 91 cm in height and 2.54 cm in diameter. (Personal communication, 1976, R. White, Trinity Engineering Testing Corporation, Corpus Christi, TX)

Following an initial decrease in permeability (compared with permeability to deionized water established in a similar sample), total breakthrough occurred on the eighth day of testing when Ranger shale was exposed to benzene in a fixed-wall permeameter under low hydraulic gradient. (Green, Lee, and Jones 1979)

Benzene did not penetrate compacted Ca-montmorillonite that was first saturated with 0.01 N calcium sulfate even at hydraulic gradients as high at 150. (Olivieri 1984)

In flexible-wall tests with a Georgia kaolinite, permeability decreased until the tests were terminated. The final value was approximately 2 orders of magnitude lower than the initial permeability. (Acar et al. 1984)

Xylene

Following an initial decrease in permeability, total breakthrough occurred on the 25th day of testing when fireclay was tested in a fixed-wall permeameter under low hydraulic gradient. In Ranger shale, a slight decrease in permeability was observed and remained steady until the test was terminated at 40 days. In Kosse kaoline, a slight decrease in permeability was followed by an increase to about the initial level, which persisted until the test was

(Continued)

Source: USEPA 1986.

Table 1 (Continued)

Xylene (Continued)

terminated at day 36; changes did not exceed half an order of magnitude. (Green, Lee, and Jones 1979)

In column tests under very low gradient, intrinsic permeabilities were higher than permeability to water by at least 1 order of magnitude in samples of Lake Bottom, Nicholson, Fanno, Chalmers, and Canelo clays. Permeabilities were slightly higher than for water in three other soils. The samples (5.8 cm in diameter and 5 cm in height) were presaturated with xylene. (Schramm 1981)

Fixed-wall tests at high gradient with four clays showed permeability increases and breakthrough followed by nearly constant permeabilities roughly 2 orders of magnitude higher than baseline permeabilities. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution. (Anderson 1981)

In fixed-wall permeameter tests at high gradient, the permeability of an unsaturated micaceous soil was 4 orders of magnitude higher when exposed to xylene than when tested with 0.01 N calcium sulfate. (Brown, Thomas, and Green 1984)

Xylene/acetone

In fixed-wall permeameter tests at high gradient, the permeability of an unsaturated micaceous soil to either pure acetone or pure xylene was greater than the permeability determined for mixtures of the two solvents. The permeability of a mixture of 87.5 percent xylene and 12.5 percent acetone was lower by 3 orders of magnitude than the permeability measured with pure xylene (though still higher than the permeability to 0.01 N calcium sulfate). When the acetone component was increased to 75 percent, the permeability was approximately the same as that determined with pure acetone (i.e., about 1.5 orders of magnitude greater than the permeability to 0.01 N calcium sulfate). (Brown, Thomas, and Green 1984)

Kerosene (a mixture of aliphatics and aromatics)

In column tests under very low gradient, intrinsic permeabilities were higher than permeability to water by approximately 1 order of magnitude in samples of Lake Bottom, Nicholson, Fanno, Chalmers, and Canelo clays. Permeabilities were slightly higher than for water in three other soils. The samples (5.8 cm in diameter and 5 cm in height) were presaturated with kerosene. (Schramm 1981)

In fixed-wall permeameter tests at high gradient, the permeability of an unsaturated micaceous soil increased by 3 to 4 orders of magnitude compared with the permeability determined with 0.01 N calcium sulfate. (Brown, Thomas, and Green 1984)

(Continued)

Table 1 (Continued)

Naphtha

The permeabilities of two clays (Na- and Ca-saturated montmorillonite) to naphtha were greater by several orders of magnitude than their permeabilities to water. (Buchanan 1964)

Soltrol C (a light hydrocarbon liquid)

Intrinsic permeabilities for samples tested with the light hydrocarbon were significantly higher than the permeabilities measured in similar samples exposed to water. (van Schaik 1970)

Diesel fuel

Fixed-wall permeameter tests at high gradient with an unsaturated micaceous illite produced highly variable data inconsistent with the pattern of permeability changes seen with other liquid hydrocarbons. Permeability was greater by 1 to 2 orders of magnitude than the permeability measured with 0.01 N calcium sulfate in a similar sample. (Brown, Thomas, and Green 1984)

Paraffin oil

In fixed-wall permeameter tests at high gradient with an unsaturated micaceous illite, permeability was greater by about 1 order of magnitude than the permeability measured with 0.01 N calcium sulfate in a similar sample. Maximum values were obtained after the passage of one pore volume. (Brown, Thomas, and Green 1984)

Gasoline

In fixed-wall permeameter tests at high gradient with an unsaturated micaceous illite, permeability was greater by 1 to 2 orders of magnitude than the permeability measured with 0.01 N calcium sulfate in a similar sample. (Brown, Thomas, and Green 1984)

Motor oil

In fixed-wall permeameter tests at high gradient with an unsaturated micaceous illite, permeability increased by about 1 to 2 orders of magnitude as 2.5 pore volumes of fluid were passed through the sample. (Brown, Thomas, and Green 1984)

Ethers

Dioxane

Kaolinite initially packed and permeated with water was permeated with anhydrous dioxane until complete displacement of the water was achieved.

(Continued)

Table 1 (continued)

Dioxane (Continued)

Replacement of water by dioxane was accompanied by about a 20- to 30-percent increase in intrinsic permeability. This permeability was much lower, however, than the values determined for kaolinite beds initially prepared with dioxane. (Michaels and Lin 1954)

Ketones

Acetone

In fixed-wall permeameter tests under low hydraulic gradient, three clays showed slight decreases in permeability (compared with permeability to deionized water established in a similar sample). All tests were concluded before 40 days. Less than 0.5 pore volume was passed through the sample. (Green, Lee, and Jones 1979)

Fixed-wall permeability tests at high gradient with four clays showed initial permeability decreases followed by increases compared with baseline. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution. Extensive shrinking and cracking in the soils were observed after permeation. (Anderson 1981)

In flexible-wall tests with a Georgia kaolinite, an immediate decrease in permeability was followed by an increase, the final value stabilizing at approximately double the initial permeability (Acar et al. 1984)

Acetone (high and low concentration)

An increase over baseline permeability (established with 0.01 N calcium sulfate in similar samples) was seen in an unsaturated micaceous soil for solutions where the acetone concentration was 75 or 100 percent. Samples tested with lower concentrations of acetone did not show appreciable changes in permeability compared with the 0.01 N calcium sulfate. Tests were carried out in fixed-wall permeameters at high gradient. (Brown, Thomas, and Green 1984)

Acetone (low concentration)

Permeability decreased slightly in a Georgia kaolinite clay tested in a flexible-wall permeameter with a solution containing a low concentration of acetone (i.e., below 0.1 percent) prepared in 0.01 N calcium sulfate. (Acar et al. 1984)

Alcohols, Glycols, Phenol

Methanol

Permeability decreased slightly (compared with permeability to deionized water established in a similar sample) when Ranger shale was exposed to methanol

(Continued) (Sheet 4 of 7)

Table 1 (Continued)

Methanol (Continued)

under low hydraulic gradient in a fixed-wall permeameter. The test was terminated after 30 days. (Green, Lee, and Jones 1979)

Fixed-wall permeameter tests at high gradient with four clays showed steady permeability increases compared with baseline. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution. Examination of the methanol-treated samples revealed development of large pores and cracks. (Anderson 1981)

Test results with Lufkin clay in flexible-wall cells showed essentially no change in permeability with time when samples were permeated with methanol. The permeability to methanol was virtually the same as with 0.01 N calcium sulfate. (Daniel 1983)

At high hydraulic gradients, kaolinite was found to have a higher conductivity to methanol than to water regardless of the permeameter types; fixed-wall, flexible-wall, and consolidation permeameters were used. In the flexible-wall and consolidation permeameters, kaolinite is about twice as permeable to methanol as to water. (Foreman and Daniel 1984)

Isopropyl alcohol

In column tests under very low gradient, intrinsic permeabilities were higher than permeability to water by almost 1 order of magnitude in samples of Nicholson, Fanno, and Canelo clays. Permeability values were the same or slightly higher than baseline in five other soils. The samples (5.8 cm in diameter and 5 cm in height) were presaturated with the alcohol. (Schramm 1981)

Glycerol

Permeability decreased slightly (compared with permeability to deionized water established in a similar sample) when Ranger shale was exposed under low hydraulic gradient to glycerol in a fixed-wall permeameter. The test was terminated after 36 days. (Green, Lee, and Jones 1979)

Ethylene glycol

Fixed-wall permeameter tests at high gradient showed permeability decreases compared with baseline followed by increases in three clays; a smectitic clay showed an initial rapid increase followed by a slower but continuous increase in permeability. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution (Anderson 1981).

(Continued)

(Sheet 5 of 7)

Table 1 (Continued)

Ethylene glycol (Continued)

In column tests under very low gradient, intrinsic permeabilities were an order of magnitude lower than permeabilities to water in Chalmers clay, Mohave clay, and River Bottom sand. Values were slightly lower in Lake Bottom, Nicholson, Canelo, and Anthony clays and slightly higher in Fanno clay. The samples (5.8 cm in diameter and 5 cm in height) were presaturated with the ethylene glycol. (Schramm 1981)

Phenol (949 mg/ℓ)

In column tests with a lacustrine clay (packed to discharge 2 ml/day), no significant effect on permeability was noted when deionized water was replaced by the phenol solution as the permeant fluid. (Sanks and Gloyna 1977)

Phenol (low concentration)

Permeability decreased slightly in a Georgia kaolinite clay tested in a flexible-wall permeameter with a solution containing a low concentration of phenol (i.e., below 0.1 percent) prepared in 0.01 N calcium sulfate. (Acar et al. 1984)

Phenol (high concentration)

In flexible-wall tests with a Georgia kaolinite and a high-strength phenol solution, an immediate decrease in permeability was followed by an increase, the final value stabilizing at approximately double the initial permeability. (Acar et al. 1984)

Amines

Aniline

Fixed-wall permeability tests at high gradient with four clays showed permeability increases and breakthrough. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution. Extensive structural changes in the upper half of the soil columns were observed following permeation wtih aniline. The aggregated structure was characterized by visible pores and cracks on the surface of the soils. (Anderson 1981)

Pyridine

The flow rate of pyridine through fireclay was of an enormously higher order of magnitude than the rate of flow for water (Macey 1942).

(Continued)

Table 1 (Concluded)

Chlorinated Aliphatics

Carbon tetrachloride

Permeability decreased slightly (compared with permeability to deionized water established in a similar sample) when Ranger shale was tested under low hydraulic gradient in a fixed-wall permeameter. The test was terminated after 14 days. (Green, Lee, and Jones 1979)

Trichloroethylene

Permeability decreased slightly (compared with permeability to deionized water established in a similar sample) when fireclay was tested under low hydraulic gradient in a fixed-wall permeameter. The test was terminated after 36 days. (Green, Lee, and Jones 1979)

Other

Acetic acid

Tests at high gradient in fixed-wall permeameters showed continuous permeability decreases to baseline in two clays. Tests with smectitic and illite clays showed permeability increases after initial decreases. Baseline permeabilities were established in the same sample with 0.01 N calcium sulfate prior to introducing the test solution. The permeability decreases were attributed to partial soil dissolution and migration of particles, which temporarily clogged the fluid-conducting pores. Progressive soil piping eventually caused the increase in permeability. (Anderson 1981)

Nitrobenzene

The flow rate of nitrobenzene through fireclay was of an enormously higher order of magnitude than the flow rate for water. (Macey 1942)

In flexible-wall tests with a Georgia kaolinite, permeability decreased until the tests were terminated. The final value was approximately 2 orders of magnitude lower than the initial permeability (Acar et al. 1984)

Table 2

Results of Permeability Tests with Wastes

- "Xylene waste" (paint solvent containing xylene with 25 percent paint pigments and trace amounts of water)

  In fixed-wall permeameter tests, the permeability of three clay soils, presaturated with 0.01 N calcium sulfate, increased rapidly upon exposure to xylene waste after the cumulative flow exceeded 0.2 to 0.4 pore volume. Permeabilities were 2 to 4 orders of magnitude greater than permeabilities measured with 0.01 N calcium sulfate. Highest permeabilities measured on initially unsaturated samples were greater by 1 to 2 orders of magnitude than for samples that were initially saturated with the calcium sulfate. (Brown, Green, and Thomas 1983)

- "Acetone waste" (a chemical manufacturing waste containing 91.7 percent acetone, 4 percent benzene, and 0.6 percent phenol)

  In fixed-wall permeameter tests, the permeability of three clay soils, presaturated with 0.01 N calcium sulfate, initially decreased (minimum permeability at approximately 0.5 pore volume) and then steadily increased. Permeabilities were 2 to 4 orders of magnitude greater than permeabilities measured with 0.01 N calcium sulfate. Highest permeabilities measured on initially unsaturated samples were greater by 1 to 2 orders of magnitude than for samples that were initially saturated with the calcium sulfate. (Brown, Green, and Thomas 1983)

- Perchloroethylene waste

  There is evidence that a perchloroethylene waste, which formed a separate, denser than water phase, contributed to the failure of a clay liner at a surface impoundment.

- "Acid prowl" (pesticide wash of very low pH; higher viscosity than water)

  After several days of exposure to a lacustrine clay packed in a fixed-wall column, the water reacted with the soil to produce chlorine gas. Over a 5-week period, the flow of liquid from the column was irregular due to clogging of pores by the gas. (Everett 1977)

- "Acid wash" (42 percent sulfuric acid with about 5 percent organics; higher viscosity than water)

  The permeability of lacustrine clay packed in shrink tubing increased by about 1 order of magnitude over a period of 19 days. The permeability was lower, however, than values obtained when the soil sample was exposed to water. (Everett 1977)

(Continued)

Source: USEPA 1986.

Table 2 (Concluded)

- "Mother liquor" (an acid wash with pH of 0.37; higher viscosity than water)

  The permeability of a lacustrine clay packed in shrink tubing was lower than the value obtained when the soil sample was exposed to water. The waste may have reacted with the soil, liberating gases and increasing pore pressures and clogging flow. (Everett 1977)

- "Hydrazo benzene" (33 percent methanol, 12.8 percent sodium hydroxide, 15.5 percent sodium formate, and 1.5 percent hydroazobenzene and azobenzene; more viscous than water)

  The permeability of a lacustrine clay packed in shrink tubing was slightly lower than the value obtained when the soil sample was exposed to water. Tests were carried out for 34 days under low gradient (less than 100 cm). (Everett 1977)

- "Acid waste" (100 mM HCl/ℓ)

  Due to reaction with carbonates, much higher permeabilities were observed in tests with lacustrine clay compared with permeabilities determined with deionized water. (Sanks and Gloyna 1977)

- "Basic water" (100 mM NaOH/ℓ)

  Permeabilities in a lacustrine clay decreased compared with the values measured with deionized water. (Sanks and Gloyna 1977)

Table 3

Permeation Rates of Six Common Solvents from a Single Multicomponent Solution Through a 1.0-mm HDPE Liner

Solvent	Concentration percent	Permeation Rate $g/m^2/hr$
Trichloroethylene	100	6.3
	16.7*	0.39
Tetrachloroethylene	100	2.5
	16.7*	0.34
Xylene	100	1.3
	16.7*	0.13
1-octane	100	0.07
	16.7*	3×10^{-3}
Acetone	—	—
	16.7*	0.06
Methanol	—	—
	16.7*	0.04

Source: August and Tatzky 1984.

* As part of a six-component solution of the six chemicals listed.

Table 4

Permeation of Common Solvents from Neat and Saturated Aqueous Solutions Through 1.0-mm HDPE

Solvent	Concentration wet %	Permeation Rate $g/m^2/hr$
Trichloroethylene	100	6.25
	0.1 (saturated)	0.25
Toluene	100	1.67
	0.05 (saturated)	0.08
Xylene	100	1.33
	0.02 (saturated)	0.07
1-octane	100	0.07
	0.001	$<4.2 \times 10^{-5}$

Source: August and Tatzky 1984.

Table 5

Water Permeation Through Flexible Membrane Liner Materials at 23° C and 50-Percent Relative Humidity (per ASTM E96 Inverted Cup

Liner Material	Values, g·mm/m²·day	Maximum g·mm/m²·day
High-density polyethylene	0.01, 0.02	0.02
High-density polyethylene - A	0.04	0.04
Low-density polyethylene	0.04	0.04
Polybutylene	0.06	0.06
Elasticized polyolefin	0.1	0.1
Ethylene/propylene/diene	0.14, 0.18, 0.29	0.29
Butyl rubber	0.02, 0.18, 0.33, 0.34	0.34
Neoprene	0.16, 0.38, 0.43, 0.54	0.54
Chlorosulphonated polyethylene	0.25, 0.27, 0.39, 0.4, 0.5, 0.68	0.68
Chlorinated polyethylene	0.22, 0.25, 0.29, 0.34, 0.62, 1.11	1.11
Polyvinyl chloride	1.24, 1.46, 1.47, 1.51	1.51
Polyester elastomer	2.1	2.1
Polyvinyl chloride - E	2.53	2.53
Polyvinyl chloride - OR	3.46	3.46
Nitrile rubber	4.2	4.2
Epichlorohydrin rubber	23.5	23.5

Source: Haxo et al. 1984.

Table 6

Physical and Chemical Properties of Sediment Samples Collected from the Lagoon Site on 25-26 July 1983

Parameter	Point of Sampling Lagoon Sump	B-2	G-7	G-3
pH	5.4	8.6	10.3	10.3
Flash point, °C	26	>60	>60	>60
Corrosivity	Noncorrosive	Noncorrosive	Noncorrosive	Noncorrosive
Ignitability	Ignitable	Not ignitable	Not ignitable	Not ignitable
Energy value,* BTU/lb	7,880			
Total residue, %	19.84	56.83	7.89	13.19

Source: Nelson, Haxo, and McGlew 1985.

* Dry-weight basis.

Table 7

Components of the Aqueous Waste and Characteristics Potentially Aggressive to the Liner in the Waste Lagoon

Waste Component or Characteristic	Sampling Point and Depth* G-3 3.0 ft	E-5 4.0 ft	Lagoon Sump 6.5 ft
Organic priority pollutant, mg/ℓ			
Chloroform	2.65	3.2	56.6
Ethylbenzene	3.30	9.6	1,080
Methylene chloride	102	140	325
Tetrachloroethane	1.7	3.8	182
Trichloroethane	28.6	90.2	9,100
Toluene	10.4	24.5	522
1,1,1-trichloroethane	0.31	--	50.0
1,2-dichlorobenzene	0.96	1.89	151
Other:			
Phenols, mg/ℓ	20	32	71
Total organic carbon, mg/ℓ	6,950	8,230	17,200
Petroleum hydrocarbons, mg/ℓ	26.0	27.8	2,100
pH	9.7	9.6	9.8
Flash point, °C	>60	>60	>60

Source: Nelson, Haxo, and McGlew 1985.

* Samples were taken from the greatest depths at three locations in the lagoon.

Table 8

Properties of HDPE Lagoon Liner After Approximately 4.75 Years in Service

Property	Direction of Test	Unexposed Sample of Similar HDPE	Sampling Location in Lagoon and Sample Number: Retained Sample,* No. 3	Slope Top, No. 8-Top	Slope Midway Up, No. 8-Mid	Slope Bottom, No. 7	Slope Bottom, No. 1
Analytical							
Volatiles, total loss, %		0.06	0.15	0.22	0.56	1.00	2.26
Over desiccant at 50° C		--	0.12	0.15	0.30	0.64	1.90
In oven for 2 hr at 105° C		--	0.03	0.07	0.26	0.36	0.36
Extractables, %		--	0.00	1.26	0.80	1.18	0.80
Physical							
Thickness, mil		103.0	102.3	93.4	103.6	100.6	92.4
Tensile at yield, psi	Machine	2,445	2,705	2,720	2,725	2,650	2,445
	Transverse	2,440	2,700	2,835	2,700	2,665	2,440
Elongation at yield, %	Machine	20	17	18	17	15	15
	Transverse	15	15	15	15	18	17
Tensile at break, psi**	Machine	4,635	3,530	4,810	4,510	3,605	3,710
	Transverse	4,445	4,065	4,355	4,885	2,735	3,885
Elongation at break, %	Machine	1,025	785	965	925	760	810
	Transverse	1,010	860	875	985	640	845

(Continued)

Source: Nelson, Haxo, and McGlew 1985.

* Sample from unused roll of liner left onsite.

** A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3 of the main text.

Table 8 (Concluded)

Property	Direction of Test	Unexposed Sample of Similar HDPE	Sampling Location in Lagoon and Sample Number: Retained Sample,* No. 3	Slope Top, No. 8-Top	Slope Midway Up, No. 8-Mid	Slope Bottom, No. 7	Slope Bottom, No. 1
Physical (Continued)							
Tensile set, %	Machine	900	680	840	805	655	700
	Transverse	890	750	760	860	550	730
S-100, psi	Machine	1,765	1,920	1,960	1,925	1,875	1,795
	Transverse	1,710	1,945	1,965	1,925	1,965	1,790
S-200, psi	Machine	1,765	1,930	1,955	1,920	1,870	1,835
	Transverse	1,720	1,940	1,963	1,925	1,955	1,790
Modulus of elasticity (psi × 10^4)	Machine	7.86	8.69	8.98	8.72	8.37	5.97
	Transverse	7.87	8.20	8.68	8.51	7.54	6.05
Tear, ppi*	Machine	839	900	920	910	855	830
	Transverse	850	885	910	890	875	830
Puncture resistance							
Gage, mil**		98.5	106	98.5	101	100	93.1
Stress, lb		131	148	139	135	134	118
Elongation, in.		0.73	0.66	0.72	0.62	0.61	0.59
Hardness, durometer points (D)							
Instant reading		--	60	58	59	59	58
5-sec reading		55	57	55	56	56	54

Table 9

Hydraulic Conductivity Test Results (× 10^{-8} cm/sec)

	Fixed-Wall Permeameter		Flexible-Wall Permeameter	
	Short-Term	Long-Term	Short-Term	Long-Term
White Stone Clay				
0.01 N $CaSO_4$	2.3 ± 0.3	1.6 ± 0.1	2.8 ± 1.6	1.6
500 mg/ℓ $FeCl_3$	3.7 ± 1.0	6.2 ± 2.0	2.1	ND*
50 mg/ℓ $Ni(NO_3)_2$	2.8 ± 0.6	3.0 ± 0.5	2.0	ND
300,000 mg/ℓ $Ni(NO_3)_2$	2.2 ± 0.5	ND	ND	ND
Hoytville Clay				
0.01 N $CaSO_4$	1.0 ± 0.3	1.6 ± 2.8	0.8 ± 0.3	ND
500 mg/ℓ $FeCl_3$	1.0 ± 0.1	ND	1.3	ND
50 mg/ℓ $Ni(NO_3)_2$	0.8 ± 0.1	ND	0.9	ND
300,000 mg/ℓ $Ni(NO_3)_2$	0.8 ± 1.4	ND	ND	ND
Faceville Clay				
0.01 N $CaSO_4$	3.8 ± 0.8	5.2 ± 1.3	6.3 ± 1.4	ND
500 mg/ℓ $FeCl_3$	6.4 ± 0.5	8.0 ± 6.9	6.2	ND
50 mg/ℓ $(Ni(NO_3)_2$	4.3 ± 2.6	11.0 ± 6.0	5.6	ND
300,000 mg/ℓ $(Ni(NO_3)_2$	5.1 ± 1.9	ND	ND	ND

Source: Peirce and Peel 1985.
* Not determined.

Table 10

Contaminant Concentration in New Bedford Harbor Anaerobic Batch and Permeameter Leach Tests

Parameter	Maximum Concentration Observed to Date, mg/ℓ Batch Tests	Permeameter Tests
Arsenic	0.0157	--
Cadmium	0.0146	0.0029
Chromium	0.356	0.375
Copper	1.060	0.017
Lead	0.396	0.01
Nickel	0.565	0.058
Zinc	1.830	<0.14

Source: Report 5.